Age-related Performance Decline Detected by a Virtual Reality Multidomain Cognitive Training Solution (Enhance VR)

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Abstract
Cognitive training systems aim to improve specific domains or global cognition by engaging users in cognitively demanding tasks. While screen-based applications can improve performance in the trained cognitive abilities, they often result in poor transferability to activities of daily living. These systems exclude the user's body and motor skills. Immersive Virtual Reality (IVR) systems, in contrast, present the user with body-related information, such as proprioceptive and visuomotor information, allowing for an immersive and embodied experience of the environment. This feature renders VR a very appealing tool for cognitive training and neurorehabilitation applications. Enhance VR is an IVR-based cognitive training and monitoring application that offers short daily cognitive workouts. The games are designed to train and monitor specific cognitive domains (memory, task flexibility, information processing, orientation, attention, problem-solving, and motor control). Enhance VR enables the collection of a large and varied behavioral dataset. Our analysis showed that age is a determinant of performance, as measured by the Enhance VR scoring system, with score games decreasing with age. Overall, suggesting that the Enhance VR app can potentially capture informative datasets that predict individual cognitive variables.

Keywords
Cognitive training, Cognitive monitoring, Immersive virtual reality, Age-related decline

1. Cognitive Training

Cognitive decline, the gradual deterioration of cognitive abilities and functioning, progresses in parallel with age and becomes more pronounced in populations at risk of neurodegenerative diseases. The deterioration of cognitive abilities has a direct influence on the execution of activities of daily living (ADLs) and negatively affects autonomy and well-being. A combination of a healthy diet, moderate exercise, and cognitive stimulation have been proposed as strategies to attempt to slow down the progression of cognitive decline [1].

Computerized cognitive training (CCT) has the potential to become a non-pharmacological intervention to maintain the cognitive functioning of cognitively impaired individuals. CCT has been shown to reduce cognitive decline in healthy aging [2], but with no clear effectiveness in delaying difficulties in instrumental ADLs. CCT programs have shown an improvement in trained cognitive abilities (i.e., memory, reasoning, or speed-of-processing) [3], which was maintained for 5 [4] or even 10 years [5]. A meta-analysis found a small and significant effect on cognitive function in healthy older adults [6]. Overall, CCT has shown promising, but heterogeneous results in global cognitive functioning [7]. However, screen-based CCT solutions have failed to show transfer to untrained cognitive categories and tasks and ADLs [3, 8]. Furthermore, computer-based interventions showed improvements in cognition and non-cognitive measures (e.g., mood), but failed to improve ADLs in people with dementia [9]. A 12-week program showed improved capacities in early-stage Alzheimer's disease (AD), without positive effects on ADLs [10].

The lack of ecological validity in screen-based CCT could, in part, explain why these systems do not result in a transfer of benefits to ADLs and general cognition. VR systems, on the other hand, yield ecologically valid environment scenarios with precise control over the experimental variables [11, 12]. VR has shown to be potentially relevant for cognitive training in the elderly population, as a result of many different features, such as the flexibility of the environments and the possibility to gather rich data, as a result of increased immersion [13]. Ultimately, improving cognitive functioning in healthy and at-risk older adults and promoting the transfer of benefits.

2. Virtual Reality Environments as a Cognitive Training and Monitoring Tool

VR scenarios offer many advantages over screen-based cognitive training methodologies. Traditional methodologies have to trade external validity (i.e., how the task accurately represents the measure in real-life scenarios)

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and the internal validity of conducting the tasks in a controlled laboratory setting with controlled variables [14]. VR, on the other hand, offers realistic scenarios with a high degree of control over desirable experimental variables [11], such as the stimuli, and the presence of distractors, among others. Additional advantages of VR systems include the possibility of creating situations that are adapted to the individual's needs or that are impossible to recreate in real-life scenarios and collecting precise measurements of physical movements while sourcing large amounts of behavioral data [14].

