Experimental Procedure for Evaluation of Visuospatial Cognitive Functions Training in Virtual Reality

Štefan Korečko[1](✉), Branislav Sobota[1], Marián Hudák[1], Igor Farkaš[2], Barbora Cimrová[2,3], Peter Vasiľ[1], and Dominik Trojčák[1]

[1] Department of Computers and Informatics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Košice, Slovakia
{stefan.korecko,branislav.sobota,marian.hudak.2}@tuke.sk
[2] Department of Applied Informatics, Comenius University in Bratislava, Bratislava, Slovakia
farkas@fmph.uniba.sk
[3] Institute of Normal and Pathological Physiology, Centre of Experimental Medicine, Slovak Academy of Sciences, Bratislava, Slovakia

Abstract. In recent years, visuospatial cognitive functions, which play a crucial role in human cognition, have sparked interest among psychologists and neuroscientists, focusing on assessment, training and restoration of these functions. Virtual reality, recognized as a modern technology, addressing the real-life aspects of visuospatial processing, provides an immersive environment that can be used for stimulation of cognitive functions and its effects that can be measured afterwards. In this paper, we describe an experimental design that involves cognitive testing and targeted, cognitively-oriented, stimulation in an immersive 3D virtual environment, rendered by a unique CAVE system. We focus primarily on a game, designed and developed to serve as the virtual environment. We also describe the experimental procedure that includes the measurement of an electrophysiological neural correlate of spatial working memory capacity – contralateral delay activity.

Keywords: Virtual reality · Training · Spatial working memory · Change detection task

1 Introduction

Visuospatial cognitive functions allow us to detect, represent, manipulate and store visual and spatial information [5]. This entails the ability to perceive visual objects, locate their position in space, orient our attention, infer various spatial relations and remember the scene. In addition, visuospatial cognitive abilities enable to perform judgments related to direction and distance among external objects and thus allow individuals to navigate in the environment [1].

A. E. Hassanien et al. (Eds.): AISI 2019, AISC 1058, pp. 643–652, 2020.
https://doi.org/10.1007/978-3-030-31129-2_59

Due to their importance in everyday life, visuospatial functions attracted attention of both psychologists and neuroscientists who have developed various means how to measure them in humans (see [4] and references therein). Most-widely applied visuospatial tests target specific functions ranging 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 [2,11]. At the same time, visuospatial training and restoration programs, exploiting the known principles of brain plasticity, have recently manifested a great interest in cognitive neuroscience [9]. 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, to improve the quality of human life [1].

In order to advance the current state of research methodology, by addressing the real-life aspect of visuospatial processing, we will utilize virtual reality (VR) technologies for training the selected cognitive functions. VR has been already considered suitable for these purposes before, when the corresponding equipment was considerably less developed and affordable [10]. The idea that virtual environments may modulate neuropsychological measures is supported by several studies, such as [7], where a virtual office environment, experienced via a VR headset, was used for assessing the learning and memory in individuals with traumatic brain injury. A recent survey [8] also advocates for VR-based function-led assessments that are closer to the real-world functioning.

In this paper, we report about an experiment that aims at evaluating how an experience in an immersive VR environment can stimulate selected cognitive functions, namely working visual memory. As a matter of fact, although our visuospatial capacities allow us to understand and infer relationships of three-dimensional (3D) objects in space, these 3D aspects of visuospatial processing are profoundly neglected in laboratories. The experiment will use VR as an experimental condition that aims at maximally exploiting the immersive 3D environment. The computerized cognitive tests will be in 2D, following the current standards, focusing on measuring targeted visuospatial functions.

The VR experience will be represented by a game, developed solely for the purpose of the experiment. The preliminary outline of the experiment was introduced in [4], where two game prototypes were initially considered: a logical, Tetris-like construction game in 3D and a first-person shooter of the tower defense genre. After considering pros and cons of both games, with respect to their suitability, the latter game was eventually chosen and the experiment procedure has been refined to its final form. Both the procedure and the game are described in the rest of the paper, which is organized as follows. Section 2 provides the basic information about the LIRKIS CAVE, a VR facility to be used in the experiment. Section 3 specifies the final form of the experiment procedure and Sect. 4 deals with the design and implementation of the tower defense game. Section 5 concludes the paper.

