Enhance VR: a multisensory approach to cognitive assessment and training

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Summary

Cognitive training systems aim to improve specific domains or global cognition by engaging users in cognitively demanding tasks. While improvement has been shown using screen-based applications, these are often criticized for their poor transferability to daily-life tasks. These systems, however, exclude the user's body and motor skills, which invariably serves to restrict the user experience. Virtual Reality (VR) 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 into a very appealing tool for cognitive training and neurorehabilitation applications. In this context, we present Enhance (Virtuleap, 2019), a VR-based cognitive training and assessment application that offers short daily workouts of immersive games designed to train and assess cognitive domains such as cognitive flexibility, short-term memory, and selective auditory attention. The aim is to test whether cognitively demanding tasks, presented in a VR setting, provide a naturalistic system to assess and train cognitive capabilities.

1. Cognitive training

Cognitive training tasks aim to improve or maintain specific cognitive processes or global cognitive abilities (Simon et al., 2012). Cognitively demanding tasks, such as in paper-based tasks or video games, have shown to improve cognitive performance (Hampshire et al., 2019). Two to three-month training periods have shown to have persistent protective benefits in trained cognitive functions (Valenzuela and Sachdev, 2009). Physically active video games have furthermore been shown to enhance global cognition in comparison with usual care and aerobic physical activity (Stanmore et al., 2017). However, while screen-based cognitive training has shown improvements in older adults, it has been restricted to the domains that are being trained. Indeed, these two-dimensional systems have failed to show transferability to real-world tasks (Ball et al., 2002). There is also no evidence to suggest that they offer an advantage compared to traditional pen-and-paper methodologies, such as solving crossword puzzles (Owen et al., 2010), cognitively demanding tasks (Stanmore et al., 2017), or when compared to active video games (Kable et al., 2017). Human cognition has been proposed to relate to cognitive activity in parallel with sensorimotor processing, and therefore to interact with the physical environment (Wilson, 2002), as physical activities are suggested to be linked to cognition through the evolutionary history of humankind(Raichlen and Alexander, 2017). While screen-based systems fail to provide body-related sensory information (e.g. proprioception), VR environments provide it innately through multisensory embodied experiences.

2. Embodiment and VR

The integration of multiple sources of sensory information creates and continually updates the representation of the body in the brain (Gallagher, 2006; Metzinger, 2003) which is essential for interaction with the environment. These sources of sensory information extend,but are not restricted to, vision, proprioception, interoception, vestibular, and visuomotor information (Matamala-Gomez et al., 2019; Perez-Marcos et al., 2018; Kilteni et al., 2015), and through the manipulation of these sources of information, the representation of a user's body is experimentally malleable.

The experimental manipulation of distinct sources of information results in the illusion of ownership over an artificial body part, such as the Rubber Hand Illusion (Botvinick and Cohen, 1998). In this illusion, a visuotactile conflict between the visible touch of the rubber hand and the felt tactile stimulation of the hidden physical hand is represented by the feeling of ownership over the artificial body part. These results have been replicated using mirror systems (Ramachandran et al., 2005) and through video displays (Lenggenhager et al., 2007). Moreover, this paradigm has been extended to VR (Slater et al., 2009, 2010; Slater and Sanchez-Vives, 2016) and has been replicated using visuomotor contingencies (Sanchez-Vives et al., 2010; Brugada-Ramentol et al., 2019).

VR systems allow for the integration of proprioceptive, visual, and motor information (Sanchez-Vives and Slater, 2005). VR, therefore, enables a stronger sensory immersion that promotes higher cognitive processing and learning (Bailenson et al., 2008; Gamito et al., 2011; Coughlan et al., 2019), and yields ecologically valid environment scenarios with precise control over the experimental variables (Bohil et al., 2011; Parsons, 2015). As such, the use of VR has become an interesting tool in the study of embodiment in neuroscience.

In addition, VR enhances the learning and the application of information compared to screen-based systems (Krokos et al., 2019). Previous studies have found positive impacts on learning outcomes when analyzing the effects of VR-based games and simulations (Bailenson et al., 2008; Gamito et al., 2011; Coughlan et al., 2019).

