Mobile Robot-based Exergames for Navigation Training and Vestibular Rehabilitation

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***Abstract*—The vestibular system is the leading sensory system that contributes to the sense of balance and to spatial orientation for the purpose of movement coordination. Vestibular disorders are incredibly common, and exhibit many different symptoms including vertigo, unsteadiness and navigation issues, but also emotional and social problems. Many of the assessment, training and rehabilitation approaches developed so far cannot guarantee the necessary degree of usability, measurability and repeatability. This paper presents the preparatory steps towards the design of a methodology for treating vestibular disorders that combines established methods with innovative, robot-based exergames to foster, among others, engagement and flexibility. Preliminary results obtained through a user study that involved non-pathological subjects offered helpful indications that could be exploited in the design and validation of novel rehabilitation protocols in the field.**

***Index Terms*—vestibular disorders, balance, spatial orientation, assessment, rehabilitation, robotics, gamification, exergames**

I. Introduction

In most mammals, including humans, the vestibular system is responsible for the sense of balance and for spatial orientation. The brain takes the information coming from this system as well as from the vision system, it combines them with proprioceptive input collected from other peripheral sensors (like skin, muscles and joints) and it uses them to understand body's dynamics and kinematics as well to control posture and coordinate movement. Besides balance, vestibular system plays a key role also in spatial navigation, i.e., in the ability to orient and move in a given environment with a determined goal.

A number of vestibular disorders are known, which challenge an incredibly high number of people with many different symptoms, from vertigo and dizziness to fatigue, unsteadiness, oscillopsy, as well as hearing loss. Disorders can also impact on cognitive capabilities, leading to poor concentration, scarce orientation and spatial representation abilities, as well as limited memory recall.

With the cochlea – a part of the auditory system – the vestibular system constitutes the inner ear. For this reason, treatment of vestibular disorders is often under the responsibility of an audiologist, who tests subjects' hearing and assesses how the parts of their ears actually work.

Despite the relevance of recalled aspects, the above specialists still lack objective tests to assess vestibular and navigation disorders which are easy to perform and quantify by also guaranteeing repeatability. Most importantly, training and rehabilitation protocols did not prove so far to be always effective. As a matter of example, two methods which can be used for assessing and rehabilitating vestibular and related disorders could be considered. The first one, known as the Cesarani's test [1], [2], has the goal to evaluate the navigation and the spatial orientation abilities while listening and executing a predefined sequence of directional commands. Test is so simple that, because of the learning effect, it cannot be used when the same subject need to be re-evaluated after some time. The second technique, which is reported in [3], is a rehabilitation exercise in which the subject is requested to memorize trivial trajectories (circles, squares, triangles) and to reproduce them by walking with open and closed eyes. Indeed, because of execution simplicity, the advantage of this methodology is that it is easily accessible to elderly or to people with severe balance impairment or spatial representation deficit; however, methodology appears to be poorly flexible, since it does not allow to train subjects on real life situations in which trajectories would be much more complicated.

Based on all of the above, in this paper the preparatory steps towards the definition of a new methodology for assessing, training and rehabilitating subjects with vestibular and navigation disorders are presented. By taking into account the limits of existing approaches, the idea pursued herewith is to leverage the opportunities offered by advancements in the field of robotics, and use them to make the tests (in the case of assessment) and the exercises (in the case of training and rehabilitation) easily configurable, sufficiently variable, properly quantifiable and highly engaging at the same time.

The methodology is grounded on recent findings in the field of robotic gaming, which led researchers to create a number of games in which players shares the play area with robots. In most of the case, existing toy robots are used to keep down costs and foster replicability. In some cases, games are developed for pure entertainment, whereas in other cases so-called serious games are developed, e.g., for educational

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purposes. In this paper, several tests and exercise games (generally abbreviated with "exergames") are designed by making use of a robotic gaming platform and a consumer-grade wheeled robot.

In these tests/exergames, the auditory and vestibular systems are simultaneously stimulated by making the robot emit sounds and move over trajectories that can be defined as needed and changed from time to time. Depending on the objective, subjects can be requested to move in the environment by looking at the robot and replicating its movements, to walk with closed eyes keeping at a given distance from it or to stand still and localize it by just listening to sounds emitted.

Preliminary experiments were carried out with normal subjects, in order to evaluate system potentialities. Promising results indicate that further work would be worth to be done in order to design a consistent rehabilitation protocol and to test the system in clinical settings. Notwithstanding, technology used (besides the robot, a home Virtual Reality setup is exploited to track the robot and the subject and to make the latter localize the former) already suggests that such a system could be particularly interesting not just for clinical but also for home use.

