Virtual City system for cognitive training in elderly

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***Abstract*— The aim of the Virtual City project is to create a complex training SW in virtual environment with high ecological validity that will enable a comprehensive exercise of cognitive abilities (working memory, declarative memory, attention and executive functions such as decision making, planning, mental flexibility, etc.). The training program could be later applied in the prevention of the cognitive deficits in healthy aging programs. The designed virtual city environment consists of several districts with key buildings and locations used in spatial navigation tasks. Individual tasks are placed in specific locations (both indoor and outdoor) of the city and are focused on various cognitive domains. Here we report on the state of development of the virtual city and individual training games. We describe the principles of the Virtual City system and characteristics of individual training games (including the modified parameters and recorder behavioural variables). We also suggest possible concepts of cognitive training using Virtual City system in elderly.**

Keywords—virtual city environment, training system, cognitive functions, elderly

I. INTRODUCTION

This paper describes the aims, methods and content of the complex training system created in virtual reality titled “Virtual City” (VC) targeted at senior population. The main aim of this project is to create a comprehensive training application in a friendly virtual city environment that allows complex training of cognitive abilities in the target group of healthy seniors in order to create cognitive “reserve”. Current training systems applied in elderly often address only some specific functions (e.g. visuomotor abilities in stroke patients [1]) or in case of complex training programs apply simple computer tasks presented on a computer screen (e.g. Happy neuron, RehaCom, PSS CogReHab, etc.). While such simple applications bring some benefits, such as easy game control allowing broad usage in homes of individuals, the limitation of these approaches is mainly in the ecological validity of the trained abilities or the training content. Concept of complex training in ecologically valid city environment was already implemented in various forms, e.g. “CIRCUITS” by Reeder and Wykes [2] applied for cognitive remediation in Schizophrenia. Another virtual city designed in 2D for cognitive rehabilitation was presented by Costa and colleagues in 2000 [3] and was aimed at traumatic brain injury patients. Virtual city environment was also proposed for the training of daily living activities, such as crossing the street in the patients with unilateral neglect [4]. In 2011 [5] the product BrightBrainer was presented for its use in the elderly. BrightBrainer also incorporates various cognitive functions that are trained across individual serious games in virtual environment presented on the monitor screen. However, while basic principles of serious games can be easily transferred from foreign applications to local region by translation of all verbal information, we believe that some specificities of the cultural context (city structure and street layout, local shopping products) cannot be easily adapted in existing projects.

The proposed project of “Virtual City” therefore incorporates training games directly located in complex city environment allowing simulation of real-like situations and scenarios that are relevant for the local region. Moreover, an immersive form of presentation using virtual glasses allows us to integrate the own movements of participant into actions performed in a virtual environment and thus increase the immersive training experience. This form of representation can also lead to the intuitive control of training games incorporating body movements, especially crucial for population with low computer experiences. The realism of virtual environments and simulated situations can also facilitate the transfer of adopted strategies in to real life.

A. Software and Hardware

The training application is developed in one of today's most used game engine - Unity, which has very good support for VR hardware. Together with the SteamVR (Valve

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VR system), VR runs on HTC Vive, Oculus Rift, Playstation VR and Samsung Gear VR VR's most popular VR applications. Due to the popularity of this engine and its active development, it is very likely that the support of the new headset will be integrated into it soon after its launch.

The Virtual City application is designed according to the model-view-controller paradigm (see diagram below) that includes two parts of the model (internal state of the application), "view" (what the user sees) and "control" (reverse interaction with the model). Due to the good scalability, we designed a general API that allows the game to dynamically register individual games (ie to open new spaces within the city) - it is possible to develop individual games (or game versions) independent of each other and run them without editing the entire application. At the same time, this API abstracts from hardware-specific parts of the code, improving application portability to other hardware, ensuring uniform functionality and appearance, and simplifying game development.

Data storage (including tracking logs, see Data recording and analysis) takes care of the SQL database system, which can be separated from the application if necessary and operated over a computer network.