Lastly, VR has proven itself useful in the study of postural instability in Alzheimer's disease (AD) patients (Gago and Yelshyna Estela Bicho Hélder David Silva Luís Rocha Maria Lurdes Rodrigues Nuno Sousa, 2016) and immersive VR game scenarios have shown improvements in working memory and sustained attention in AD patients (Anguera et al., 2013). VR is also increasingly being used in the field of cognitive rehabilitation, such as rehabilitation of post-stroke patients (Perez-Marcos et al., 2018) and indicated potential applications with respect to Parkinson's disease (Triegaardt et al., 2019).

3. Cognitive decline in healthy ageing and pathological conditions

Cognitive abilities, such as multitasking ability (Anguera et al., 2013; Clapp et al., 2011) or working memory (Park et al., 2002), deteriorate across the lifespan of an individual without additional neuropathological factors. Cognitive decline is more present in people suffering from dementia, which is one of the most significant public health concerns in ageing populations (Hardy et al., 2015). Brain changes associated with dementia may begin 20 or more years before symptoms appear and present a progressive decline for both cognitive functions and overall functionality (Villemagne et al., 2013). Dementia is a broad term that includes AD, which accounts for around 60-80% of the diagnosed dementia cases (Alzheimer's Association, 2009; Sacco et al., 2012), and Mild Cognitive Impairment (MCI), which is present in approximately 15-20% of the senior population (i.e. 65 years of age or older). It is estimated that between 10-15% of MCI patients progress to AD annually (Mitchell and Shiri-Feshki, 2009; Knopman and Petersen, 2014).

As the senior population continues to grow, with a projection to reach 1.6 billion globally by 2050 (Wan He, Goodkind Daniel and Paul, 2016), cognitive training could become a potential tool to assess and potentially maintain effective cognitive functioning, including body movement. Together with a healthy diet and physical activity, cognitive training has been proposed to have a positive impact in preventing cognitive decline over time (Klimova et al., 2017), and lowers the risk of progression to AD (Huckans et al., 2013).

4. Enhance: VR cognitive assessment and training

The Enhance app (Virtuleap, 2019) is a cognitive training and assessment application that aims to take advantage of the multisensory experience of VR environments alongside the physical aspect that is implicit to the activity. Furthermore, the app aims to assess and train specific cognitive areas (i.e. short-term memory, auditory selective attention, and cognitive flexibility), by engaging not only the visual and auditory systems but also providing visuomotor and vestibular information.

The Enhance VR app offers daily, short ($\sim$10 minutes/session) and cognitively demanding workouts, with each session consisting of three games, whereby each game is designed to assess performance in a specific cognitive area. The player progresses through the levels as their performance improves, which in turn increases the difficulty of the game and allows each player to track their performance by means of their respective user index score (UIS). UIS is a combined score for all cognitive abilities and compares the player's individual UIS against a population-normalized score.

5. Cognitive domains targeted in Enhance

5.1. Cognitive flexibility and response inhibition

Cognitive flexibility (CF) and Response Inhibition (RI) are part of the cognitive group of executive functioning. CF or also often referred to as one of its two subcategories, task switching, is the ability to shift between attentional demands depending on the context or situation (Monsell, 2003; Diamond, 2013), by adapting strategies to face new and unexpected conditions. CF is intrinsically linked to attentional processes (Cañas et al., 2003). In contrast, RI, also referred to as inhibition control, is the ability to control and focus one's attention, behaviour, thoughts, and emotions on a specific task and suppress other stimuli depending on the context or situation (Diamond, 2013).

