Assessment and training of visuospatial cognitive functions in virtual reality: proposal and perspective

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Abstract—**Visuospatial functions play a crucial role in human cognition, which has elicited over years a great deal of research focusing on their assessment, training and restoration. Interestingly, although our visuospatial capacities allow us to understand and infer relationships of 3D objects in space, these 3D aspects of visuospatial processing are profoundly neglected in laboratory tests, and instead, 2D designs are commonly used. Aiming to increase the ecological validity of such tests, we propose an experiment to evaluate the capacity of a 3D virtual space to stimulate cognitive functions. The experiment involves cognitive testing, EEG measurements, and cognitively stimulating tasks in an immersive 3D virtual environment rendered by a unique CAVE system. This paper focuses primarily on two game prototypes that will serve as the virtual environment and describes a natural movement control using the Myo armband, incorporated into one of the games. We also briefly discuss cognitive testing design using the selected brain electrophysiological variables measured on human subjects before and after the virtual reality game use, in order to assess the potential effect of the game.**

I. INTRODUCTION

Visuospatial functions subserve cognitive abilities related to detection, representation, manipulation, and storage of visual and spatial information [1]. They allow us to perceive visual objects, locate their position in space, orient our attention, infer various spatial relations, and remember the scene. Furthermore, visuospatial cognitive abilities enable performing judgments related to direction and distance among external objects and thus allow individuals to navigate in the environment [2].

Given their crucial role in everyday life, adaptive behavior, and normal functioning, visuospatial functions have been in focus of psychologists and neuroscientists who have developed various means how to measure [3], [4], train [5], [6], and restore [7] them in humans. Most-widely applied visuospatial tests target specific functions that range from relatively automatic perceptual and attentional abilities to more complex and deliberative cognitive faculties, such as visuospatial short-term or working memory, mental rotations, and executive visual attention [8], [9]. On the other hand, visuospatial trainings and restoration programs employ the known principles of brain plasticity, which have recently attracted a great interest in cognitive neuroscience [10]. The primary goal of such assessment methods and interventions is to diagnose, maintain, improve, or at least delay cognitive and brain decline of the visuospatial cognitive functions, which are critical to functional independence of individuals across lifespan [2].

Interestingly, although our visuospatial capacities allow us to understand and infer everyday relationships of three-dimensional (3D) objects in space, these 3D aspects of visuospatial processing are profoundly neglected in laboratories. In fact, most of the typical methods and paradigms developed for assessment and training of visuospatial capacities include only two-dimensional (2D) visual presentation (for more details concerning training of visual attention, mental rotation and working memory functions, see [11], [12], [13]) and therefore, reduce the real-life complexity of visuospatial processing.

This issue may raise some concerns with respect to the (i) ecological validity of the cognitive tests, (ii) generalization of the findings they bring, and (iii) optimization of the training and restoration programs [14]. More generally, by neglecting the brain‘s ability to process (i.e., represent, infer, predict and store) complex 3D relations that are inherently present in the natural environment, we might reach an incomplete or perhaps, misleading understanding of the crucial mechanisms underlying the human visuospatial cognition. Importantly, it is somehow surprising that although the technologies enabling a more naturalistic, engaging, and ecologically valid means of assessment and stimulation of visuospatial cognition are getting more affordable, this trend has not been reflected in research practice.

In order to address and advance the current state of research methodology in visuospatial cognition, we propose to utilize virtual reality (VR) technologies for training (and ultimately, also testing) the selected cognitive functions. VR provides an appropriate approach to stimulate the real-life aspect of visuospatial processing, including the processing, representing and storage of complex 3D structural and dynamical relations and contents. VR has been already considered suitable for these purposes more than a decade ago [15], when the corresponding equipment was considerably less developed and affordable. The idea that virtual environments may modulate neuropsychological measures is supported by several studies, such as [16], where a virtual office environment, experienced via a VR headset, has been used for assessing the learning and memory in individuals with traumatic brain injury. Another example is a recent survey [17], which also advocates for VR-based function-led assessments that are closer to the real-world functioning. As a first step in the proposed VR utilization, we plan to proceed with an experiment to evaluate the capacity of virtual environments to stimulate selected cognitive functions. The experiment will use VR as an experimental condition that

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will be sandwiched by cognitive event-related potential (ERP) test involving an electroencephalographic (EEG) measurement, applied before and after the VR.

