A Virtual Reality-Based Physical and Cognitive Training System Aimed at Preventing Symptoms of Dementia

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Abstract. This work presents a physical and cognitive training program, based on virtual reality technologies, designed with the aim of preventing the occurrence of symptoms of dementia in elderly with Mild Cognitive Impairment (MCI). The system foresees a physical task to be performed on a cycle-ergometer and two virtual environments for cognitive stimulation. In this paper, results of different validation phases conducted on both healthy and MCI subjects are described. The presented validation path allowed to implement, in parallel, the two current versions of the setup: the former, optimized to assess the efficacy of the intervention in a randomized clinical trial, which will take place in the next future, and the latter, more experimental, which foresees the employment of immersive environments to increase subjects' engagement and motivation.

Keywords: Mild cognitive impairment · Physical training
Cognitive stimulation · Virtual reality · Oxidative stress

1 Introduction

Patients with Alzheimer's Disease (AD) may initially be affected by the so-called Mild Cognitive Impairment (MCI), that is the presence of an impairment in at least one cognitive domain, without a significant deterioration of autonomy in activities of daily living [1]. MCI population has an increased risk to develop dementia, even if a

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consistent percentage remain stable or reverse to normality during the years [2]. Therefore, subjects with MCI represent a reasonable target population for interventions aimed at halting and reducing AD progression, in particular for strategies centered on modifiable risk factors for dementia [3].

Several clinical trials have been conducted in recent years to identify non-pharmacological interventions capable of reducing the risk or, at least, slowing down the occurrence of the symptoms of dementia. Though there is still uncertainty on the efficacy of such interventions, promising results seem to be provided by either the separate or concurrent provision of cognitive stimulation (CS) and physical activity (PA) [4]. Starting from these evidences, the presented system was developed with the aim of providing elderly with minor cognitive disorders with an effective and easy accessible technological tool for physical, cognitive and functional stimulation, in order to prevent the occurrence of new symptoms of dementia. Virtual Reality (VR) has been used as the enabling technology due to its capabilities of reproducing controlled training environments with high ecological validity and of engaging and motivating the patients [5, 6]. In the following paragraphs, the system and the validation path followed to test and improve the first-designed setup are presented.

2 The Training System

The system was designed to allow MCI patients to both perform physical exercise and train their cognitive abilities with a single experimental setup. To facilitate the transfer of the capabilities acquired during the training into real life, three VR-based scenarios representing activities of daily living were implemented. In details, they simulate the following activities: (1) riding a bike in a park, (2) crossing roads - avoiding cars – and (3) making the grocery shopping in a supermarket. The first scenario is dedicated to the accomplishment of the PA, whereas scenarios (2) and (3) are designed to provide the CS and, in particular, to train visuospatial abilities, which correspond to one of the domains commonly impaired in AD and thus require proper stimulation.

The hardware devices composing the training system are: a cycle-ergometer (Ergosana Eurobike 320), a smart garment (Wearable Wellness System, Smartex) – aimed at measuring the hearth rate in real time, a finger touch projector (EB-1430WI, Epson) and a PlayStation controller anchored on the cycle-ergometer handlebars. The choice of the cycle-ergometer was motivated by safety reasons, since, with respect to a treadmill (the only other equipment allowing an easy modification of the workload), is associated with a lower risk of injury, especially in case of an elderly user.

2.1 Physical Activity

While performing the physical task (scenario 1), the patient rides the cycle-ergometer, facing the projected screen and wearing the smart garment, as shown in Fig. 1. Exercise intensity is chosen as to correspond to about 65–70% of individual maximal heart rate (HR), previously determined on the basis of the age-predicted value.

During the training session, the work rate is adjusted in real-time, through a digital controller, which tunes the workload to make the subject maintain the target HR. The

Fig. 1. The system setup. The dashed line represents Bluetooth connection; continuous line represents connections through cables.

Virtual Environment (VE) represents a trail in a park (Fig. 2, top-left) that flows according to the pedals velocity. The VE has the aim of increasing the user's engagement and of providing him/her with the information needed to control the exercise, such as speed, covered distance, round-per-minute, time elapsed and heart rate.