CF is assessed by cognitive assessment tests, such as the Wisconsin Card Sorting Test (WSCT) (Grant and Berg, 1948) and the Stroop task (Stroop, 1935). In the WCST, the participant needs to classify a card according to one of three rules (i.e. colour, shape, or the number of objects), without a prior indication of which rule they need to follow. After each attempt, they receive feedback on whether the classification was correct or not. After a given number of plays, the paradigm changes without the participant knowing, and they need to adapt the rules that they are following. The subjects need to adapt their behaviour to the changing contingencies, focusing only on one aspect (e.g. colour) while ignoring the others (e.g. shape and number of objects). In the Stroop task (Stroop, 1935), participants are required to report the colour of the word while ignoring the semantic meaning of the colour. The Stroop interference refers to the increase in reaction times and errors when the meaning of the word and the colour are incongruent. Both the WSCT and the Stroop tasks also measure response inhibition, which is the ability to suppress a predominant motor response.

5.2. Visual short-term memory

Short-term memory (STM) is the temporary storing and recalling of information, such as events, movements, and cognitive information (Aben et al., 2012). STM is restricted to a limited number of items (Atkinson and Shiffrin, 1971; Miller, 1956) and has shown to be impaired in AD (Huntley and Howard, 2010).

The Visual Patterns Test (VPT) requires the subject to reproduce a pattern previously shown on a grid (Sala et al., 1997) and has been used to assess STM. The difficulty of the VPT increases by increasing the number of components in the pattern. Another test used to assess the working memory is the Corsi block tapping task (Corsi, 1973), which is designed to test visuospatial short-term memory. This assessment test requires the patient to memorize a sequence of cubes shown by the experimenter and reproduce it by tapping the specific cubes. The difficulty of the test increases by incrementing increasing the length of the sequences and hence increasing the cognitive load.

5.3. Selective auditory attention and audiospatial orientation

Selective Auditory Attention (SAA) is the ability to direct attention to one desired sound while tuning out the rest of the auditory objects (Golden et al., 2015). In a crowded auditory scenario, focusing on a single auditory object results in the inability to recognize characteristics of the unattended message, such as in the Cocktail Party Effect (Cherry, 1953; Dalton and Fraenkel, 2012; Bronkhorst, 2000). Attentively selecting a single stimulus becomes more challenging with the increasing number of auditory objects and the similarity between the objects(Murphy et al., 2017).

Audiospatial Orientation (ASO) is the ability to recognize the origin of a sound, which assists with the awareness of the surroundings and oneself. Humans, like many animals, calculate the direction of the source of a sound by comparing the times of interaction of the sound with the left and right ear (Ihlefeld et al., 2019). Auditory spatial processing impairment is often associated with AD and Posterior Cortical Atrophy (PCA) (Golden et al., 2015), and there is evidence that it accelerates cognitive decline (Hardy et al., 2015). Furthermore, SAA has shown to be impaired in the aged population (Gatehouse and Akeroyd, 2006; von Wedel et al., 1991).

SAA has been shown to improve with auditory cognitive training (O'Brien et al., 2017) and, as a result, of musical training (Strait and Kraus, 2011). SAA can be assessed by methods that require the discrimination of a target sound (e.g. a list of words) among competing messages, as in the Selective Auditory Attention Test (Chermak and Montgomery, 1992), and also by discrimination differences in volume (Pardo-Vazquez et al., 2019).

6. Enhance game series

React is a categorization game inspired by the WCST and the Stroop task that includes a cognitively demanding task along with a physical activity; as in hand-eye coordination movement. The player is presented with a stream of incoming stimuli that have to be classified into the two categories represented as portals in the game. The classification is completed by aiming the target objects to the portals by swinging a paddle (**Figure 1-left**). As the game progresses, the target objects are mixed with distraction shapes that the participant needs to ignore. Additionally, implicit to the mechanics of the game, React also engages the motor system.

Memory Wall is a memorization game primarily motivated by the VPT and is related to STM. The player is shown an n-by-n grid of cubes (n is determined by the level, starting at n = 3 at the first level). Similar to the VPT, a number of the cubes light up creating a pattern to be memorized by the player and subsequently reconstructed using the input device (**Figure 1-center**). If the pattern is reproduced correctly, the player moves on to the next level. The difficulty of the task increases with each level by increasing the size of the grid and the number of cubes that form the pattern. On the other hand, if the player fails to recall any of the positions of the cubes, the game moves down one level.