2 LIRKIS CAVE

The virtual environment for the experiment will be provided by LIRKIS CAVE [3], a compact and transportable cave automatic virtual environment, built at the Technical University of Košice. It features a $2.5 \times 2.5 \times 3$ m display area, made of twenty LCD panels. The panels are 55 in. LCD TV sets with passive stereoscopy, made by LG. Fourteen of these panels are positioned vertically, forming seven sides of a decagon. Thank to this arrangement, the CAVE offers a 250° panoramic space. Six panels are positioned horizontally. They form the ceiling (3 panels) and the floor (3 panels). The whole display area is mounted inside a self-supporting steel frame. This means that the CAVE doesn't need to be fixed to the walls, ceiling or the floor of the room where it is installed. The interaction between the CAVE and its human users is provided by a variety of input devices. These include the usual ones, such as mouse and keyboard, the gaming devices (joystick, gamepad) and VR-specific peripherals such as the Myo armband[1] and OptiTrack[2]. The OptiTrack system of 7 cameras captures the user movement. Rendering of virtual scenes, user interaction and control over the whole system are the responsibility of a cluster of 7 computers, equipped with the NVIDIA Quadro graphics cards. The CAVE is shown in Fig. 1(b).

3 Experimental Procedure

For each participant, the experiment procedure starts with filling a form with basic information (name, age, gender, education, handedness), exclusion criteria and a questionnaire about mood, mental energy and fatigue. Exclusion criteria are psychological or neurological diagnosis, traumatic brain injury, learning disability and psychoactive medicaments taking. Due to the lateralized nature of the main cognitive test used in this study, only right-handed subjects can participate. The entire procedure, applied to the experimental group, can be split into two phases – preparation and training.

3.1 Preparation

First two visits consist of performing a change detection task (CDT) in which the capacity of spatial working memory is assessed for each participant. The task consists of a specific number of red (targets), blue and green (distractors) rectangles in various orientations. At the beginning of each trial, an arrow (cue) indicates visual hemi-field to which the participant is supposed to pay attention. The rectangles (sample array) are presented only for a limited time (200 ms) followed by a retention period of 1 s. The task of the participant is to keep in his or her memory the orientation of all target (red) rectangles from the hemi-field indicated by the cue. Afterwards, a probe (test array) containing the same sample array, with or without a change in orientation of one target rectangle, is

[1] https://support.getmyo.com.
[2] https://optitrack.com/.

displayed and the subject should indicate whether he or she noticed any change in orientation in comparison to the sample array. During this task, participants' eye movements are recorded using electrooculography (EOG) to assure they are moving only their attention and not their gaze (as the neural correlate connected to the spatial working memory capacity is lateralized, see below, contralateral delay activity, CDA).

For CDT evaluation and for measuring the performance (accuracy in detecting the change in one of the targets), we need to identify invalid trials, i.e. those during which undesirable eye movements have been detected (because those would violate the experimental design). As a preset threshold, the number of invalid trials must not exceed 20% for including the participant into the group. The semi-automatic procedure for detecting eye movements is based on evaluating pre-collected EOG signals, when the subject was instructed to move his or her eyes, and blink, in a controlled manner, such that appropriate thresholds could be set based on visual inspection of the preprocessed eye signals (detecting horizontal and vertical eye movements).

3.2 Training

The first day of training in LIRKIS CAVE starts with the same questionnaire mentioned above and is followed by CDA pre-test assessment. The task is the same CDT as described above, and in addition, event-related electroencephalographic (EEG) potentials are being recorded. Approximately 250 ms after the sample array onset, a large negative electrical deflection can be seen over the posterior parietal sides opposite (contralateral) to the targeted side (target hemifield indicated by a cue). This deflection, named Contralateral Delay Activity or CDA is considered a neural correlate of working memory capacity as its amplitude changes with the number of items held in memory [6]. The difference wave is calculated as a difference of an average signal from all contralateral and ipsilateral (same side) electrodes. EEG is measured from four left and four right posterior electrode sites plus three midline spots (P3, P7, PO7, O1, P4, P8, PO8, O2, Fz, Cz, Pz) using a high-performance and high-accuracy biosignal amplifier g.USBamp with ground electrode on AFz and reference electrode attached to left earlobe and digitally re-referenced to linked earlobes. If the person performing the task cannot filter out the distracting stimuli, the number of items in their memory increases and their CDA changes correspondingly. Therefore, we can use this as a sensitive method for estimating changes induced by training in VR.

