Development of virtual environments for patient-centered rehabilitation

Analysis of workflow and data validity by example of a mental maps task

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Abstract—**Context-sensitive rehabilitation integrates the individual background, needs, and strengths into the therapy of brain-injured patients [1]. Virtual environments can potentially enrich such individual rehabilitation approaches by providing realistic, lifelike situations for patients to train in. Virtual scenarios mostly are of high ecological validity, but usually require a long and costly development process. In order to use virtual environments for context-sensitive rehabilitation, an efficient workflow needs to be created which allows for rapid, cost-efficient development of such computer-based tools. The present study describes the requirements that are necessary for a clinic-based workflow and addresses each requirement in detail. Several complex virtual rooms within a rehabilitation hospital have been created and tested. Workflow efficiency, realism of virtual environments and validity of task-based use of these applications have been evaluated with healthy and brain-injured individuals. The virtual scenarios met requirements for timely production, and realism. The outcome of a mental map task, which was integrated intone environment, supports the validity of virtual cognitive assessments. Overall, results of this study suggest that individual virtual environments are a feasible addition to traditional context-sensitive rehabilitation.**

Keywords-virtual environments;context-sensitive rehabilitation; cognitive training; task development.

I. INTRODUCTION

Virtual environments (VEs) have seen increasing use in rehabilitation and therapy over the last two decades [2]. By combining VEs with immersive displays and natural interfaces, virtual reality applications have become possible for a wide range of therapeutic scenarios. Treatment of phobias [3], post-traumatic stress disorder [4], pain distraction [5], motor rehabilitation [6], and assessment of attention [7], memory [8] and problem-solving [9] are among the most common applications of virtual reality technology. VEs enable researchers and clinicians to simulate complex environments and precisely control exposure to critical stimuli. Inaccessible or dangerous environments can easily be made available for training and therapy. The resulting applications are of high ecological validity and allow for precise measurements of the user's behavior [10].

Despite their advantages, VEs cannot be considered mainstream applications for therapy and rehabilitation yet. Development of VEs is considered a costly and time-consuming process and cost-benefit analyses for virtual reality therapy tools are still rare. However, acceptance of VEs for rehabilitation has been increasing steadily [10] and computer and internet use are constantly rising [11]. With more than 50% of U.S. adults 65 years and older using computers, 67% of U.S. households playing video or computer games in 2010 [12], computers, avatars and digital worlds are part of many people's lives in the 21st century. Consequently, researchers and clinicians have started to adopt widespread consumer technology like the Nintendo Wii [13] or Microsoft Kinect[1] for therapeutic use. With further advances in such affordable technologies and the fast-growing video games industry (USD 10.5 billion in 2009 sales, [12]), "exergames" and interactive media will continue to supplement traditional therapies in a clinical context. These games provide a strong contrast to traditional cognitive trainings that use less-engaging mini games and cognitive tasks to train logic, memory and attention (e.g. CogPack [14]). Even though these traditional trainings might not be as immersive and interactive, they are grounded in cognitive science and trains individual skills that are relevant for the patient.

Relevance of training tasks is especially important for therapeutic use, because frequent task repetition can adversely impact a patient's motivation. High ecological validity with realistic and relevant content is one of the key advantages of VEs. Only few applications currently make use of this advantage and provide flexible solutions based on the patients' needs (e.g. NeuroVR [15]). Most VEs are rendered fairly realistically to create scenarios that are similar to the real world. However, these scenarios do not necessarily represent a world that is meaningful to the patient. Locations, objects, sounds and interactions often do not reflect the complex

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[1]For more information see www.games4rehab.com

situations that the patient is faced with once rehabilitation or therapy sessions are finished. Context-sensitive rehabilitation accounts for these individual circumstances of the patient and incorporates them into clinical practice [1]. Personal strengths and weaknesses are identified and therapeutic goals towards empowering the individual in his or her relevant environment are formulated. To realize this philosophy means moving away from generic training content to customized tasks and training programs. This patient-centered approach for VE-based therapy can be accomplished with modern game engines and hardware, but its efficacy and viability have yet to be evaluated. The present study describes the requirements for using VEs in context-sensitive rehabilitation. The realization of each requirement is addressed and the VE's recognizability and validity of gathered data are tested and discussed.