This paper reports the current status of the experiment preparation and is organized as follows. Section II outlines the experiment and deals with two choices related to the VR part: a utilization of a cave automatic virtual environment (CAVE) system for the experiment and a VR game as the experimental condition. Section III describes the CAVE system to be used. Section IV specifies the criteria for the VR game, outlines two proposals and describes already implemented prototypes. Section V sketches neurocognitive testing for evaluating the effects of VR on visuospatial cognition. Section VI concludes the paper, evaluates the game prototypes and discusses next steps in the experiment realization. It also links the current work to the cognitive infocommunications field.

II. EXPERIMENT OUTLINE

The goal of the experiment is to assess the influence of a cognitively stimulating virtual reality experience on the visuospatial cognitive performance. For each participant, the experiment will be carried out in three blocks:

1) Cognitive ERP test.
2) Virtual reality experience.
3) Cognitive ERP test.

The participants will be divided into two groups. The VR experience for the treatment group will involve cognitively stimulating tasks while the experience for the control group will not. The cognitively stimulating VR experience will be provided by the game, played by each participant for a certain amount of time. The game form has been chosen because appropriate cognitive tasks can easily be incorporated into it and it is attractive for the participants. Another choice that seems to be made to increase the appeal of the experiment is the VR equipment to be used. We decided to utilize the unique CAVE system instead of much more widespread VR headsets. However, the choice to select the CAVE system is also practical. The EEG recording requires electrode placement of the subject's scalp, either directly or mounted in an elastic cap. Since the VR step occurs between two EEG measurements, the VR headset utilization would require removing the electrodes after the first measurement and putting them back before the second one. This manipulation is not necessary if the CAVE is used: the electrodes may be kept on the participant's head during the whole experiment.

III. VIRTUAL REALITY SYSTEM

The VR system chosen for the experiment is LIRKIS CAVE [18], built at the Technical University of Košice and shown in Fig. 1. It is a compact and transportable VR environment with a 2.5×2.5×3 meters display area. Its visual output is rendered on twenty 55-inch stereoscopic LCD panels. Fourteen of these panels are positioned vertically along 7 sides of a decagon. Thank to these properties, the CAVE provides a 250 degree panoramic space. The remaining 6 panels are positioned horizontally forming the ceiling (3 panels) and the floor (3 panels). The CAVE supports a wide variety of input devices for user control. These range from the usual ones, such as mouse and keyboard through gaming devices (joystick, gamepad) to special peripherals such as the Myo armband [19] and OptiTrack [20] for capturing the user movement. Rendering of virtual scenes and user interaction are performed by a cluster of seven computers, equipped with the NVIDIA Quadro graphics cards.

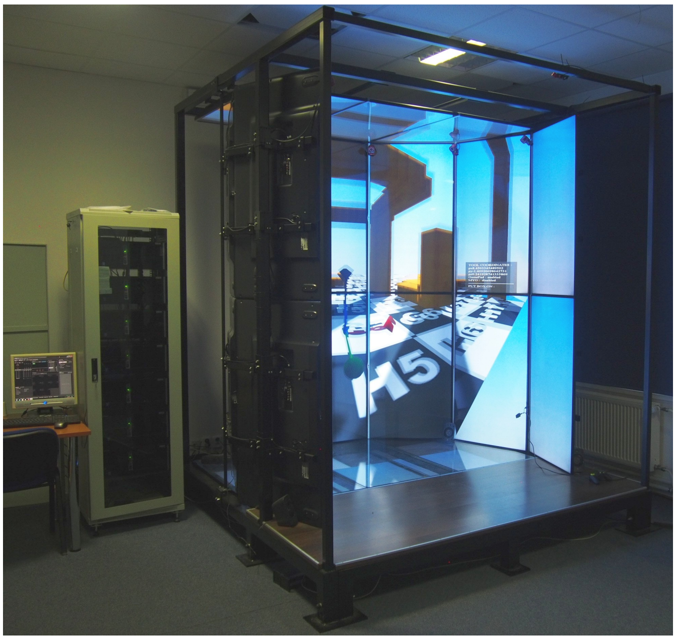

Fig. 1. The LIRKIS CAVE system. From left to right: the LCD display with OptiTrack control software GUI, the computer cluster and the display area.