When choosing a hardware solution, we put the emphasis on the good availability of the hardware type and the realistic (i.e. immersive) VR experience the solution offers. While mobile virtual reality is more affordable for end users, the current drawback of today's mobile phones is the lack of performance to realistically visualize the virtual world in the VR and the lack of precision in head and body movement (mobile phones now only allow to track head rotation, not its shift). Moreover, VR applications for mobile VRs does cannot get the user to “immerse” in such extend. For this reason, we decided to focus on virtual reality mediated by special VR headsets that connect to a computer by a cable. Since the VR set typically consists of a high-resolution headset (~ 1Mpx / eye), drivers, and external headset and driver sensors, it achieves higher head and driver movement sensitivity and, thanks to high PC performance, it can display virtual world in sufficient detail.

The most famous representatives of this category are HTC Vive, Oculus Rift and PlayStation VR. Regarding realism, all three VR sets offer the user a comparable experience. However, the HTC Vive set has a significant advantage over its competitors in the ability to monitor headset and controller movements across the space of about 8m3, ie back to the sensor, and we have chosen it as the most suitable candidate for the development of immersive VR applications. At the same time, HTC Vive headphones can now be wirelessly connected to a PC.

Migration to another VR HW (Oculus Rift headsets, Playstation VR and Samsung Gear VR) is possible by using the Steam VR system (see above). The compatibility of several prototypes has been successfully tested using the HTC Vive and Oculus Rift headsets.

Note that only one HTC Vive controller (or two controllers with mirrored functionality) is used in the project in order to achieve transferability also to headset systems with one controller and also to minimize the functionality that has to be learned by the seniors). Moreover, special function enables automatic change of the viewing/body height in individual virtual scenes, especially useful in seated participants with limited whole body movements or affected posture balance.

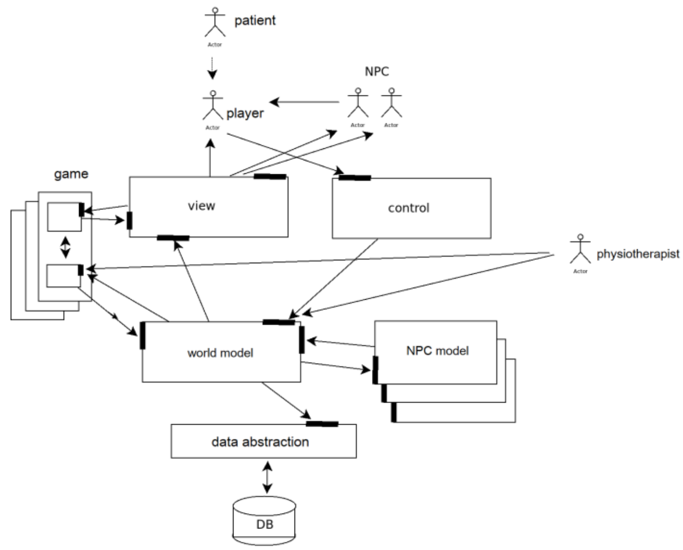

Fig. 1 Simplified City Design Software Design Chart

B. *Virtual City Training Concept*

The designed virtual city environment consists of several districts that include key buildings where individual training tasks take place (both indoor and outdoor) and locations used in spatial navigation tasks (office buildings, post office, city hall, park, historical sites, cinema, theatre, etc.). The proposed spatial structure of the city is large enough for training of spatial memory and orientation, but the distance between travelled locations is short in order to prevent lengthy movements over longer distances.

Individual tasks are placed in specific locations of the city and are aimed at various cognitive domains. The selection of trained functions is based on the findings of past studies on the effectiveness of cognitive training in healthy seniors and on the known extent of cognitive deficits in individual domains associated with increasing age or neurodegenerative changes. Current studies demonstrated that the strongest effect can be achieved in domains of executive functions (working memory and processing speed) and memory abilities [6][7]. The training tasks applied in VC project therefore focus on the above-mentioned cognitive skills. However, long-term memory functions are emphasized in our training program in order to focus on various memory functions including verbal memory, spatial memory and episodic memory. Higher number of memory tasks corresponds to the knowledge that memory deficits represent the most common subjective complaints in the aging population [8] and are also the first functions weakened by the aging process [9].

C. Additional tasks and gaming features

The design of the city also includes locations such as the Zoological Garden, which is intended as a motivational or gamming element. Seniors collect tokens in individual training tasks that can be exchanged for various objects they need or want for their virtual household or virtual character (such as clothing, accessories, etc.). Tokens can be exchanged also for tickets to entertainment areas (e.g. Zoo, Relaxation Zone, etc.). These supplementary games do not fulfil the main training purpose but represent a reward element to enhance the motivation of participants in tasks that are key to cognitive skills training.