II. REQUIREMENTS FOR INDIVIDUAL VE-BASED REHABILIATION

Ideally, a computer-based training combines advantages of modern computer technology with evidence-based practice. It further addresses the individual background, deficits, strengths and weaknesses of each impaired individual. Lastly, based on the patient's performance, the program gives a solid foundation for clinical decision-making. This foundation is based on valid and reliable data that is collected within the computer-generated environment. Before such an application is used in clinical day-to-day practice, all of the following requirements need to be addressed.

A. VE Development

Effective clinical use of VEs requires a fast and cost-effective development workflow. Average length of stay for stroke patients in inpatient rehabilitation facilities ranges between 15 days (US, [16]) and three to four weeks (Germany, [17]). Thus, to allow for two weeks of repeated, supervised training, the finished application should be available within the first 24 to 48 hours after admission to the rehabilitation unit. Within this timeframe, the patient needs to be briefed, the real environment has to be measured and photographed, the VE has to be modeled to scale and cognitive tasks and interactivity need to be integrated based on the patient's needs. Further, the developed VE has to be flexible enough to adapt to the patient's progress throughout the training program. Gradual changes to the VE need to be possible at any time during the rehabilitation process. These changes are vital to allow the patient to train in a variety of environments and promote generalization of practiced abilities.

B. Recognition of VEs

The VE needs to be modeled realistically enough for patients to recognize the environment. Enough details and realistic textures need to be provided in order to allow for orientation within the environment. Due to the particular importance of this requirement, we present a short study on this topic later in the paper.

C. Usability

The clinical use of VEs requires the adherence to strict safety standards. Two major causes for simulator sickness when displaying VEs on immersive displays are performance lag [18] and restricted, unintuitive movement control within the VE [19]. Therefore, the developed application may not produce any noticeable delay during virtual movement. The threshold for noticeable delays largely depends on the pace of movement within the VE and often 25 frames per second are sufficient to guarantee a good user experience. Stable performance at 25+ frames per second on a wide range of PCs and online via web browser are desired to make the applications easily available to therapists and patients.

D. Accessibility

Accessibility for patients with motor and cognitive deficits needs to be taken into account. Ideally, input device and user interface are adapted for patients with hemiplegia and even allow patients with little computer experience to use the program without many instructions. Alternate interfaces are available for patients with severe motor impairments and tetraplegia.

E. Data recording

Accurate recording of user behavior is critical to evaluate task efficacy and training outcome. As one of the key advantages of VEs, the application records sufficient data to allow for evaluating training progress. The collected data has to be used to give direct feedback to the patient and allow the clinician to manipulate task difficulty according to the patient's performance. Further, if collected data is used for clinical decisions, validity and reliability of collected data have to be established in controlled clinical trials. Data validity is assessed in a short evaluation using a mental map task.

F. Individual training content

Cognitive tasks are integrated into the VE based on the individual needs of the patient. Specific functional goals are determined by therapists after admission to the rehabilitation clinic. These goals build the foundation for any virtual training tasks so that choice of target objects, locations and tasks depend on the individual situation of the patient. Relevant training locations are at the core of this rehabilitation approach, so that the patient's home, workplace or any other relevant environment are replicated for the purpose of cognitive training. The current paper establishes the foundations of using VEs for the purpose individual cognitive training. However, the clinical evaluation of individual training content is beyond the scope of this paper and will be discussed elsewhere.

III. SYSTEM EVALUATION FOR CONTEXT-SENSITIVE REHABILITATION

The biggest challenge for a clinic-based system of virtual training environments is their timely development. Choice of tools and workflow are paramount when attempting to create interactive real-time 3D environments in a matter of hours.

Tools and development process are discussed and tested for their efficiency. In addition, all previously listed requirements are evaluated in order to demonstrate the viability of patient-centered VEs for clinical practice.