IV. STIMULATION GAMES

While the CAVE provides suitable hardware and software, the stimulation games for the experiment have to be newly developed. To fulfill the experiment goals, the games should satisfy the following criteria:

- *Natural inclusion of the physical space of the CAVE to the game design.* The LCD panels can render any kind of environment, however they present an impassable barrier for user's movement. In addition, the LCD panel bezels are thin but visible. To preserve a high level of immersion, both of these limitations should feel natural in the virtual world.
- *Adherence to the cognitive goals.* The game play should include elements that are both attractive for the players and cognitively stimulating.
- *Appropriate difficulty.* The game should not be exhausting, such that we could assume the same mental conditions for participants with the VR condition and for the control group.

There is also an additional, technical, criterion, namely a *relatively fast and effective implementation*: The game should be implementable in a relatively short time (few months) and should provide a fluent scene rendering. This means that the design should be rather simplistic and use already existing models. To achieve the fluent rendering and interaction with

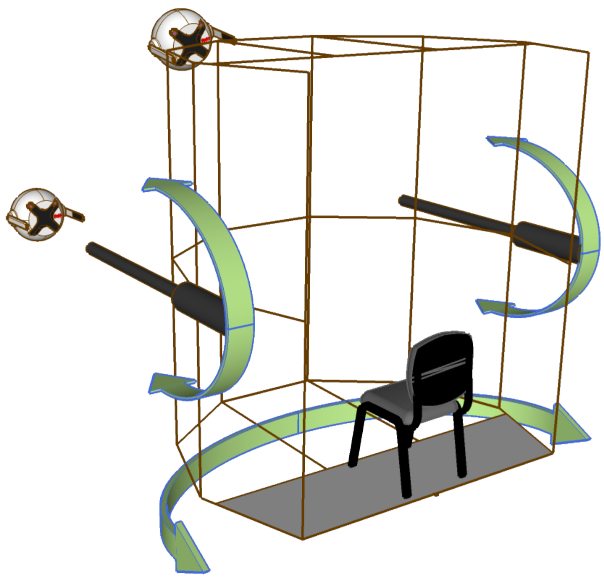

Fig. 2. Conceptual design of the tower defense game.

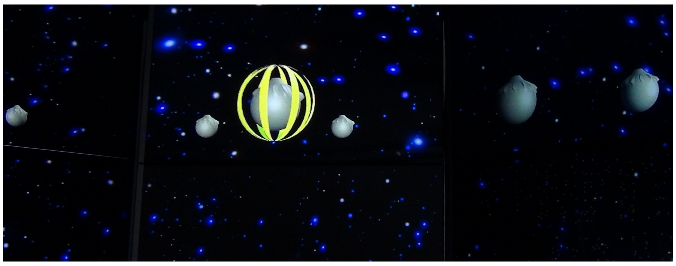

Fig. 3. Tower defense game prototype in the CAVE.

Property	**Meaning**
speed	speed of the drone.
droneShotPower	turret damage by one drone shot.
droneShotProb	probability that the drone hits the turret.
droneShotFreq	drone fire rate.
dronePassEv2City	defines how the drone affects the defended location. after passing the turret (positively or negatively).
dronePassEv2Turret	defines how the drone affects the turret after passing it (positively).
dronePassEvProb	probability that the previous two effects happen.

TABLE I. BEHAVIORAL PROPERTIES OF A DRONE

the user, the autonomous objects should have simple behavior and their models should be close to the common 3D primitives.

Considering these criteria, two different proposals have been prepared and partially implemented: an arcade *tower defense* and a logical Tetris-like *3D constructor* game. Despite differences in their nature (shooting versus object manipulation), they both involve the same cognitive functions such as visuospatial processing, memory, or pattern discrimination. In both games, the CAVE presents an operator cabin with the shape and dimensions identical to the LCD panel bezels. All actions take place outside the cabin's walls. As the CAVE cannot move in the physical world, its movement in the virtual world is limited to the rotation around its vertical axis and horizontal movements. This should eliminate the simulation sickness caused by the difference between the perceived virtual environment and other physical sensations. Both games are set in fictional worlds.

A. Tower Defense

In this game, whose conceptual design is shown in Fig. 2, the player is supposed to defend a fixed location for a given amount of time. The CAVE represents a defense turret, which can rotate to the left or right. The turret is equipped by beam canons whose line of fire can be adjusted vertically. The enemies are represented by drones, approaching the turret from the front. They can attack the turret or the location it is defending (e.g. a city). The interaction between the turret and an enemy drone (i.e. firing at each other) may occur only before the drone passes the turret location. After the enemy passes the turret, it can attack (bomb) the defended location. The player loses if the turret or the location is destroyed before the preset amount of time passes. The primary cognitive element is that friendly drones are approaching, too, carrying supplies critical for the survival of the turret and the defended location. The player has to distinguish between friendly and enemy drones on the basis of the shape, color and simple behavioral differences (e.g. blinking versus not blinking).