II. Background

Vestibular disorders can largely impact on all daily life activities, diminishing significantly the quality of life of affected subjects. As said, besides balance-related symptoms, vestibular disorders have been identified to be associated with spatial representation and navigation impairments (since these cognitive functions require vestibular input), as well as with various emotional problems like anxiety and depression. In many cases, these problems also lead to relational issues, as subjects tend to adopt sedentary behaviors in order to avoid the occurrence or the worsening of symptoms [4], [5].

For many subjects, deficit is so important that recovery from a vestibular system damage cannot be achieved through surgical treatments. However, evidences demonstrate that good results can be obtained through rehabilitation [6]. Exercises devised for vestibular rehabilitation leverage adaptation and compensation processes, which make the brain use other senses to substitute the deficient function.

Vestibular rehabilitation programs generally include habituation, gaze stabilization, balance and postural stability recovery as well as daily-life training exercises. Habituation exercises consist in the repeated exposure of subjects to specific movement and vision stimuli that causes symptoms appear [7], which is expected to reduce the magnitude of the response to stimulation itself. Gaze stabilization exercises are meant to improve ability to focus on a stationary object while the head is moving, by acting on the control of simultaneous eye and head movements [8]. Balance and postural stability recovery is used to improve subjects' steadiness by increasing their reliance on visual and somatosensory cues and letting them identify efficient and effective postural movement strategies replacing normal ones [9], [10]. Finally, the goal of daily-life training is to enable subjects return to their normal activities. Exercises generally encompass various tasks exposing subjects to a plurality of sensory and motor stimuli. Programs generally involve walking exercises (e.g., on a treadmill), though customized activities matching subjects' age, status and interest can be developed, thus reducing monotony and fostering engagement.

The earliest vestibular rehabilitation therapy was developed by Cawthorne and Cooksey [11], [12]. The therapy includes exercises belonging to more than one of the above categories, which are designed to encourage subjects relaxing the neck and shoulder, training eyes to move independently of the head, practicing good balance in everyday situations, practicing the head movements that cause dizziness and improving general coordination. The value of these exercises in managing various forms of vestibular disorders rapidly became apparent and, although variations have been developed over time, they still represent the cornerstone of any vestibular rehabilitation program.

Although for most of the subjects, standard exercises could be sufficient, in some cases more complex stimulations are needed [13], capable to better challenge diverse sensory strategies and better replicate everyday situations [14].

In this respect, new technologies have started making their way in many rehabilitation tasks since several years [15], [16]. For instance, Virtual Reality is used in [17]–[21] to let the therapists offer patients a wide range of highly specific stimuli and sensory conflicts with varying degrees of complexity in safe environments, whereas mobile devices and their sensors are being exploited to vehiculate rehabilitation exercises and perform assessment [22], [23]. Comparisons between conventional and technology-enhanced approaches are also available in the literature [24].

Taking into account the above considerations, this paper proposes to cope with the above challenges by combining serious games and robotics. The use of gamification approaches in rehabilitation of various disorders, including vestibular ones, is not new [25], [26]. At the same time, robots proved to be able to support rehabilitation processes in a number of contexts [27], [28]. Thus, by building on the concept of Phygital Play [29] and of Physically Interactive RoboGames (PIRG) [30], in this paper a robot-based methodology for treating vestibular disorders is proposed which includes several toy robot-based tests and exergames leveraging the robotic gaming platform presented in [31].

III. Treatment of Vestibular Disorders

In cases of chronic difficulty in adapting to a vestibulopathy, pharmaceutical and surgical treatments can fail in providing satisfying results. Hence, alternative solutions based on rehabilitation treatments have been developed [6]. The goal is not an anatomical recovery from the pathology, but rather the restoration of the altered functions which exploit adaptation properties and learning capabilities of the central nervous system. Basically, in vestibular rehabilitation the balance function is "reprogrammed" (reeducated) by acting on subject's cognitive-behavioral functions that control posture, pace, temporal and spatial orientation, etc. Rehabilitation of vestibular disorders is generally demanded to audiologists. Given the relation between the auditory and vestibular systems, audiologists often resort to tests and exercises that are meant to assess and train, e.g., balance, posture and spatial navigation skills, but also hearing-related capabilities.