A. VE Development

The first step when creating a realistic, to scale VE is the measurement of the real environment. Measurements need to be as precise as possible to increase data accuracy of the finished application. Floorplans (Autodesk Design Review 2011), laser distancemeters or 3D scanners can potentially simplify this process. For the purpose of this study a tape measure, hand drawn sketches and photographs were used. Photos were taken with a webcam connected to a netbook (Fig. 1). Measurements were manually added to each photo using MS Paint and a Wacom Intuos Tablet as input device. High-resolution pictures of surfaces, signs and materials were taken with a 12-megapixel digital camera. These photos were corrected for distortion and turned into tileable textures using Genetica 3.51 Basic. Measurements and textures were used to model each environment with Google SketchUp Pro 8. SketchUp was chosen for its capability to quickly model architecture. It has to be noted that SketchUp does not give precise control over the number of created polygons/vertices during modeling. Consequently, each model is made up of more polygons/vertices compared to other 3D modeling software (e.g. Blender, 3DS Max). The resulting models show lower performance when used for real-time 3D applications. However, when appropriate hardware is used to run the finished VEs, the modeling speed of Google SketchUp by far outweighs the disadvantage of lower real-time performance. After models were completed within SketchUp, they were exported to the Unity game engine using the fbx-file format. Unity was used to add interactivity, lighting, collision detection, data recording and cognitive tasks to the VE. Many game engines, simulation engines and editors are available for this purpose, but only few are suitable for cost-effective production, rapid prototyping, and small development teams. After evaluating Unreal Development Kit, Quest3D, Vizard, NeuroVR, Unity3D, and TorqueEngine, Unity emerged as the engine with the fastest asset pipeline, meaning that 3D models, textures, sounds and other assets can be quickly imported and updated. Also, the Unity game engine is known for its easy deployment to web browser, PC, Mac and smartphones. Most of the required functionality is available with the free version of Unity. All cognitive tasks have been developed with Unity and can simply be added to any 3D model within the game engine. Setting up a task is as simple as choosing the appropriate task (e.g. memory, navigation) and placing it into the VE via drag and drop within the Unity editor. Targets, instructions and task difficulty can be configured in a matter of minutes. The finished task and VE are then published as a standalone executable which can be run on any of the supported platforms. Modifications to the VE are possible at any time. Changes can be applied to the 3D model in Google SketchUp or within Unity. Lighting can be changed to simulate day- and nighttime, textures, objects and even building structures can be modified easily to provide gradual changes in training environments. After modifying the VE, the application is simply published again through the Unity editor.

Figure 1.   Recording station for photos and measurements

1) Workflow Test

To test the described workflow, four separate locations within the Asklepios Rehabilitation Klinik, Schaufling, Germany, were randomly chosen and modeled. Selection was based on a random draw from all rooms and corridors within the clinic. Each VE and the corresponding real-world photograph can be found in Fig. 2.
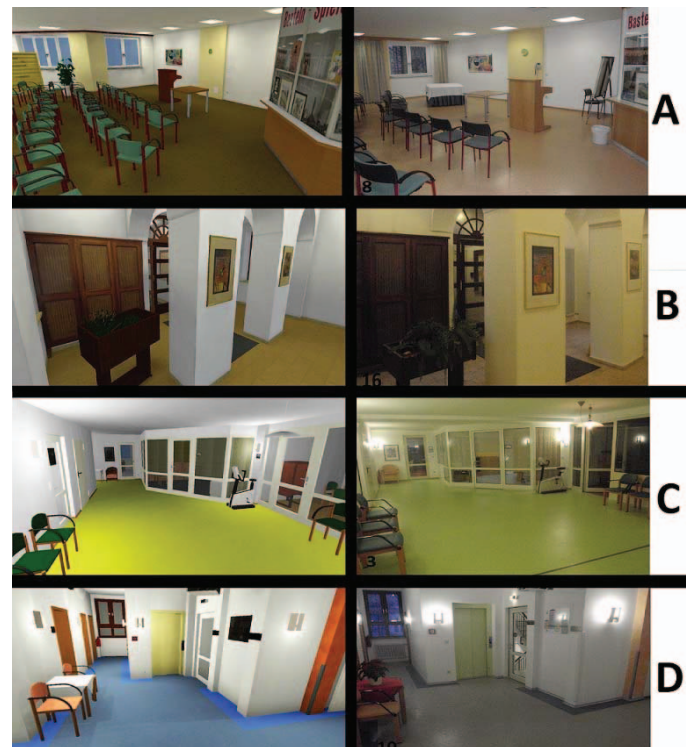