A prototype of the game has been already implemented. Its appearance can be seen in Fig. 3, which captures a moment when six bomber drones approach the turret. The one aimed by the player is indicated by a yellow surrounding spherical object. To be able to easily adjust the game for the experiment, we designed the game with a number of configurable parameters. In addition, the properties related to the physical appearance of a drone are completely separated from the behavioral ones. Therefore, drones with different behavior (e.g. a friend and an enemy) may have the same appearance and drones with the same behavior may have different designs.

The appearance-related drone properties are a 3D model for the drone, simple animation properties and an additional 3D model shown when the drone is aimed. The behavioral properties are listed in Table I. In theory, they allow to specify a drone as a friendly and enemy at once, however we do not plan to use such drones during the experiment. When a drone is destroyed or passes the turret, it reappears at a random location and approaches the turret, again. The time of its first and last appearance can be set, too. The properties from Table I do not need to be static; they may change linearly by each reappearance of a drone to increase the game difficulty. The game provides additional parameters to define the pace of the change. This game uses classical input devices to control the turret and the cannon, primarily a gamepad.

B. 3D Constructor with Myo Control

The second proposal is a construction game with a 3D Tetris-like game mechanics. The player sits in an operator cabin that can move along the walls of a closed cylindrical construction area, as shown in Fig. 4. The object under construction is situated in the middle of the area and blocks to be added to it are coming from all directions. The player is able to move the incoming blocks until they come into contact with the object. In order to see the side to which a new block is heading, the player is also able to move the cabin. The pace and complexity of the incoming blocks increase with time.

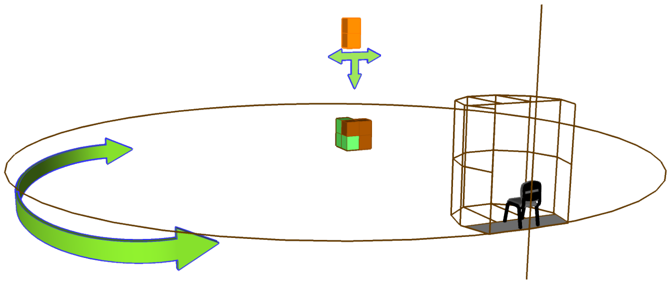

Fig. 4. Conceptual design of the 3D constructor game.

The implementation of this game does not proceed as fast as the first one. The reason for this is a more complicated gameplay and our intention to incorporate a less traditional input device, the Myo armband whose support has been implemented for the CAVE recently [21].

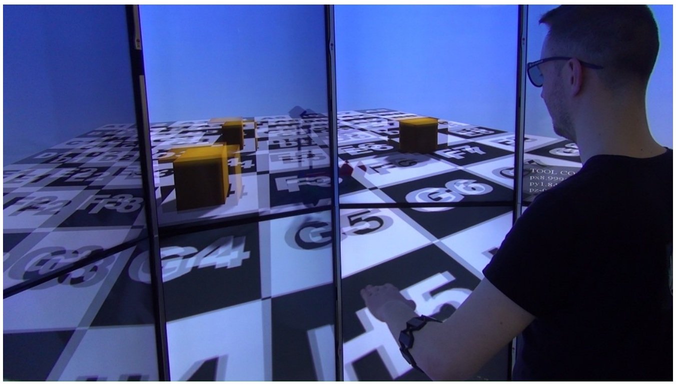

Fig. 5. Myo-controlled interactive scene for box placement activities. The box is placed at the location F4 and the cursor is moved out of the location. The user initiates the end of activity by the "hand down" gesture.

The early prototype of the constructor game focuses on object manipulation by means of the Myo armband. It has a form of an interactive virtual scene, consisting of a chessboard grid surface, a three-axis cursor and a sky background (Fig. 5). The chessboard grid is marked with letters A to H and digits 1 to 8. Movement of the three-axis cursor is controlled by Myo, which captures the orientation and movement of the user's arm. The yaw, pitch and roll angles values from Myo are used for the x, y and z axis movement of the cursor. The user performs a simple mental activity consisting of placing a box to a specific location at the grid surface. The location coordinates (a letter and a number) are displayed on the screen before the activity starts. Then the time is measured from the beginning of the activity to its completion. The user has to move the cursor to the location by arm movements and place the object there by a hand gesture. Then the user moves the cursor out of the location and signals the end of the activity by another hand gesture. If the user makes a mistake and puts the box on a wrong place, a new activity can begin, or it is possible to repeat the previous one to get better results. The measured times are stored in a log file together with the coordinates of the three-axis cursor.