A common tool used by the audiologists to deal with balance and posture problems is the stabilometric platform [32]. This tool can be exploited both in diagnosis and rehabilitation to assess the stability of a subject (patient) with vestibular loss and his or her postural strategies. Pressure sensors in the base allow the platform to determine the position of the subject's center of mass (center of pressure, or COP).

The platform can be used to carry out various types of exercises, both with close and open eyes; in the latter case, a screen can be used to display information relevant for the exercise. In a typical exercise on static posture, the subject sees his or her COP represented as a figure on the screen (e.g., a pendulum), and he or she has to keep it under given bounds by balancing his or her body (i.e., by controlling oscillations on the frontal plane). Another typical exercise requests the subject to intentionally control COP's movements with a goal. In this case, dynamic posture is addressed. COP is represented by a figure on the screen, and the goal for the subject is to "hit" a number of targets by swaying his or her body. Subject is not allowed to move his or her feet from the center of the platform and, depending on the goal set, he or she is requested to implement diverse postural strategies to succeed.

Tests are rather easy to perform for the subject, but hard to interpret for the specialist. In fact, a number of parameters are collected by the platform, including: average COP's coordinates on x (frontal plane) and y (sagittal plane) axes, surface (S) of the ellipsis which contains 90% of the sampled COP's coordinates (which corresponds to the precision of postural system), length (L) of the global COP's "path" (which is a proxy of the energy spent by the postural system), average velocity (V) of the displacements (standard deviation, in particular, provides insights on their uniformity), length as a function of the surface (LFS) reporting the correlation between L and S (under normal conditions it should be equal to 1), Fast-Fourier Transform (FFT) of oscillations (to study oscillations' frequency separately on the two planes), Romberg's index (RI), i.e., the ratio between values measured with closed and open eyes (basically describing the impact of vision on posture), stabilogram (which is the distance covered between consecutive samples) and statokinesigram (describing the position of the COP w.r.t. plantar stand, thus allowing to identify possible pathological COP's displacements), etc.

Concerning navigation, as said a rather common approach to assessment is based on the so-called Cesarani's test [1], [2]. The test is split in two phases, named *execution* and *reproduction*. In the first phase, the subject, blindfolded, is requested to carry out a sequence of movements based on commands received via headphones (to remove any possible spatial reference). Command sequence is standard, and is meant to define a given path on the floor which the subject is requested to remember by creating a sort of mind map of his or her position and displacements. In the second phase, the subject is requested to draw the path on a piece of paper based on his or her understanding of it. No time limit is set. Commands are reported in Table I, together with the corresponding evaluation criteria. The maximum score is 20. A normal subject usually obtains a score between 18 and 20 in the execution phase and between 15 and 20 in the reproduction phase. Although rather simple, the test analyzes quite complex mental processes concerning the ability to execute basic motor commands, to create mind maps, to use short term memory and to create spatial representations.

TABLE I: Cesarani's test: Commands and evaluation criteria (i.e., points assigned for motor and paper reproduction).

Command	**Motor repr.**	**Paper repr.**
One step to the left	2	2
Two steps forward	4	4
Rotate 90° clockwise	1	5
Two steps forward	4	4
Two steps to the right	4	4
Return to initial position	1	1

With respect to rehabilitation, several approaches already exist. For instance, the Cawthorne-Cooksey protocol [11], [12] mentioned in Section I is meant to treat vertigo and dizziness caused by vestibular disorders. The treatment includes four groups of exercises to be executed in bed, sitting, standing and moving about, and requires the presence of a specialist. Similarly, the Brandt-Daroff protocol [33] includes simple head movement exercises that can be performed at home without the need for a specialist. A technique which is specifically meant for the rehabilitation of navigation skills is reported in [3]; the technique requests the subject to look at a path drawn on paper or on screen (path can be any piecewise linear curve, in principle, through in general simple, geometric shapes are used), memorize it, and reproduce it by walking with closed eyes, then with open eyes, and then again with closed eyes. The aim of the exercise is to potentiate the spatial analysis and retention capabilities, by leveraging subject's ability to correlate vestibular and proprioceptive input with spatio-temporal movements performed.

With respect to the auditory system, basic assessment includes pure tone and speech audiometry tests.

The goal of pure tone audiometry test is to determine subject's hearing threshold. In a pure tone audiometry, subjects are requested to listen to pure tones in the range between 125 and 8000 Hz (doubling the frequency at each step) and tell the level at which they can hear the sound. Sound is generated by a machine which is calibrated in dB HL (Hearing Level). The test produces a so-called audiogram, i.e., a plot of hearing system response for each frequency. A pure tone average (PTA) measure is computed by averaging hearing threshold levels at specific frequencies (typically, 500, 1000, 2000 and 4000 Hz). Normal subjects have PTAs in the 20–25 dB HL range, whereas 95 dB is typically the PTA of subjects with a hearing function close to zero.