Figure 2.   Screenshots (left) and photos (right) of all four relevant environments

Time to complete each VE was measured from the first photograph to the execution of the finished Unity application (Table 1). All environments were ready for immediate use by a patient. When using this workflow for a patient's home or workplace, the number of rooms, necessary detail and additional travel time to the real locations have to be taken into account. Patient and caregivers have to be briefed and the clinical team needs to agree on therapeutic goals in order to implement those goals into the VE. Nonetheless, modeling a small apartment or one floor of a residential house is still possible within the given timeframe of 48 hours after the patient has been admitted to the rehabilitation clinic. With constantly evolving software and a growing library of reusable furniture models, the VEs' realism and pace at which they are created are steadily increasing.

B. VE Recognition

The realism of all produced VEs has been evaluated by testing how participants recognized each location and how pictures of real and virtual locations were associated with each other. 43 therapists, employees and interns (12 male - 31 female; average age 31.95 years) were shown the four screenshots as depicted in Fig. 2. On average, participants have been working at the clinic for 74.2 months (STD = 91.6, range: 2 weeks - 23 years). Screenshots were presented on the 7-inch-screen of a Samsung Galaxy Tab tablet PC without time restrictions. Locations A and B were correctly identified by almost all participants (Table 1, identification rate). Locations C and D were more generic and more often mistaken for similar-looking wards and corridors. Because some of the locations were not familiar to interns and new employees, an additional recognition task was used. After showing the four screenshots, 20 real photographs were presented to each employee. Participants were instructed to recognize each scene which was shown on the previous four screenshots. 16 distractor items and the four correct photos (as in Fig. 2) were shown in the same order for each participant. Recognition rate across all locations was 94.1%, so that almost all participants recognized all four locations (Table 1, recognition rate). During rehabilitation, patients will be faced with very familiar interactive environments and sounds instead of photographs which should further increase the familiarity of the VEs.

TABLE I. RESULTS OF RECOGNITION SURVEY

Location (as seen in Fig. 2)	Results			
	Time for Measuring (minutes)	Time for Modeling (minutes)	Identification Rate (percent)	Recognition Rate (percent)
Meeting Room (2-A)	40	162	97.6	97.6
Entrance (2-B)	52	266	90.6	100
Neurology Ward (2-C)	65	270	55.8	93.0
Corridor (2-D)	~50	~250	76.7	88.3

C. Usability

Each developed VE was running steadily at 25 to 30 frames per second. None of the participants showed any symptoms of simulator sickness. However, a high-end workstation with hexa-core CPU and 2GB NVidia GTX 460 graphics card were necessary to achieve stable performance. Further optimization of the VEs and cognitive tasks are necessary to make the applications available on a wide range of PCs.

D. Accessibility

Usability of each VE largely depends on the specific task that is used for training. Several experiments have been conducted to evaluate the validity of the virtual cognitive tasks. No actual usability trials have been carried out yet, but when confronted with a VE-based spatial memory task, none of the 39 participants of a validity evaluation reported any usability issues [20]. 38 out of 39 participants were able to use a computer mouse to move around virtual target objects without any prior instructions. One participant with no prior computer experience gave verbal instructions so that the experimenter was able to move the target objects instead.

In a second validation study participants had to navigate through a complex VE in first-person-perspective [21]. Three out of 36 healthy participants had to withdraw from the study due to symptoms of simulator sickness. However, the VE was rendered on a setup of three theatre-like screens with 180 degrees field-of-view which is unlikely to be used in a clinical context. Instead of using computer mouse and keyboard, user input was only mapped to a mouse to facilitate navigation through the VE. Unfortunately, several participants had difficulties using the mouse for perspective rotation so that additional options for unrestricted navigation through a VE need to be explored in future studies.