Hide and Seek is an auditory-discrimination and spatial-localization game with the aim to measure spatial orientation skills, as in auditory spatial cognition. The user is presented with a binaural environment, whereby a dynamic high-pitched discrete sound is presented in a single location. At the same time, a constant distraction sound (of different frequency and dynamics) is also played. The participant has to localise the source of a sound in their immediate environment (**Figure 1-right**). The difficulty increases as more distraction sounds are added, increasing the cognitive load and, thus, decreasing the ability to discriminate the target sound as easily.

7. Research motivation

We aim to (1) validate whether the active use of the Enhance VR games improves the participant's performance in the targeted specific cognitive domains. Additionally, we aim to (2) test and assess whether the

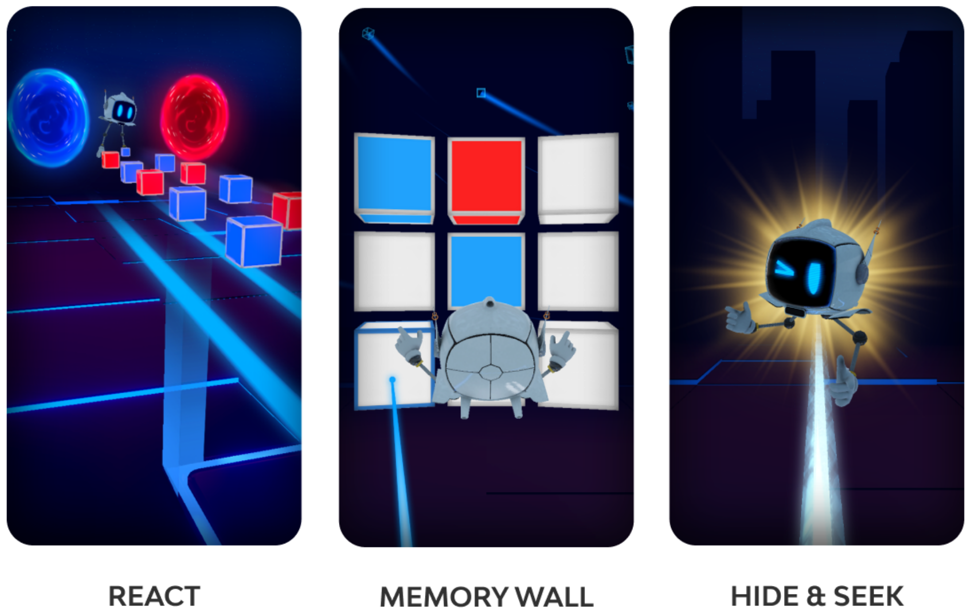

Figure 1: ***Games***. *Enhance is composed by a battery of three games. "React" is the categorization game. The user is required to classify the incoming shapes into the matching portal while ignoring distractor shapes (not shown). "Memory Wall" targets short-term memory. The task is to memorize and reproduce a pattern that lights up in a grid of cubes. "Hide and Seek" is an auditory based task. The player is required to reveal the hidden robot (shown in the figure) by localizing the a high-pitch sound produced by the robot.*

added multisensory component provided by virtual scenarios improves the transferability of cognitive training to daily-life tasks compared to two-dimensional or paper-based equivalents. Further, we aim to (3) validate the Enhance VR app as a potential cognitive assessment tool by testing the efficacy of the games compared to the already existing and established cognitive assessment tools. Finally, with the use of the collected data we aim to (4) find behavioural markers of neurological disease progression that could potentially support an early-stage diagnosis of progressions from MCI to AD or other forms of dementia.