D. Social element of the city

The city environment includes also social aspect in the form of animated, computer-controlled characters (NPCs) and other active environmental elements that include not only virtual characters, but also vehicles (cars) or animals. The NPCs can be of two types: 1) *Common* - they form a realistic social environment of the city (movement, interaction with other NPCs present and objects such as benches, lifts, etc.); and 2) *Main* - create a specific social situation - perform the scenario of the action. The system created consists of three modules: the NPC management module, a graph path search module for effective NPC movement in the game environment, and a module for management of scenario and sub-tasks. Individual NPC categories (cars, people) respond to the presence of distinct objects and follow distinct routes (for example, cars react to traffic lights), pedestrians can get in the car or respond to objects near pedestrian areas (bench, elevator, entrance to the building etc.).

Fig. 2 Example of an NPC character interaction with an NPC of car in a city prototype.

Fig. 3 Example of a path search module and setting of automatic trajectories for movement of individual NPC types (characters - blue, cars - green).

E. Serious games focused on individual cognitive functions

We describe a battery of serious games created in virtual scenes (locations) of the city environment (for a more detailed description see Principles of individual training games). Each of the training tasks meets the following criteria:

1. Gradually increasing level of difficulty according to player's success in the task;
2. Contains a TXT file for editing task-specific configurable parameters;
3. Recording (logging) of performance data of the trained person.

We have created prototypes of the following serious games:

- *Practice* - used to practice movement and actions control in virtual space.
- *Activity Planning* - requires multimodal information processing in order to schedule a daily program – Focused on executive functions: decision-making and planning.
- *Navigation* - requires navigation to individual city locations – training of spatial memory.
- *Objects* - requires memorizing of the spatial and temporal context while searching for objects – training of episodic memory (context of events).
- *Flies* - requires find and hit a sitting fly – training of attention, psychomotor speed and visuo-motor control
- *Supermarket* - requires memorizing the shopping list and searching for products in the supermarket area – focused on verbal memory
- *Shooting range* - demands differentiation of targets from non-targets - training of selective attention, psychomotor speed and inhibition control
- *Carousel* - requires orientation in separate spatial frames while searching for hidden locations – training of mental flexibility, working memory and spatial orientation

Additional game concepts will be realised in future SW development in order to address some other more specific skills (such as body movement and posture exercise, social skills and decision making), missing in the current state of the Virtual City project.

Note: While some of the existing games are fully prepared for testing in target population of elderly (see Pilot study), some game prototypes are ready for internal testing.

II. Principles of Individual Training Games

F. *Practice task*

In order to prepare elderly subjects for the usage of serious games in VR and even before they enter virtual city environment, they are first familiarized with the specificities of the movement control, functionalities generally used across the tasks (pick-up or drop object etc.). The practice task was designed to practice control and movement in the virtual space (using one HTC vive controller as you can see in the Fig. 3). In particular, it trains the ability to move freely in the interiors or to teleport to larger distances in the virtual city space. In terms of movement they are first familiarized with the active motion feedback in the VE (synchronisation of the spatial view with the head and whole-body movements) and specific controller for teleportation (using multi-function trackpad). Subsequently they are explained using the game how to apply functionalities general for all games or specifically for situations presented in individual games, (dual-stage trigger can be used e.g. for actions such as pick-up or drop of the objects, opening the doors or drawers, etc.). Moreover, HD haptic feedback is given in some situations to provide information about some action, such as touching or dropping of objects. The Practice task also requires confirmation of the text instructions provided throughout the practice procedure.

Fig. 3 Visualisation of the HTC vive controller adjusted for VR city environment.

Fig. 4 Illustration of the Practice game (teleportation practice, pick-up practice).

G. *Activity Planning*

The task Activity Planning requires the senior person to process complex information provided from different sources and schedule the daily program on the basis of information obtained. The task uses simulation of media (television or radio) in a virtual household. Here, players are presented with comprehensive information including weather, cultural and sport events, etc. Some local information (personally related) is gained also by the person who visits the house or by phone. Based on the information obtained, the person should decide practical output such as choosing the appropriate clothing and accessories according to the weather and the planned activities (dressing subtask), planning a daily program using a calendar (calendar subtask) and picking up the objects that he / she needs to perform the daily tasks such as wallet, medication, ID card etc. (to go packaging subtask). The task ends with the training day finished (it thus creates quest system - scenarios for the training day). Adjustable parameters: number of informational sources providing the information, number of activities to plan, etc. Recorded variables: number of errors in the dressing subtask and in to go packaging subtask, number of tasks planned and completed in the calendar/scheduler, time needed to finish individual subtasks, number of moves (incl. corrections) in the subtasks.