In the present study viewpoint rotation was required to point towards unseen targets. Arrow keys on a standard keyboard were used for rotation and no virtual ambulation of any kind was possible. None of the 31 participants reported any problems with using the keyboard.

In addition to standard user input, a prototypical interface for patients with severe motor impairments has been set up to work with several of the cognitive tasks. By using an Emotiv EPOC brain computer interface, the user is able to emulate key strokes which can be used as input for each of the tasks. The EPOC captures distinct cortical activity, but is more reliable when used with facial gestures such as blinks, smiles or moving eyebrows. This interface implementation is still an early prototype which needs to be evaluated with participants in upcoming trials.

E. Data Recording

Each 3D model is created to scale so that measurements in the VE are comparable to real-world dimensions. The three-dimensional nature of the application allows for precise recording of positions and rotations of all important objects (i.e. user, target objects, target locations). Each location is saved as a vector in 3D space so that angles and distances can be calculated either while the program is running or after

training sessions have been finished. All data is saved in text files to the local hard drive of the training PC. When publishing VEs for use in a web browser, data can be saved to online SQL databases. If the application is running at high frame rates and data is saved once every frame, the amount of saved data can accumulate very quickly. In addition, eye-tracking, head-tracking, psychophysiological recordings and video recordings of the patient using the application can complement the data which is gathered within the VE. However, with such recording capabilities, complexity of data analyses and interpretation of this large amount of data easily surpass standards of non-VE-based tests and trainings.

F. Data validity and interpretation

Before any conclusions can be drawn from data collected by a VE-based task, validity and reliability need to be tested in controlled clinical trials. Further, it needs to be established whether human perception and cognition are equivalent in real and virtual space. Using the previously described VEs, the validity of cognitive tasks for human navigation, orientation [21] and spatial memory [20] have been evaluated. In both experiments it became apparent that because of the data's complexity, comparisons to traditional pen and paper tests did not yield straightforward results. Many tests of spatial abilities (e.g. Mental Rotations Test, [22]) and memory (e.g. Rey-Osterrieth Complex Figure Test, [23]) are easily interpreted by scoring individual test items as either correct or incorrect. In contrast, VEs allow for more differentiated analyses of user performance by recording complex paths, distances and reaction times. Whenever a VE-based task is developed, the task results either need to be scaled down to correct /wrong answers or results need to be conceptualized in a way that is graspable without sacrificing much of the collected information. For example, navigation performance could easily be classified by either taking a correct or a wrong route towards a target. Without much simplification, the same data could also be scored by using pathfinding algorithms which are very popular for programming artificial intelligence. The question remains whether the underlying logic of such algorithms is useful in a clinical context to explain the performance on a cognitive test. Consequently, the utility of VE-driven data collection with its inherent complexity needs to be studied thoroughly in future investigations.

G. Validity evaluation – Mental map task

As previously described, four VEs were created to demonstrate the effectiveness of the proposed workflow. Before these VEs can be used in a clinical context, cognitive tasks have to be embedded in each environment. To explore such clinical use and investigate the validity of collected data, one of the four environments was chosen for a virtual orientation task. Neurological patients were recruited to interact with the VE and point towards unseen targets in a real and virtual scenario within the clinic building. This test intended to assess the patients' mental representations of their surroundings. If mental maps of real and virtual environments are equivalent, the virtual task's data can easily be used with a patient's individual VE to assess orientation performance in locations outside of the rehabilitation clinic (i.e. home or workplace).

1) Participants

31 patients (16 male, 15 female; average age: 43.9 years; age range: 18-65 years) at the rehabilitation clinic Asklepios Klinik Schaufling, Germany, took part in this clinical trial. Patients with severe traumatic brain injury (3), subarachnoid hemorrhage (2), brain tumor (4), hippocampal sclerosis (1), stroke (mostly right-hemispheric, 8), normal pressure hydrocephalus (1), syringomyelia (1), multiple sclerosis (3), anaphylactic shock (1), idiopathic epilepsy (2), cerebral encephalitis (1), cerebral hemorrhage (1) and four patients from non-neurologic departments were recruited for this study. All patients were able to give informed, written consent.