After the CDA pre-test, the participants undergo first training in LIRKIS CAVE. Each training session takes 30 min and consists of three atomic sessions. One *atomic session* refers to the 8-min block of continuous playing and there are 3-min breaks between them. In subsequent two weeks the participants continue with training resulting in 5 sessions (days) before the next CDA measurement (mid-test). In the next two weeks, the training continues with five more sessions and it finishes the day after the last training with the final CDA (post-test) assessment. During each training day, participants fill in the questionnaire. The whole protocol is performed by an experimental group. The same protocol, except the training in the CAVE, is followed by a control group. The procedure was tested in a small pilot version on five subjects to adjust the protocol and its parameters. As a result we decided to use a combination of two, three and four target stimuli (red rectangles) and zero or two distractors (blue or green rectangles). One CDA session consists of 240 trials in total and takes 20 min plus four brakes for approximately 3 min.

4 Tower Defense Game

After an evaluation of the two prototypes, described in [4], the tower defense has been selected for the experiment. It has been chosen primarily because its prototype was further developed than the construction game, it is more adjustable and the fact that no performance-related issues were observed during its testing.

4.1 Design

To ensure a high level of user immersion, the game is designed in such a way that the physical constraints of the CAVE are a natural part of it. The most significant constraints are

1. *Limited user movement.* The user can move freely inside the CAVE, but the LCD panels present an impassable barrier.
2. *Fixed position of the CAVE.* The CAVE itself cannot move in the real world. Therefore, at least the horizontal position should be maintained during a VR experience to minimize the risk of the simulation sickness. It is also best to avoid simulated movements where the sensations related to the acceleration or deceleration should be felt.
3. *Visible LCD panel bezels.* While the distance between LCD panels is kept at minimum, their bezels are still visible in the CAVE.

To incorporate the constrains, the CAVE itself represents an interior of the operator cabin of a fictional defense tower, armed with laser cannons. The LCD panels serve as the glazing of the cabin and their bezels form the frame of the glazed part. As can be seen in Fig. 1(a), the only movement allowed for the turret and the cabin itself is a rotation around its vertical axis. Just the cannons can move up or down. The final appearance of the game is shown in Fig. 1(b). The dark background with stars has been chosen to make important objects well recognizable. The most noticeable difference between the concept and the actual game is the absence of the cannons. We decided not to show the cannons as they may block the view significantly and because of potential performance issues. In the actual game, only the cannon beam is visible when fired and it originates from underneath the operator cabin.

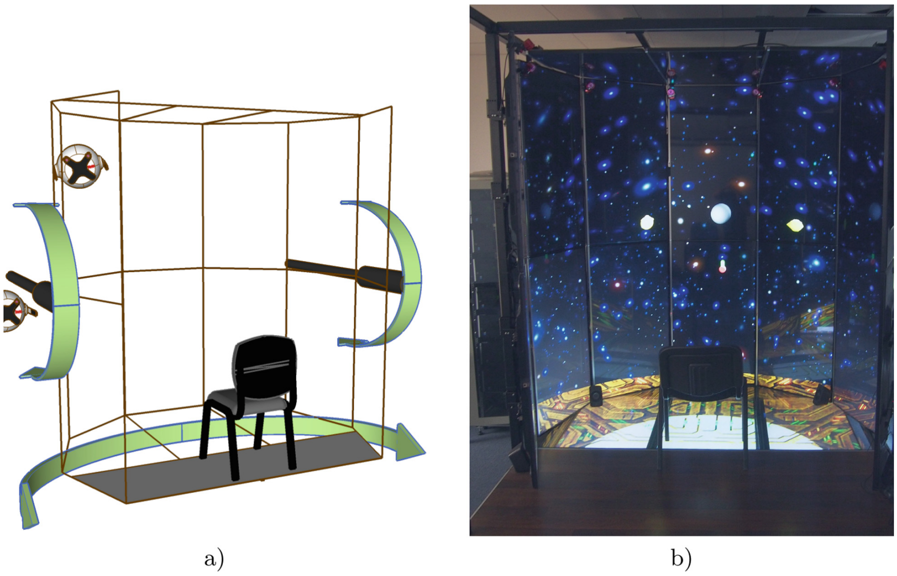

Fig. 1. Game appearance: (a) the concept and (b) implementation in LIRKIS CAVE.

4.2 Gameplay

From the player's perspective, the goal of the game is to defend the turret from invaders for a given period of time. The invaders are represented by drones flying towards the turret in groups (of various sizes). Six different 3D models are used for the drones, shown in Fig. 2.

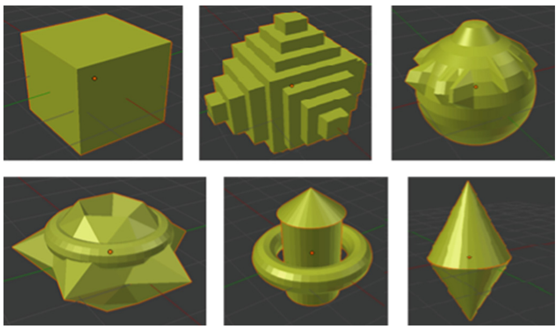

Fig. 2. Drone models used in the game.