Aim 1: Assess the improvement in target cognitive functions

Cognitive training has, together with a healthy diet and physical activity, been proposed to have a positive impact on preventing cognitive decline (Klimova et al., 2017; Huckans et al., 2013). We therefore aim to quantify the potential improvements in healthy individuals in three different domains (i.e. visual short-term memory, cognitive flexibility, and auditory selective attention) after a one-month period of daily exposure to the three Enhance VR games. Furthermore, we aim to test whether cognitive training helps to improve specific cognitive functions in clinical patients such as dementia, MCI, or AD after using the battery of daily game tasks in the Enhance VR app.

Aim 2: Test whether the use of VR environments improves transferability

Screen-based cognitive training systems have failed to provide proof of a transfer of benefits to core activities in daily-life situations (Ball et al., 2002) and do not indicate an improvement or advantage compared to pen-and-pencil tasks (Owen et al., 2010). However, exposure to an active video game itself has been shown to result in a transfer of benefits between tasks (Anguera et al., 2013), which was maintained up to a six-month follow-up period. Thus, gaming environments have been shown to be a promising tool for a transfer of benefits (Boot et al., 2011). Additionally, VR environments engage the sensorimotor system and enhances embodiment and immersiveness (Sanchez-Vives and Slater, 2005). We, therefore, propose that exposure to cognitively demanding, physically engaging, and sensory-rich VR environments as offered through Enhance VR games should increase the transferability of skills to daily-life tasks (Hertzog et al., 2008; Raichlen and Alexander, 2017). We aim to validate and test the transferability of the Enhance VR games and further compare them to already existing screen-based brain training systems, as well as no-contact control groups.

Aim 3: Validate Enhance VR as a potential cognitive assessment tool

Cognitive assessment is a critical tool for the evaluation of the neuropsychological condition of the ageing population. Traditional cognitive assessment tests have been proven effective to evaluate separate cognitive areas, as well as global cognitive function (Strauss et al., 2006), and detect neuropsychological deficits. For instance, they facilitate the detection and measurement of cognitive impairments (Folstein et al., 1975) and the differentiation between AD and other types of dementia (Mathuranath et al., 2000). Specialized video games have also proven useful to cognitive functions in both healthy and clinical populations (Anguera et al., 2013; Coughlan et al., 2019).

The Enhance VR games have derived their design according to validated cognitive assessment tools, such as the VPT. We propose that the VR versions of the cognitive assessment tests will provide a more naturalistic approach towards the measurement of cognitive capabilities since VR promotes multisensory body-related information (Martini et al., 2015). VR tests, for example, have been proven useful in the assessment of memory functions (Parsons and Rizzo, 2008). Therefore, by comparing the performance in Enhance VR games with already validated cognitive assessment tools, we aim to validate Enhance VR games as a potential approach towards the effective and expedient assessment of cognitive functions.

Aim 4: Determine behavioural markers of cognitive decline

Both biological and imaging markers have been proven useful for detection and prediction of neuropsychological disease progression (Hampel et al., 2008; Counts et al., 2017; Prell et al., 2019). Moreover, cognitive testing has proven to be an effective non-invasive approach to AD detection (Fernandez Montenegro and Argyriou, 2017). Therefore, while playing Enhance VR games, not only the performance of the participants is recorded, but also a large number of game-related variables. Some of these variables include motor outputs (e.g. movement coordinates and hand preferences, etc) reaction times, and velocities among others. Data collected from young healthy, older healthy, and neuropathological populations, combined with supervised machine learning algorithms, may provide non-invasive behavioural markers of cognitive status for the detection of different stages of cognitive diseases.

Conclusions

Screen-based cognitive training systems have failed to show improvements in additional cognitive domains beyond the domain specifically targeted by the task. However, a precondition of these systems is that they do not provide body-related information, such as proprioceptive or visuomotor information. VR systems, on the other hand, present the user with a multisensory environment, resulting in an immersive and embodied experience of the virtual scenario. By taking advantage of this feature, the Enhance app aims to assess and train cognitive functions by means of cognitively demanding immersive games. The presentation of seemingly naturalistic environments could provide an advantage over screen-based systems, whereby VR can become a validated tool for cognitive assessment and training.

Conflict of interest statement

The authors were employed by the company Virtuleap Inc.. They declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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