Fig. 5 Illustration of the Activity Planning game (television, virtual person visits, scheduler).

H. *Navigation*

The Navigation game was inspired by the Virtual city spatial navigation task [10]. During each training day, the participant has to visit several city locations (spatial locations or buildings). In these places, she/he must first point towards the navigated spatial position (directional information) and then move actively towards it. The participant can use the navigation elements (town minimap with the spatial directions and or the navigation arrow leading to the target) before they familiarize with the city environment. However, after some training they are requested to use own navigation skills and find the location if possible, without such navigation tools. Adjustable parameters: navigation aid availability, the distance between the player's position and the navigated location, etc.). Recorded variables: Angle error and pointing time, Trajectory length, number of deliberated stops with or without directional change, travelled trajectory length, time to find the location, success rate (ideal vs. true distance), what navigation aid was used and for how long (% of navigation aid usage time ratio of travelled time).

Fig. 6 Illustration of the Navigation game (navigation using arrow, visible city map).

I. Objects

The game Objects was inspired by the episodic-like memory task applied as testing method in previous studies (e.g. [11]) and trains episodic memory for events in a simplified form of so called episodic-like memory (What, Where When) [12]. Each level of the game consists of two phases - the acquisition phase and the retrieval phase presented after a prespecified time pause. In the first part, the arrow navigation tool is used to navigate the participant to individual items (objects) that have to be collected in a virtual home environment. The task of the participants s to remember the items (What) together with the order in which they were collected (When) and locations (Where) they collected them. In the second phase the participant has to identify the correct items (from a set of misleading items presented) and return them in the correct order to the correct locations. Items are generated randomly and in random places across all rooms and outside locations.

Fig. 7 Illustrations of the game Objects (a preview of the arrow leading to the object during learning and selection of objects during the equipment stage).

Adjustable parameters: initial number of objects (the number of items that are memorized is gradually increasing in case the level is completed without errors), sets / categories of stimulus generating objects, length of delay (the time of delayed recall can be extended). Recorded variables: Errors can be analysed in all three memorised parameters (What, Where, When), the time required to complete the task and the length of trajectory travelled is compared to the initial trajectory length in the acquisition phase, number of moves (incl. corrections).

J. Flies

The task is embedded in the virtual kitchen environment in which flies fly around. The flies emit sound and sit at the places around the person standing in the kitchen. The task of the player is to kill a fly in the shortest possible time after it sits down on the kitchen furniture and walls (or other surfaces within the indoor environment where the game is presented). The role is focused on attention, visuomotor coordination and psychomotor speed. At each moment, the player gets information about the accuracy (number of flies killed vs. present). Adjustable parameters: number and length of play rounds (for each level of difficulty); the number of places on which the flies can sit (predefined locations referred to by numbers); the number of flies in each round to be hit; flight speed of the flies, number of flies present simultaneously, min and max time that flies fly or sit, etc. Recorded variables: reaction time, the number of successful hits, number of missed flies, speed of fly-flap movement, etc.

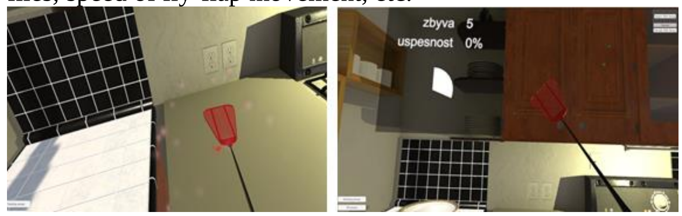

Fig. 8 Illustrations of the Flies game (Fly-flap and feedback of successful hit, Success statistics, timer).