Moreover, immersive VR (IVR) systems that are displayed through a head-mounted display with embedded head-tracking, which updates the environment according to the participant's movement, allow for a naturalistic interaction with the environment. In these scenarios, the behavior of the environment matches the expected physical and motor consequences of the participant's action. This is also referred to as the plausibility illusion. Furthermore, IVR environments engage the sensorimotor system enhancing the illusion of embodiment over a virtual body or body part [15, 16]. By providing immersive experiences of the scenarios, virtual environments provide the feeling that the virtual world is the real world and provide the feeling of actually "being" in the virtual environment (i.e., placement illusion). The feeling of presence in a virtual environment has been shown to increase motivation for learning and attention to the task [17].

Sensorimotor contingencies are, thus, important for immersion. VR systems are particularly interesting for this matter, as they allow for the integration of proprioceptive, visual, and motor information [18]. Ultimately, VR scenarios provide a high degree of realism that elicit naturalistic behaviors from participants [19]. The naturalistic interaction with the environment provides a higher degree of ecological validity than current screen-based or pen-and-paper solutions. As a result, VR systems become interesting tools for the training and rehabilitation of cognitive functions in distinct populations [20].

3. Developing a Cognitive Training and Monitoring Solution in VR

The Enhance VR app (https://virtuleap.com/download/) is designed to be played regularly in the form of short workouts. Each workout is composed of three randomly chosen games. The mechanics of each game is motivated by the mechanics of validated neuropsychological principles. Every game stems from the collaboration between scientists and game designers to ensure that the mechanics of each test are maintained. At the same time, the experience is a gamified and engaging representation of the neuropsychological validated tests. The Enhance VR is compatible with a wide range of commercially available headsets.

The Enhance VR app consists of a library of games that engages seven main cognitive categories. As of October 2022, the library offers 15 games divided across all of these skills: Pizza Builder, Whack-a-mole, Shuffled (Attention), React (Flexibility), Assembly and Harmonize (Information processing), Memory Wall, Maestro, Magic Deck (Memory), Stacker and Odd Egg (Problem-solving), Slinger and Balance (Motor Skills), and Orbital and Hide and Seek (Spatial Orientation) ([21], Table 1).

The design of each individual Enhance VR game can be compared to other workflows proposed for the design of cognitive assessment exercises [22]. Whenever the need for a specific cognitive category is identified, different classical paradigms are selected and evaluated to maximize the training abilities in an IVR environment. Once the candidate paradigm has been identified, the extensive literature review identifies task requirements. Namely, (1) the mechanics of the paradigm, (2) the actions that are required from the participant, (3) the category and type of stimuli, (4) the outcome measures that evaluate the specific cognitive ability, and (5) identify the parameters that can be modified to increase the difficulty of the task. These parameters will define the design of the gamified virtual reality exercise, developed by a team of game designers, developers, artists, and quality assessment.

The difficulty of the Enhance VR app is dependent and controlled by adjusting the relevant parameters for each exercise. The Enhance VR app tests the baseline performance for each game by presenting a first longer session (hereafter, benchmark session). From there on, every session starts at the level where the user left off.

4. Enhance VR Enables the Collection of Behavioral Data for the Detection of Cognitive Performance

Individual progression is tracked by the Enhance VR Performance Index (EPI), calculated as an aggregate of weighted performance across all cognitive categories in addition to scores for each game, the main cognitive categories, and subcategories scores. The app collects data on self-reported mood and sleeping hours at the start of each workout. Upon registration, users are required to input demographic data, such as age. The Enhance VR app is compliant with GDPR and HIPAA regulations.

IVR systems enable the collection of large and varied behavioral datasets [13]. As the participants engage with the Enhance VR games, the system collects not only the performance of the participants but also a large number of game-related variables. Some of these variables include motor outputs (e.g., movement coordinates or hand preferences), and reaction times, among others. Thus, the Enhance VR app collects behavioral data obtained by game-specific events. These variables would provide a sensitive description of the individual cognitive status and allow for a self-to-self comparison of cognitive changes. Thus, we propose that the behavioral data from Enhance VR could help identify age-related cognitive decline.