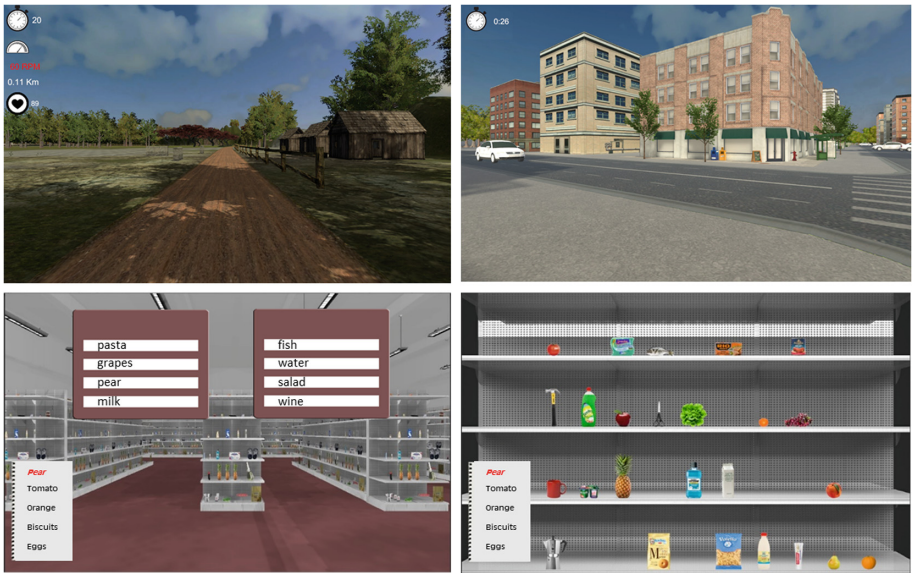

Fig. 2. Screenshots of the developed VEs: above, the park (left) and the crossing-road (right) scenarios; below, the two tasks of the supermarket scenario: aisle (left) and shelf (right).

2.2 Cognitive Stimulation

The CS starts after a predefined time lapse (15 or 20 min), when the park displayed on the projected screen turns into an urban route. In this second scenario, the user has still

to ride the cycle-ergometer, but the task is not more physical (the workload is set to 0), but cognitive: he/she, in fact, has to face the crossing of five traffic-congested and non-regulated crosswalks.

The trial participant has thus to perform different visuospatial and attentional tasks: (1) pedaling to reach the border of the sidewalk, (2) brake when being near it, (3) check on both sides if there are cars moving closer and, if not, (4) restart pedaling to reach the following cross. Braking and turning the point of view can be accomplished using, respectively, the X button and the joystick of the PlayStation controller. This choice was motivated by the impossibility of implementing a real brake by accessing the wheel compartment without affecting the CE certification of the ergometer.

After the completion of this first cognitive task, the user reaches the entrance of a supermarket (scenario 3) and has to get down from the cycle-ergometer and do the shopping of some grocery items indicated on the shopping list that the system generates randomly. To buy a product, the user has first to find and tap on the projected screen the aisle whose sign is containing the name of product (*aisle task*) and then tap on the right product, placed on the shelves in a random position, among other distractors (*shelf task*, see Fig. 2).

Different levels of difficulty were implemented for both tasks. The increase in difficulty is obtained mainly by the increase of *distractors* and of their similarity. For the aisle task, a further complication to promote language and attentional training is obtained by the introduction of a word that is orthographically or semantically similar to the target object name. For the shelf task, higher levels are characterized by the presence of different formats and discounted versions of the same product, so that the attentional and visuospatial demands are increased.

For both the described tasks, if the user commits an error or does not interact with the VE for more than 45 s, the system intervenes providing a hint to help him/her proceed to the next task.

3 Validation Path

For the validation of the designed intervention, different phases have been already accomplished and others will be completed in the next future (see Fig. 3). In particular, with respect to the previously presented achievements this work adds the results from the preliminary tests on the immersive version of the system and includes the description of the randomized trial that will be held using the third version. Each past phase – described in the subparagraph hereinafter – allowed collecting different kind of data that led to the improvement of the hardware devices and of the VEs' design and functionalities.