The goal of speech audiometry is to assess subjects' ability to discriminate the verbal message communicated by a given sound, i.e., to recognize and understand words and phrases in a given language. The subject needs to be informed beforehand of the audio material that will be used during the test (e.g., a list of 10-20 monosyllabic or bisyllabic words, logotomes, i.e., terms without a meaning, etc.). During the test, different types of masking noises can be added to sound in order to reduce intelligibility. Different sound levels are used, and the subject is requested to repeat the message heard. Results are reported on a plot, where the axis of abscissae reports the level in dB SPL (Sound Pressure Level), where the axis of the ordinates gives the percentage of correct answers. Three thresholds are computed: the detection threshold, i.e., the level at which the subject perceived the message but he or she was not able to repeat what he or she heard (usually equal to 0 dB SPL in normal subjects); the perception threshold, i.e., the level at which the subject understand 50% of the messages (10 dB SPL for phrases, 15 dB SPL for words and 20 dB SPL for logotomes in normal subjects); the intellection threshold, i.e., the level at which the subject understand 100% of the messages (20 dB SPL for phrases, 25 db SPL for words and 30 db SPL for logotomes in normal subjects).

IV. Proposed Assessment and Training Methods

As said, existing assessment and rehabilitation methods exploited in the treatment of vestibular disorders suffer from several issues which make them unsuitable in a number of application scenarios. In fact, they can be regarded as poorly flexible, too easy to remember and somehow hard to quantify.

In this paper, a robot-based methodology is proposed to assess and train balance, navigation and related (i.e., auditory) capabilities. The methodology is based on three phases, referred to as *pre-training*, *training* and *post-training*. In the pre-training phase, several routine tests for the evaluation of vestibular and auditory systems are combined with a robot-enabled test which is aimed to overcome the above limitations. In the training phase, two exergames are proposed, which builds upon existing rehabilitation exercises illustrated in Section III and extends them using robotic technology. Lastly, the post-training phase is meant to assess changes in a number of indicators possibly brought by training; to this purpose, tests in the pre-training phase are repeated with small variations.

In the following, the robotic platform will be first illustrated. Afterwards, tests and exergames will be described in detail.

A. Robotic Platform

The tests and exergames designed in this paper leverage a platform for robotic gaming that is being developed at Politecnico di Torino. The platform is meant to support the implementation of so-called "phygital games", i.e., games that integrate digital and physical contents by letting players seamlessly interact with them. Digital contents are created in Augmented Reality and displayed on the floor using a projector. Human players and robots are tracked using the Lighthouse's laser tracking technology developed by Valve (https://www.valvesoftware.com) and HTC (https://www.htc.com) for home Virtual Reality settings (though other technologies may be used as well): to this purpose, robots are endowed with a HTC Vive Tracker (a light, wireless receiver), whereas players hold a controller (which is a receiver too) in their hand or on their chest.

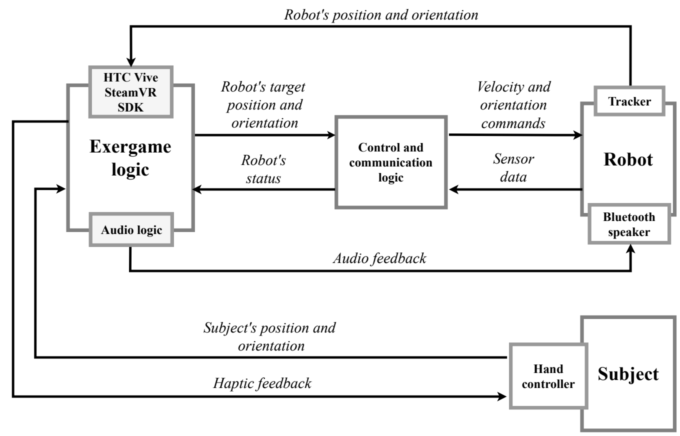


Fig. 1: High-level architecture of the devised system supporting the implementation of robotic tests and exergames.