K. Supermarket

The Supermarket game is focused on verbal declarative memory and executive functions (such as planning and categorisation). The task of the player is to remember the shopping list (with increasing number of items). Each game level consists of two phases - the acquisition phase and shopping phase. In the first phase, the buyer is presented with a shopping list, which he/she has to remember. After a delay (adjustable length) the items should be collected in a virtual supermarket environment. The validity of this task has already been demonstrated in patients with schizophrenia and in healthy volunteers using in the computer game presented on a monitor screen [13]. The training version allows to randomly generate shopping lists and increase difficulty level only after the existing level is successfully completed. Adjustable parameters: initial number of items, increment - number of items increasing between levels, number of categories selected from during the shopping list is generated, time to finish the task, etc. Recorded variables: accuracy rate (number of collected items on the list), the time needed to complete the task, the length of trajectory travelled is compared to the initial trajectory length in the acquisition phase, number of moves (incl. corrections). The task also analyses two types of errors, the missing items and the extra items that are not from the list (confabulations).

Fig. 9 Illustration of the game Supermarket (product preview with local czech packaging).

L. Shooting range

Shooting Range - Task is a variation of the Go / Nogo task [14] that focuses on attention, psychomotor rate and ability to inhibit the behavioural response. The game requires to distinguish target GO objects (e.g. dangerous animals such as wolf, shark. etc.) when they appear at shooting location (might appear at various places and levels of the spatial layout). In the same time the person ignores objects that are NOGO objects (other animals e.g. fish, rabbit). The game does not require precise spatial aiming (the ball always strikes the target object), however fast recognition of the target stimuli and the fast reaction speed (throwing the ball) are crucial for the success in the task. Adjustable parameters: number of sets of target/non-target objects, number of target objects to be presented or time limit, number of throwing balls, speed of objects pop up and disappearing. The objects themselves vary in game levels (increasing difficulty). In the higher levels of the game, so-called "STOP" signals are presented that serve as confusing stimuli (during their presentation the ball can't hit the target - pointed different direction), such complex combination of stimuli requires more complex decision-making before the action is initiated. Recorded variables: time to complete the task or number of targets completed in time limit, number of correct hits (targets), number of incorrect hits (non-targets), number of missed hits (stop signal in targets), number of balls used, etc.

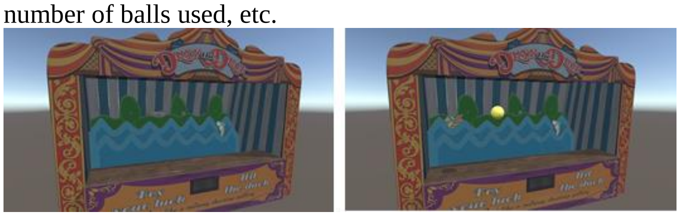

Fig. 10 Illustration of the Shooting game (before and after the throwing of the ball).

M. Carousel

The Carousel game was inspired by assessment methods applying a rotating arena principle both in avoidance and preference protocols (see [15], [16]). The task requires finding hidden places and orientation in separate spatial frames created by the constant slow rotation of the carousel/arena (carousel plate and its surroundings). The game aims at spatial working memory, mental flexibility (adaptability to changing conditions and rules) and spatial orientation in a dynamic environment. The game requires switching of spatial maps and navigation in one of the two reference frames according to the rules and select relevant landmarks and orientation cues either on the carousel itself or in its surroundings. The training task begins with a simple navigation on a stable carousel to familiarise with the task first. The carousel then starts rotating and the player searches for a hidden target position (not visible until it is found) first placed in the carousel frame and then bound to the outer landmarks. The goal of the player is always to find the destination without using the navigation aid. In the final stages, the player navigates as instructed between several positions that occur alternately in both reference frames. Adjustable parameters: number of sets of target locations to be found, number of targets in each set, time limit to find the target. Recorded variables: time to locate the target, number of targets found, the length of trajectory travelled compared to the direct trajectory, etc.

Fig. 11 Illustration of the Carousel game (overview and detail of the circuit).

III. Data recording and analysis

The training system records performance of seniors in individual games for each trained session and provides a graphical representation of progress achieved in individual domains. Besides standard behavioural data output (such as the number of errors or incorrect answers or time to complete the task) the Virtual city system enables us to analyse also the spatial movement of each participant in virtual environment as it tracks the participant's coordinates in the real time. The virtual movement is associated with the player's spatial ability and strategy used to solve the task. We are thus able to visualize the trajectory, which could facilitate the implementation of cognitive strategies [17].