The drones may seem very basic and strange-looking, however this is intentional: As the shapes in the CDT, the drones are divided into two groups - *targets* and *distractors*. The targets are enemies to be shot down by the user, while the distractors are friendly drones to be ignored. All the drones of the same model are either targets or distractors. And because of the nature of the tests, used in the experiment, it was required that all drones are the same color. Therefore, the only way to easily tell one from each other was to use very different models for them.

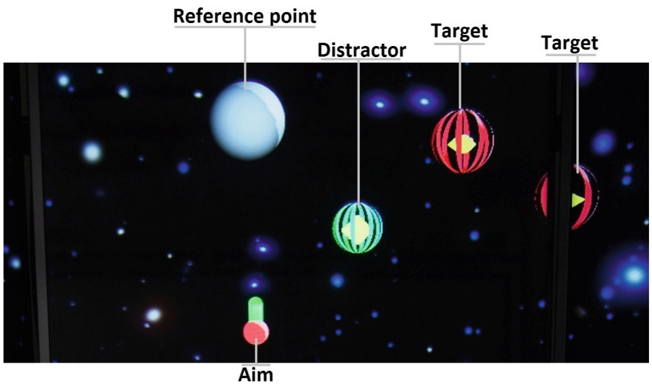

Fig. 3. The middle section of the view from the user's position in the CAVE with important objects labeled.

Each 8-min-long atomic session is a sequence of separate episodes. Each episode involves an attack, performed by a group of drones, and proceeds as follows:

1. The number of targets (n_T) and distractors (n_D) in the attack is computed as
$$\begin{aligned} n_T &= n_T^l + \delta_T \\ n_D &= n_D^l + \delta_D \end{aligned} \tag{1}$$
where n_T^l and n_D^l is the number of targets and the number of distractors for the difficulty level of the session and δ_T and δ_D are random values, drawn from the discrete uniform distribution on the interval $[-r, r]$. The value r is set to 1.
2. A group of n_T target and n_D distractor drones is generated. 3D models and trajectories are randomly assigned to the drones.
3. The group is displayed in the game.
4. For one second, the drones are marked (Fig. 3) to inform the player which ones are distractors and which are targets.
5. The attack begins. All the drones in the group move towards the turret at a constant speed.
6. Once per episode, a blackout event occurs. The time of the event is chosen randomly from the interval $[0.2T_e, 0.6T_e]$, where T_e is the supposed duration of the episode. The duration of the blackout is random, from the interval [600 ms, 900 ms]. The drones disappear from the screens during the blackout.

7. When all the drones pass the turret or are shot down, the episode ends.

All random values mentioned in the episode description are uniformly distributed. The supposed episode duration (T_e) is the time when the last drone in the group passes the turret. The next episode in the sequence starts only after the T_e of the previous one passes, even in the case that the player shoots down all the drones sooner. This is because all atomic sessions must have the same duration and all episodes in a session have to be completed.

The visual output of the game during the first second of an episode can be seen in Fig. 3. There are three drones: one distractor with green marking and two targets with red marking. The rightmost target is just passing the border between two LCD panels. The aim is used for targeting the drones and can be moved using joystick, gamepad or keyboard. If a drone is aimed, it is marked in the same way as all the drones during the first second, but in yellow. The reference point is positioned in the center of the virtual environment and helps the player to navigate. It has been added when the tests of the game prototype revealed difficulties with returning to the central position after an episode ended.

4.3 Levels of Difficulty

Each participant will spend 240 min in total playing the game and the game should train his or her visuospatial cognitive abilities, so it is only natural that the difficulty cannot remain the same all the time. The game has several configurable properties and four of them have been selected to define the levels of difficulty:

- *Drone speed* (v_d in Table 1). The constant speed by which the drones move towards the player can be set to *low* (L in Table 1), *medium* (M) or *high* (H). The speed also defines the number of episodes in a single atomic session.
- *Drone placement* (p_d). It determines how the drones are positioned in the virtual world. Again, there are three options: The easiest setting is *centered* (c), where the drones are concentrated around the reference point. In the *normal* (n) setting the drones appear inside the three middle columns of the LCD panels. Such situation is captured in Fig. 1(b). The most difficult is the *widespread* (w) setting, where the drones may also appear on the next two columns of the LCD panels.
- *Number of drones*. It is defined separately for targets (n^l_T) and distractors (n^l_D). The actual number for given episode is then computed by (1).