In this work, projection was not exploited and a single player (trainee, patient) was considered. Although the platform can support, in principle, different types of robots, a Jumping Sumo mini-drone was used. The Jumping Sumo is a commercial off-the-shelf wheeled robot which is sold by Parrot (https://www.parrot.com) for about 100 USD. It is robust enough to carry both the HTC Vive Tracker (it could not be tracked, otherwise) and a Bluetooth speaker requested for sound reproduction (although the robot has an embedded speaker, it could not be used to reproduce custom sounds). System was exploited to create the test and the exercises described in the next sub-section.

The high-level architecture of the platform devised for this work is depicted in Fig. 1. As it can be seen, robot tracking data are sent to the system using the SteamVR SDK. The system includes a logic component implemented in Unity (https://unity3d.com), which is responsible to manage test/exercise's state, drive the robot and provide the subject with the appropriate feedback.

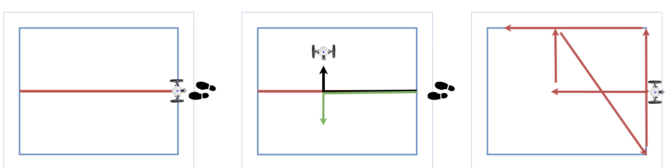
For the experiments, an 2.5×2.0 m area was defined for the robot and the subject to move into. Around this area, 25 cm were additionally considered to manage robot's overshoots.

B. Robotic Tests and Exercises

As said, in the pre-training and post-training phases, a test that leverages the functionalities of the robotic platform was included. Furthermore, two robotic exergames were developed for the training phase. Exergames were designed to be executed in visual deprivation conditions, in order to force the subject to use only his or her hearing system and short term memory to navigate the environment and localize the robot.

1) Robot Path Reproduction Test: This test has been designed to assess subject's navigation capabilities. The robot is used to address the limitations of the Cesarani's test, which make use of navigation commands that are too easy to remember and of a path that is too simple, by also lacking commands/path personalization possibilities.

The test builds upon the exercise exploited in vestibular rehabilitation which requests the user to execute a memorized path with his or her body [3]. The robot is programmed to travel a given path. The test is split in two steps, in which the subject is requested to reproduce the path both physically and on paper. In the first step (motor reproduction), the robot is positioned on one of the short edges of the rectangular area tracked by the HTC Vive system, facing the area itself, with the player right behind it so that they share the same orientation (Fig. 2a). The robot first travels the path, and the subject looks at it; when the robot has reached the opposite edge of the area, the subject is requested to reproduce the path, but specularly, i.e., by mirroring all the direction changes (Fig. 2b). In the second step, the subject is requested to reproduce on paper the path traveled by the robot. Like in the Cesarani's test, the idea is to assess subject's ability to recall a number of direction changes by keeping the same memory span. Hence, the path includes four direction changes at +/- 45°, 90° and 145° degrees. Two paths were designed for the robot, one for the pre-training phase, another for the post-training phase; path traveled by the robot in the pre-training phase (Fig. 2c) basically corresponds to path to be reproduced by the subject in the post-training phase, and vice versa. Subject was asked to keep on his or her chest a the hand controller, in order to track the path he or she traveled during the test.

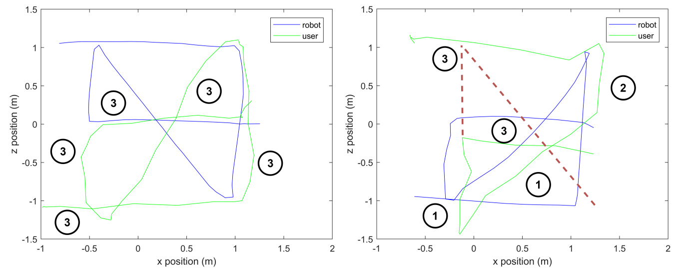


(a) (b) (c)

Fig. 2: Robot path reproduction test: a) initial position of the robot, with the player standing behind it, b) example of mirrored movement, c) path defined for the pre-training phase.

Assessment is based on a comparison between robot's and subject's traveled paths, by considering expected and actual stretches (movements, traits). Stretches' direction and length are evaluated according to criteria in Table II. Four directions are considered, namely straight (0°), left and right (+/- 90°) and oblique (+/- 135°), and missing and unrequested stretches are considered. In the motor reproduction, subject's stretches need to be flipped before being evaluated. Two examples of assessment with and without errors for a motor reproduction are reported in Fig. 3.

2) Robot Pursuit Exergame: This is one of the two exergames implemented for the training phase. The goal is to enhance subject's balance and spatial orientation capabilities.