V. COGNITIVE TESTING

Cognitive tests were designed focusing on targeted visuospatial functions whose objective neural signatures will be investigated. For this, we will measure the EEG signal in order to capture the event-related potentials (ERPs), i.e. time- and phase-locked electrical responses of the brain to a specific event (usually a visual or an auditory stimulus). Due to inherent noise in the EEG signal, averaging over a number of trials (40 or more) is applied, in order to reveal a low-amplitude wave of interest. The ERP protocols from the domain of visual working memory and spatial attention were implemented. This represents an experimental design [22] which elicits contralateral delay activity (CDA) and N2-posterior-contralateral (N2pc) ERP components [23].

CDA represents a well defined neural correlate of working memory capacity, as shown in multiple studies [24]. The amplitude of this delayed negativity that can be seen over the posterior regions of the scalp (typically occipital and parietal areas) during the period of maintenance of information in one's memory, has been shown to correlate with the memory load as well as efficiency of filtering irrelevant distractor information. In a typical experiment, it is assessed in a 2D task where the visual field is split into two hemifields, each containing a sample array with a specific number of objects, e.g. colored squares [22]. Participant's task is to remember the color and the position of all objects from the visual hemifield that was indicated by a cue (an arrow just before the sample array appeared). To assure only the attention and not the participant's gaze, it is moved toward one hemifield, the sample array is presented only for a limited time, less than needed for the saccadic movement. This is followed by a retention interval during which the participant needs to retain the visual information in the visual working memory for a prolonged period of several seconds. During this time interval, a CDA can be seen from approximately 250 ms after the onset of the sample array in the hemisphere contralateral to the targeted visual hemifield. After each retention period a probe (test) screen appears containing exactly the same objects as the sample array or with a small difference, and the participant should indicate whether it is the same or different from the sample. At the end, all ipsilateral ERPs (from the same hemisphere as the target visual hemifield) are averaged for the same trial type (memory load) together, and all contralateral ERPs for the same trial type are averaged together. Finally, the resulting difference wave is calculated as a difference between the ipsilateral and the contralateral ERPs. In this way, electrophysiological corelates of cognitive functions, such as CDA, can be used as a highly sensitive tool for estimating even subtle changes in cognitive functions after visuospatial training in VR.

VI. CONCLUSION

We outlined an experiment, which represents one of the first designs toward using a more ecologically valid experimental condition utilizing 3D, rather than 2D, space, as commonly used in research. This is expected to more closely correspond to the real experience that taps on various cognitive processes and we believe it is an important step in psychological and cognitive research nowadays. The crucial element of the experiment, the VR game, has been designed and implemented in the form of two different prototypes. Both prototypes have been evaluated by multiple users in the LIRKIS CAVE system. Only a single problem has been detected, namely a significant frame rate drop after a user had dropped about 50 boxes in the 3D constructor game. The cause of the problem is that the time needed to add a new 3D object to the scene increases with the number of objects. Fortunately, such a situation is unlikely to occur during a typical gameplay of the 3D constructor. This experience also affected the tower defense game design where all the drones used during the gameplay are instantiated before the game begins. The evaluation also revealed that despite their simple design and gameplay, the games are attractive enough for a significant time period (10–15 minutes). The experience of several users can be paraphrased as “I will not play this game on my computer, but here it is really interesting and immersive.” Considering the current development stage of the games, the tower defense is the primary candidate for the actual experiment. This is also supported by the fact that thanks to the number of configurable parameters the defense game can be adjusted for both the treatment group and the control group. The effect of the VR game will be evaluated by standardized cognitive ERP tests, to make the results comparable with previous works.

Last but not least, the work presented here is related to the field of cognitive infocommunications (CogInfoCom) that focuses on targeted engineering applications in which artificial and/or natural cognitive systems are enabled to work together effectively [25]. VR technology offers a new dimension for interaction with human users, and its multi-faceted added value has already been mentioned in the literature. For example, a recent experiment confirmed the higher effectiveness of the 3D VR educational platform (MaxWhere), compared to traditional 2D interfaces, in terms of various operations and workflows constituting the core of digital literacy [26]. MaxWhere 3D platform has also been tested as an effective tool for education and cooperative learning [27].

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