Based on these properties, 30 levels have been defined (Table 1); one for each atomic episode, played by a participant during the experiment. The difficulty doesn't increase automatically, but only if the condition (2) holds for the previous atomic session, played by the participant.

$$(n^d_T - n^d_D)/n_T > 0.5 \quad (2)$$

In (2), n^d_T is the number of destroyed targets, n^d_D is the number of destroyed distractors and n_T is as in (1).

Table 1. Difficulty settings for the levels (Lv.) of the game.

Lv.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
v_d	L	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H	H
p_d	c	c	c	n	n	n	n	w	w	w	c	c	c	n	n	n	w	w	w	w	c	c	n	n	n	w	w	w	w	w
n_T^l	2	2	3	3	3	4	4	4	4	5	3	3	4	4	5	5	4	5	5	5	3	4	4	5	5	4	5	5	5	6
n_D^l	2	3	3	3	4	3	4	4	5	4	3	4	4	5	4	5	5	5	6	7	4	4	5	4	5	5	5	6	7	7

5 Conclusion

The experimental procedure, described in this paper, should bring us closer to understanding how VR experience may improve our visuospatial cognitive functions. The procedure and the tower defense game are results of several testing trials, performed with the corresponding prototypes. The game has both the typical features of the tower defence genre and features specific for the procedure. The most prominent of the specific features are an inclusion of the targets and distractors in a way similar to the CDT and the blackout event, which resembles the retention period from the task.

While the main results of the experiment will be derived from the CDT and CDA outcomes, collected before, in the middle and after the training, additional statistics are also computed and stored by the game itself. These include identification of the player, episode, difficulty level and information about every shot fired. The information consists of the time-stamp and success of the shot. The availability of these statistics promises to find correlations between the test results and performance in the game, beyond the main goal of the experiment.

Acknowledgements. This work has been supported by the APVV grant no. APVV-16-0202: "Enhancing cognition and motor rehabilitation using mixed reality".

References

1. de Bruin, N., Bryant, D., MacLean, J., Gonzalez, C.: Assessing visuospatial abilities in healthy aging: A novel visuomotor task. Front. Aging Neurosci. **8**, 1–9 (2016)
2. Dijkstra, N., Zeidman, P., Ondobaka, S., Gerven, M.V., Friston, K.: Distinct top-down and bottom-up brain connectivity during visual perception and imagery. Sci. Rep. **7**(1), 1–9 (2017)
3. Korečko, Š., Hudák, M., Sobota, B.: LIRKIS CAVE: architecture, performance and applications. Acta Polytech. Hung. **16**(2), 199–218 (2019)
4. Korečko, Š., Hudák, M., Sobota, B., Marko, M., Cimrová, B., Farkaš, I., Rosipal, R.: Assessment and training of visuospatial cognitive functions in virtual reality: proposal and perspective. In: Proceedings of 9th IEEE International Conference on Cognitive Infocommunications (CogInfoCom), Budapest, pp. 39–43 (2018)
5. Kravitz, D., Saleem, K., Baker, C., Mishkin, M.: A new neural framework for visuospatial processing. Nat. Rev. Neurosci. **12**(4), 217–230 (2011)

6. Luria, R., Balaban, H., Awh, E., Vogel, E.: The contralateral delay activity as a neural measure of visual working memory. Neurosci. Biobehav. Rev. **62**, 100–108 (2016)
7. Matheis, R.J., Schultheis, M.T., Tiersky, L.A., DeLuca, J., Millis, S.R., Rizzo, A.: Is learning and memory different in a virtual environment? Clin. Neuropsychol. **21**(1), 146–161 (2007)
8. Parsons, T.D., Carlew, A.R., Magtoto, J., Stonecipher, K.: The potential of function-led virtual environments for ecologically valid measures of executive function in experimental and clinical neuropsychology. Neuropsychol. Rehabil. **27**(5), 777–807 (2017)
9. Paulus, W.: Transcranial electrical stimulation (tES - tDCS; tRNS, tACS) methods. Neuropsychol. Rehabil. **21**(5), 602–617 (2011)
10. Schultheis, M.T., Himelstein, J., Rizzo, A.A.: Virtual reality and neuropsychology: upgrading the current tools. J. Head Trauma Rehabil. **17**(5), 378–394 (2002)
11. Shipstead, Z., Harrison, T., Engle, R.: Working memory capacity and visual attention: top-down and bottom-up guidance. Q. J. Exp. Psychol. **65**(3), 401–407 (2012)