(a) (b)

Fig. 3: Robot path reproduction test: a) application of the evaluation criteria in case of a correctly reproduced path and b) errors in the reproduction (wrong direction in two cases, wrong length in another case).

TABLE II: Robot path reproduction test: Evaluation criteria (same for motor and paper reproduction).

Criterion	Points
Stretch direction and orientation (forward, left, right)	2
Stretch direction and orientation (oblique)	2
Stretch (oblique) not passing line of symmetry	-1
Stretch length (forward, left, right, oblique)	1
Unexpected stretch present	-1
Expected stretch missing	-3

Subject, blindfolded, is requested to smoothly pursuit the robot which moves within the tracking area and emits a periodic sound. Robot's path and sound's characteristics were defined based on a number of empirical observations. In particular, different paths with multiple, heterogeneous direction changes were experimented, studying how well they were capable to confuse the subject. However, the limited tracking area and the need to prevent the subject from taking shortcuts led to an 8-shaped path (Fig. 4), with long stretches and 90° turns. Initially, robot and subject stand in a given point of the above path, at a distance of about 30 cm (which was assumed to be a reasonable step size when blindfolded). During the exercise, subject was requested to move while keeping this distance as constant as possible. To this aim, he or she was requested to keep the controller on his or her chest: when distance fall under the above distance, a vibration informed him or her to slow down. Since the subject could be able to follow the robot by listening to the noise produced by its wheels, sound emitted was chosen to confuse him or her. To this purpose, a sound in the 800-1000Hz range at 80 BPM was used.

3) Robot Localization Exergame: This is the second exergame designed for the training phase. The exergame is meant to stimulate the sound localization abilities of the subject. Subject is standing in the center of the tracked environment, blindfolded. The robot is moving around him or her on a circular path with a 1 m radius. The robot stops at predetermined points (identified by a given angle w.r.t. to subject's facing direction) and, after a certain time (randomly selected in the 1–5 seconds range) emits a given sound. Angle and sound

TABLE III: Tests performed in the pre-training and post-training phases.

Test	Goal and execution details	Evaluation metric
Pure tone audiometry	Evaluation of the hearing threshold for including subjects in the experiments	Pure Tone Average (PTA)
Speech audiometry	Evaluation of subject's intellection capabilities w.r.t. 20 logotomes (50dB SPL signal, female voice, and a 45dB SPL white noise)	Number of disyllabic logotomes correctly identified
Balance	Evaluation of subject's postural control on a stabilometric platform with both open eyes (OE) and closed eyes (CE)	Surface of the ellipsis (in mm^2) and length of the track (in mm)
Target hitting	Evaluation of subject's ability to control his or her COP by making him or her hit 20 targets	Number of hits and time
Cesarani	Evaluation of subject's navigation abilities in terms of spatial orientation capabilities and short term memory use (motor and paper reproduction)	Score and time
Robot path reproduction	Evaluation of subject's navigation abilities spatial orientation capabilities and short term memory use with the robot (motor and paper reproduction)	Score and time

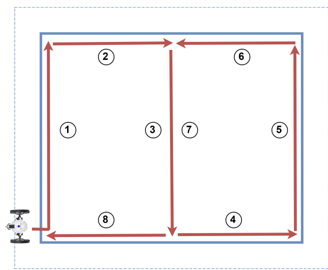


Fig. 4: Robot pursuit exergame.

frequency for each stop can be controlled by the specialist. In the experiments, eight angles step 45° and three frequencies were considered (800 Hz, 1500 Hz and 3000 Hz), for a total of 24 configurations. In order to confuse the subject, a sequence was designed for stops which had to be traveled by the robot partly clockwise, partly counter-clockwise. Subject was requested to localize the robot by pointing it with the hand controller and pressing the trigger button (Fig. 5). Controller was placed on a flat surface in front of the subject, and he or she simply had to rotate it, making it easier to point at locations behind him or her. Vibration feedback was used to provide the subject with a feedback about hit/missed targets (with a 22.5° tolerance).

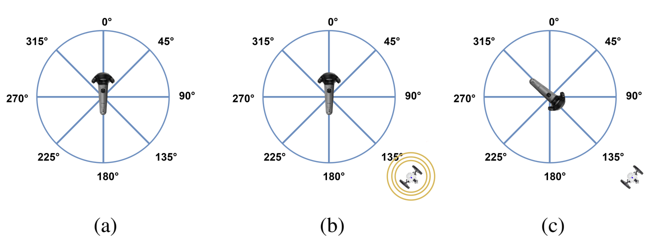


Fig. 5: Robot localization exergame.