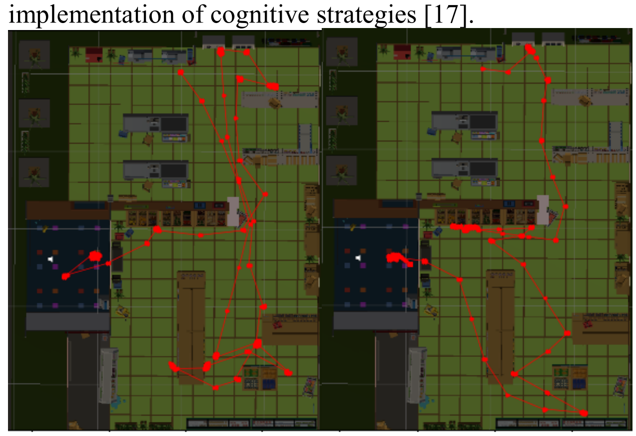

Fig. 12 A visualization of two different types of spatial strategies in the Supermarket when solving the same task (recollecting 5 items from the shopping list).

IV. Options of application of the Virtual City project in elderly

The designed SW will be first implemented in clinical and day-care programs in Czech Republic (mainly NUDZ clinical facility) and in Slovakia (Center MEMORY Bratislava). The program could be however applied also in other senior centres aimed at daily programs for healthy aging and mental health prevention in general.

The Virtual City training program should be applied in elderly in individual setting (using one virtual glasses per participant). This way the senior receives the maximal training effect and therapist might provide individually related advise on strategies to improve performance. However, we suggest that the system could be applied also in group settings (presenting the game in the VR glasses and mirror it using video projector to the others in the group) in case the individual training is not possible. This approach provides more accessible use of the Virtual City SW in day-care programs in various facilities associated with seniors. Moreover, such form enables us to operate with the group dynamics not available in individual approach.

Recently, we have started the first pilot study on effectiveness and usability of developed prototypes.

A. Cognitive training in group setting - pilot study

The objective of the study is to examine the effectiveness and usability of the application of the Virtual city game prototypes in cognitive training applied in the group settings.

a) Method

As the Virtual City requires the use of the VR hardware not available in many day care centers especially for group of participants, the first pilot study is administered in a group setting using HTC Vive headset and video projector, where the VR game view is mirrored.

b) Participants

The first group of ten cognitively healthy seniors (9 female, 1 male) were recruited into the training program through a website advertisement. Their age ranges from 57 to 79 years (average=68.1∓6.2).

c) Prototypes

Four prototypes are used during the pilot study assessing training program in the group setting - Practice task, Supermarket, Objects and Flies.

d) Outcome measures

Prior to the beginning of the training the participants were evaluated by standard neuropsychological methods. Specifically we used the Rey Auditory Verbal Learning Task [18] and subtest Symbols from the repeatable Battery for the Assessment of Neuropsychological Status RBANS [19].These methods were chosen for their short administration time and availability of parallel versions in Czech language. Moreover, the subjects filled out an online questionnaire focusing on their subjective cognitive complaints [20] (10 items) and quality of life (8 items inspired by Fahrenberg Life Satisfaction Questionnaire [21]).

e) Procedure

The training is scheduled for 10 weekly sessions (duration of 60 minutes). During the first session a baseline evaluation and familiarization with the HTC device using Practice task took place. During individual sessions the participants are switching the VR glasses among themselves, while the rest of the group can watch the virtual scene on the large projector screen. Importantly, even that each participant uses the glasses during each session, participants are cooperating on the tasks solving all the time, therefore the achieved level of difficulty could increase faster comparing to results of individual training sessions and such data can’t be analysed using standard procedure. The cognitive training is therefore focused also on the cooperation of participants in the group and on adoption of meta-cognitive strategies. After 10 weeks of the training the participants will be evaluated again with the outcome measures in order to determine if this training approach could be effective.

V. Conclusion

During the conference venue the Virtual City system will be presented in means of training concepts, games’ design with specific cultural context and preliminary data obtained in individual serious games. The system aims at complex training of cognitive functions in ecologically valid situations and tasks, including spatial navigation and planning of activities. We suggest that the immersive VR headset used for the training procedure could increase positive effects of the training due to immersive presence experience in individual tasks. In addition, intuitive movement control increases the user-friendly experience in elderly with low or missing computer skills (situation still frequent in the central European region). Moreover, active movements required during the task performance might increase the activity of trained elderly subjects. The results obtained in the ongoing pilot study with training system used in group setting will be compared with the results of individually applied (personal) cognitive training sessions.

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