4.1. Enhance VR Scores are Affected by Age

The Enhance VR app is available commercially in VR stores, such as HTC Vive Port and Oculus store. Data collected from these users is anonymized. Users with non-plausible age ranges (>100 years old) or a combination of age and education (e.g. those who reported being 12 years old with a Master's degree) were removed from the analysis. Age groups above 80 were excluded from the analysis due to insufficient data points for all the games. The analysis was performed on a sample of 21,230 users. Furthermore, only data from the benchmark sessions were selected.

We observe a decreasing trend in the cognitive scores measured by the Enhance VR app with increased age groups. The highest median value was obtained by the groups 11-20 and 21-30. The lowest median score was observed in the 71-80 group (Figure 1).

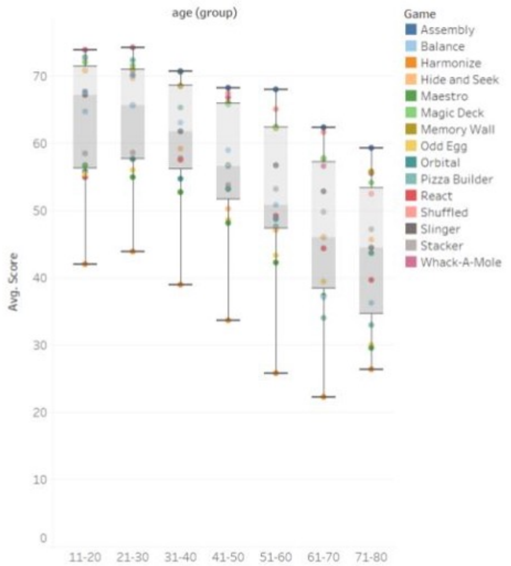

Figure 1: Median benchmark game scores organized by age groups.

5. Discussion

IVR scenarios offer an ecologically valid environment that can potentially improve global cognitive functions and have the potential to transfer benefits to untrained cognitive abilities. The Enhance VR app takes advantage of the immersive and ecological validity of VR environments to provide a structured and controlled setting for cognitive training. The Enhance VR app offers mentally challenging exercises that aim to train specific cognitive skills presented in a structured manner and extracts behavioral measures of cognitive fitness [23].

Increasing age has been previously related to a slow decline in cognitive abilities. Our preliminary analysis shows that the Enhance VR app scoring system reflects an age-related trend of performance decline. Thus, suggesting that the Enhance VR app has the potential to describe the individual profile. The next steps include the analysis of behavioral data. Evaluation of the Enhance VR app will require confirmation of the face and content validity of the tests since the inclusion of a strong motor component may add confounding variables despite careful co-design between scientific and development teams. Age-related cognitive decline can also be related to an increasing prevalence of systemic disorders that are also associated with cognitive impairment.

The advantages of IVR are not only restricted to cognitive training but also to provide immersive scenarios for cognitive assessment [24]. As a result of the naturalistic interaction and realistic scenarios, VR cognitive assessment offers the opportunity to accurately measure the individual's cognitive performance. Digital biomarkers are objective, quantifiable physiological and behavioral data that are collected by digital devices. Previous studies have found a positive correlation between behavioral data obtained from gameplay patterns from specialized and off-the-shelf games such as mouse clicks and cognitive function [25, 26]. Thus, these data could be used to monitor biological or pathogenic processes and assess responses to pharmacological interventions [27].

The Enhance VR collects longitudinal behavioral information that, when combined with supervised machine learning algorithms and clinically relevant data, could provide novel non-invasive digital biomarkers of cognitive status. Ultimately, the ability to identify patterns of impaired cognitive and motor performance at a preclinical stage could act as the earliest manifestations of cognitive impairment and would be key in the development of prevention and treatment strategies. Integrating these digital biomarkers with current diagnostic methods could provide an earlier, more sensitive, and specific detection of cognitive changes, as well as monitor disease progression and act as proxies for the efficacy of pharmacological interventions in clinical trials for disease-modifying drugs, as well as side effects.

The potential application of Enhance VR is not exclusive to age-related diseases cognitive impairment is a hallmark of several diseases and conditions, including ADHD, traumatic brain injury, multiple sclerosis, long COVID, and even a common side effect of chemotherapy. The large diversity of areas covered by our games enables the creation of curated playlists for these different clinical indications, maximizing our reach and impact.

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