3.1 Phase 1: Preliminary Tests

First experiments on the developed system were performed enrolling healthy subjects. For the PA, a cardiologist tested the algorithm that regulates the cycle-ergometer workload according to the user current and his/her maximal heart rate [7]. Thanks to his suggestions, modifications were made to the controller to adjust the slope with which

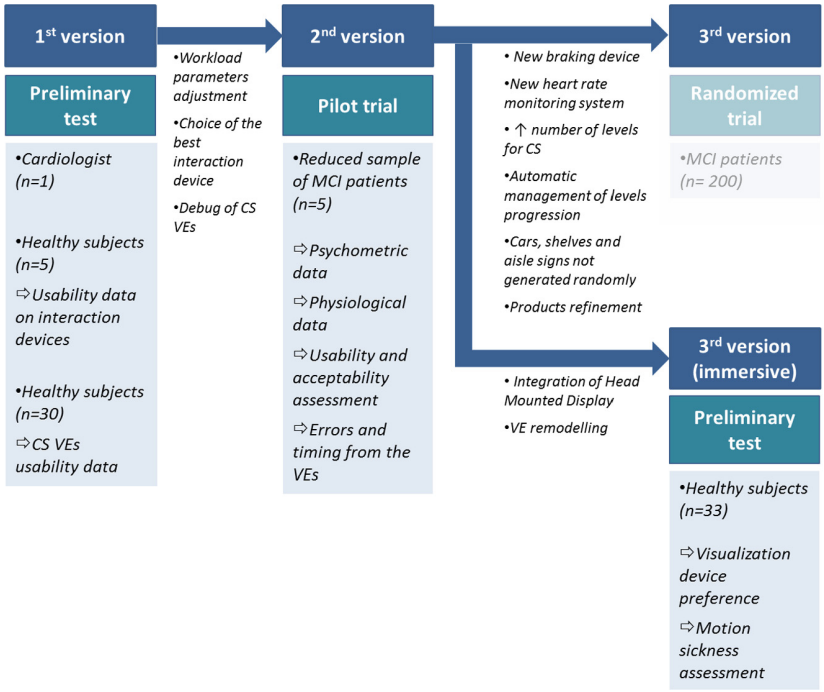

Fig. 3. The validation path: the setup version used, the type of experiment performed, its outcomes (indicated by arrows) and the subsequent modification to software and hardware devices. Grayed-out blocks indicate that the trial is currently ongoing.

the increase or decrease of the workload is made, to avoid too sharp variations in the users' HR.

Dealing with the CS environment, two different experiments were performed. The former, described in [8], allowed to define the best interaction device for selecting the aisle and the grocery items from the shelves. The touch-projected screen resulted the best in terms of intuitiveness and fatigue, with respect to Kinect-based solutions, Leap Motion and 3D mouse in tests conducted on 5 healthy subjects. The latter experiment involved 30 healthy participants with the aim of identifying potential criticalities in the supermarket scenario. Each subject was asked to perform the shopping tasks and then to fill in a questionnaire assessing the usability of the system and to provide suggestions for improvement. The collected feedback led to the replacement of certain products, which resulted confounding due to the screen resolution or to potential ambiguity (i.e. Grana Padano vs. Parmigiano Reggiano) and to the modification of the clickable area in the aisle scenario: the entire aisle was turned into a button, after it was observed that many users clicked the lane area instead of the aisle sign.

3.2 Phase 2: The Pilot Trial

After the validation on healthy subjects, the developed system was tested in a first randomized pilot trial conducted on elderly with MCI. Ten subjects responding to inclusion criteria (age $\geq$ 65 years, one or more test scores indicating compromised visuospatial abilities, one or more test scores indicating cognitive decline) were randomized in two groups. A set of variables to collect before, after and during the trial, was defined with the aim of assessing the feasibility (the practicality of a solution), the acceptability (the social, psychological and ethical acceptability of a certain treatment) and providing first insights of the efficacy (the benefits measured by improvements in health) of the designed program. Results of the trials, reported in Table 1, are more extensively described in [9, 10].

Table 1. Results of the pilot trial. EG: Experimental Group, CG: Control Group.