V. Experiments

Experiments were carried out by involving 40 normal subjects. Subjects were split in a study group and a control group (20 subjects each).

A. Setup

Subjects in the study group were 23.70 years old on average (SD = 5.19); 14 were males, 6 were females. Subjects underwent the pre-training phase, which encompassed the tests reported in Table III. Afterwards, training was performed by requesting subjects to go through the two robotic exergames. Lastly, post-training phase was carried out by repeating tests of the pre-training phase (simply mirroring the path in the robot path reproduction test). The experiments lasted about 40 minutes per subject, on average. Subjects in the control group were 25.25 years old on average (SD = 5.40), 13 were males, 7 were females. Subjects in this group did not underwent the training. Moreover, the motor robot path reproduction test was not executed, since subjects did not have a change to experiment the robot pursuit task. The post-training phase was executed about 30 minutes after the pre-training, thus mimicking conditions of the study group.

Pure tone audiometry test was used for selecting subjects to be included in the experiments: only participants with a PTA in the 20–25 dB HL range (normal hearing conditions) were included, as the goal of this paper was to perform a preliminary evaluation of the methodology to be possibly followed by the definition and validation of a rehabilitation protocol.

Results obtained for subjects in the study group in the pre-training and post-phases are reported in Table IV. Statistical significance was evaluated using paired t-tests; p-values are tabulated in the last column, and significant differences ($p < 0.05$) are marked with *.

It can be immediately observed that number of logotomes correctly identified growth significantly from the pre-training phase to the post-training phase, passing from 26% to 49%. However, results concerning stabilometry had an opposite trend. In fact, a general increase in the ellipsis surface and in the track length was observed after the training (with the exception of track length with closed eyes).

Concerning navigation, both the Cesarani's and the robot path reproduction tests were characterized by an increase in the assigned score between the pre-training and the post-training.

Basically, it looks like the increase in the subjects' intellection and navigation capabilities was paid by a decrease in subjects' ability to maintain balance and control posture (in fact, they were requested a higher mental and physical energy

TABLE IV: Results of pre-training and post-training phases for the study group.

Indicator	Pre-training	Post-training	p-value
Logotomes	5.25 (3.71)	9.75 (4.04)	0.00001*
Ellips. S (OE), mm^2	111.90 (64.98)	132.95 (110.26)	0.18869
Ellips. S (CE), mm^2	188.55 (120.77)	201.00 (155.13)	0.30017
Track L (OE), mm	272.60 (82.93)	328.00 (143.57)	0.02243*
Track L (CE), mm	538.85 (257.15)	466.25 (188.34)	0.02239*
Num. target hits	9.25 (1.41)	9.20 (1.88)	0.44027
Hit target time, s	39.95 (4.89)	39.55 (6.87)	0.37007
Cesarani mot. sco.	17.35 (2.62)	18.90 (2.53)	0.01184*
Cesarani pap. sco.	15.55 (4.93)	17.25 (4.17)	0.02285*
Cesarani pap. time, s	58.55 (49.90)	27.55 (12,76)	0.00400*
Robot motor sco.	10.10 (4.83)	12.10 (3.85)	0.01990*
Robot pap. sco.	11.00 (3.83)	12.40 (3.14)	0.04481*
Robot mot. time, s	40.55 (31.15)	32.20 (20.21)	0.09538

TABLE V: Results of pre-training and post-training phases for the control group.

Indicator	Pre-training	Post-training	p-value
Logotomes	6.75 (3.86)	7.30 (2.98)	0,21382
Ellips. S (OE), mm^2	112.75 (67.19)	89.20 (34.88)	0.05951
Ellips. S (CE), mm^2	171.55 (98.67)	137.20 (61.18)	0.02744*
Track L (OE), mm	279.60 (75.30)	278.10 (84.12)	0.44999
Track L (CE), mm	484.25 (201.40)	425.40 (139.41)	0.03267*
Num. target hits	8.00 (2.05)	7.85 (1.66)	0.36199
Hit target time, s	43.40 (5.98)	42.25 (5.81)	0.15917
Cesarani mot. sco.	17.15 (2.46)	18.35 (2.32)	0.00713*
Cesarani mot. time, s	40.10 (13.69)	29.70 (12.98)	0.00178*
Cesarani pap. sco.	15.50 (3.65)	18.45 (4.70)	0.00178*
Robot path pap. sco.	12.67 (3.01)	13.80 (2.68)	0.37512

to carry out the tests).

Results obtained for subjects in the control group are given in Table V. It can be easily noticed that improvement in the recognition of logotomes from pre-training to post-training was far less appreciable (from 34% to 37%, not significant from a statistical point of view). Improvement in the number of logotomes recognized in the control group was eight times lower than for subjects in the study group. The above finding was associated by a trend in stabilometric tests which was reverted with respect to the study group (whereas results concerning navigation were comparable with those in the study group). In fact, a general decrease in all the indicators could be observed, indicating an improvement in subjects' ability to maintain balance and control posture. Statistical significance of differences between the study and control group was evaluated using un-paired t-tests: significance was verified for the logotomes test and for the track length with open eyes, confirming (at least partially) the impact of training on indicators considered.

At the conclusion of the experiment, each subject was requested to fill in a questionnaire organized in two sections. The first section was meant to evaluate the usability of the devised system according to the System Usability Scale (SUS) in [34]. The section included 10 statements to be rated in a scale from 1 (strong disagreement) to 5 (strong agreement). Results were then normalized in a 0–100 scale. The second section was based on the Physical Activity Enjoyment Scale (PACES) defined in [35]. Subjects were requested to rate 18 questions on a 1 to 7 bipolar scale (with 4 indicating a neutral reaction). To make PACES results comparable with SUS, they were normalized in a 0–100 scale.

Average SUS score was equal to 74.13 (SD = 7.58), which indicate a good usability of the system: subjects found system's functionalities well integrated and easy to use. They feel confident in using the system, and would like to use it in the future, judging its complexity as adequate. Similarly, average PACES score was equal to 79.07 (SD = 10.84), suggesting that subjects liked the experience. In particular, they had fun with it, they found it pleasant, interesting, engaging and original.

VI. Conclusions and Future Work

Preliminary experiments carried out so far suggest that the training performed produced an increase in the percentage of logotomes recognized, which translated into a higher expense of cognitive resources and a reduction of subjects' ability to maintain balance and control posture. Results could be explained by considering the role played by attention, which allows humans to focus cognitive resources onto specific functions (like hearing and balance, in this case). During the training, subjects had to carry out several exercises in vision deprivation conditions, which requested their cognitive system an extra effort (with a refocus of attention and a redistribution of mental resources) to compensate for the reduced set of information available. The need to keep concentration for a prolonged period (40 minutes) generated a sense of fatigue (both mental and physical), which negatively influenced subjects' balance and posture control capabilities.

Results obtained with the Cesarani's and the robot path reproduction path tests may suggest a connection between the improvement of audiometric indicators (intellection) and a potentiation of navigation capabilities (spatial orientation and representation). Findings may be associated with the role played by the hippocampus, which intervenes in spatial navigation, but also in memory processes (e.g., in the declarative memory as well as in the transformation of short-term memory to long-term memory). Indeed, these are just speculations at this stage, which require further investigation. With respect to the objectives of this paper, it can be observed that results obtained indicate that, as hypothesized, Cesarani's test may not be capable to gather meaningful results when tests have to be repeated. As a matter of fact, subjects in both the study group and in the control group improved their score between the pre-training and post-training phases, but the latter did not underwent the training: hence, improvement was reasonably due to learning effects (this fact may be confirmed also by time requested to complete the test, which was significantly lower in the post-training phase for both the groups).

In this respect, the devised robot path reproduction test could be regarded as more effective than the Cesarani's test. In fact, time differences are not significant between the pre-training and post-training: this finding could be an indication of the fact that test was harder to remember that Cesarani.

Moreover, for the robot path test (paper reproduction), no significant change in score was observed in the control group, as expected (whereas in the study group, subjects got higher scores in the post-training than in the pre-training). Combined with subjective results concerning usability and likeability of the physical experience, these facts represent a preliminary confirmation of the potential of the devised methodology.

Despite promising results, further work is certainly needed. For instance, an improvement can be observed in the study group between pre-training and post-training also for the motor reproduction of the designed test, but there is no data for the control group to confirm that this finding is not due to learning or to chance. Moreover, the experience with the robot during training (with the robot pursuit exercise) may have contributed at improving subjects' understanding of robot's behavior, introducing a bias in the results.

As said, experiments carried out so far with normal subjects and over a short time period were intended to determine whether the application of the devised methodology could introduce significant changes in relevant indicators. Results obtained will drive next developments that will be aimed at designing a rehabilitation protocol for pathological subjects encompassing periodical (e.g., weekly) sessions.

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