Outcomes	Assessment methodology	Results and conclusion
Psychometric tests (pre/post)	Mini-Mental State Test, Rey-Osterrieth Complex Figure Test, Clock Drawing Test, Trail Making Test-A/B, Frontal Assessment Battery, Word and Non-Word Repetition Task, Verbal fluency tests, Functional Assessment Questionnaire.	EG showed improvements in the MMSE, in visual-constructive and visuospatial tests, while the CG worsened. The EG had a greater improvement in the executive, memory and verbal functions. No difference was statistically significant, reasonably due to the small sample and its heterogeneity. However, the highlighted tendency can be considered encouraging.
Oxidative stress measurement (pre/post)	Detection of Reactive Oxygen Species (ROS) concentration by Electron Paramagnetic Resonance, antioxidant status and oxidative damage [11, 12].	The EG after training intervention showed statistically ($p < 0.05$) lower ROS production rate. The training may help to delay neurodegenerative damage caused by oxidative stress.
Software data (acquired during the training)	Durations of the PA and CS. Accident, errors and hints occurred during the CS.	Good adherence to both PA and CS. Levels of CS training were indeed of increasing difficulty, but too easy to complete for patients with only mild cognitive impairments. Few products were confounding.
Subjective evaluation (post intervention)	Questionnaire on satisfaction, desire to continue, enjoy and comfort. Suggestions for improvements through open questions.	EG reported high levels of engagement and motivation, enabled mainly by VR technologies. Feedbacks on the VEs revealed appreciation: participants would continue with the program also at home.

Despite positive feedback from the experimental subjects, the observations of the sessions and the collection of the psychologists and the patients' comments highlighted a few critical aspects to be improved in a third version of the system (Fig. 3). A 3D-printed braking device, equipped with a potentiometer, was anchored on the cycle-ergometer handles to allow a more natural interaction; the smart garment was replaced with more practical heart rate monitor (a finger pulse oximeter), which allows more participants to use the same equipment. The software was made able to handle automatically the level selection, excluding potential errors committed by operators. Moreover, all the road crossing, the aisle and the shelf tasks proposed are now previously computed and just loaded during the sessions, so that more precise and comparable data will be available for further analyses.

The resulting third version, improved according to the feedback collected during the pilot study and thanks to the promising results obtained on MCI patients, will be tested in the next months in a multicenter randomized controlled trial (§4).

3.3 Phase 3: Preliminary Test on the Immersive Version

Another aspect that would have been interesting to address in order to improve the second version is the possibility to provide the users with a more immersive experience. Solving this issue requires the replacement of the projected screen with a Head Mounted Display (HMD), whose use often causes physical drawbacks [13]. Therefore, there is the need of testing the immersive solution on healthy subjects before integrating it into an elderly/frail people-dedicated system. Due to this reason, an alternative version of the system was developed in parallel to the non-immersive third setup. The park and road crossing VEs were adapted to be visualized using the Samsung GearVR headset; an *ad-hoc* client/server application, which allowed the data exchange between the cycle-ergometer and the VEs running on the Android smartphone placed in the GearVR, was implemented.

A within-subject experiment comparing the projected screen and the HMD was then conducted on a sample of 33 healthy young adults, who were asked to answer the Simulator Sickness Questionnaire (SSQ) [14] and to select the device they prefer after 10 min of cycling in the two VEs. Preliminary results revealed that SSQ total scores were significantly higher using the HMD ($p < 0.001$, $z = -4.79$). However, most of the subjects ($n = 24$, $\chi^2 = 9.64$, $p < 0.05$) reported to prefer the experience with the HMD, indicating that subjects are capable of tolerating small malaises in exchange of a more involving and engaging experience. Only subjects who reported a high number of symptoms (≥ 4), in fact, preferred the projected screen; moreover, they often reported discomfort in this less-immersive condition too.

4 Conclusion and Future Works

This paper presents a system developed to provide MCI patients with physical and cognitive training and describes three different validation phases and the technical and methodological improvements implemented after each phase. In the next future, the last non-immersive version (#3) will be part of a multicenter randomized clinical trial,

involving about 200 MCI patients. Further studies will be performed also on the immersive environments, which are more engaging and more intuitive, trying to improve the VEs design with the aim of reducing as much as possible the physical drawbacks. When the navigation and the interaction while wearing an HMD will be comfortably tolerated by a population of young adults, first tests on elderly will be conducted taking into account the proper safety equipment (e.g. harness).

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