2) Procedure

For this within-subjects design, each participant went through the same order of assessments for a total of approximately one hour. Patients were briefed about the experiment, signed a consent form and completed pen&paper and VE-based versions of a pointing task.

3) Task and materials

The pointing task included eight highly-familiar target locations within the clinic which were not visible from the testing room. Targets were skipped if the location was unknown to the patient. For each target participants were given the target name and an A4-sheet of paper with a circle (diameter = 14cm) drawn in the center of the paper. The participants were instructed to imagine the middle of the circle as their current location. The circle was used to mark the direction towards the target. In addition, participants were asked about the linear distance towards the target and the difference in height between the floor at their current location and the floor at the target.

The computer-based pointing task was displayed on a 24-inch monitor, 60cm in front of the participant. The experiment was carried out with the same PC which was used to create the VEs (hexa-core CPU, 8GB memory, 2GB NVidia GTX 460 graphics card). The task environment was situated at a different location than the pen&paper test, but still familiar to all patients (Fig 2-D). Participants were not allowed to move away from their virtual location but were able to look around using the arrow keys of a keyboard. A red dot in the middle of the screen was explained to be the marker for pointing towards the target. The virtual viewpoint had to be moved by the participant so that the red dot pointed exactly towards the target. The participants were told to imagine the red dot to be similar to the index finger for pointing. After choosing a direction, the participants were asked again for distance and height difference for each target. Order of targets for both pointing tasks was identical for each participant. No feedback about pointing performance was given until the end of the test session.

4) Results

Angular deviation from target directions, distance and height judgments were averaged across all eight targets and subject to detailed analysis. Absolute values were used for angular deviation and height difference. A percentage measure was used for distance estimations (100% equals true distance). Initial Levene's tests revealed that the assumption of homogeneity of variances was violated for the angular

deviation measure. Additionally, significant Shapiro-Wilk tests indicated that our data for all three variables were drawn from non-normally distributed populations. Consequently, non-parametric analyses were used throughout this analysis. Statistical equivalence can be established using the procedures of Tryon [24] and Tryon and Lewis [25]. However, these methods rely on the calculation of t-values for confidence intervals. There is no established test procedure for non-parametric analysis of equivalence yet. Thus, Wilcoxon Signed-Rank tests were performed and effect sizes according to Morris and DeShon [26] (equation 8) were calculated (Table 2). Non-significant differences and very small effect sizes for all three measures were hypothesized in order to support the equivalence of real and virtual mental maps.

TABLE II.   NONPARAMETRIC ANALYSES AND EFFECT SIZES FOR POINTING TASK IN VE AND REAL ENVIRONMENT

Variables (unit)	Results					
	Mean $\pm$ STD, Median VE	*Mean $\pm$ STD, Median Pen & Paper*	*Wilcoxon's z*	*p*	*N*	*Effect Size*
Angular Deviation (degrees)	48.20 $\pm$ 24.27, 44.56	46.23 $\pm$ 36.56, 30.66	-0.76	0.442	27	0.07
Height Error (meters)	3.09 $\pm$ 1.92, 2.40	4.37 $\pm$ 5.16, 3.13	-1.48	0.137	26	0.43
Distance Estimation (%)	153.34 $\pm$ 215.22, 69.13	176.71 $\pm$ 198.70, 99.56	-1.20	0.228	26	0.21

5) Discussion

The employed analyses do not allow for firm conclusions about the equivalence of virtual and real environments, but non-significant differences and very small effect sizes are expected if both scenarios are very similar. When patients pointed towards unseen targets, their judgment errors did not show significant differences in VEs and real environments. The resulting effect size is very small. The small and medium effect sizes for distance and height estimations respectively, suggest that length is generally not judged equally in real and virtual scenarios. Moreover, several participants tremendously overestimated distances in both environments (i.e. >500%). In order to account for these outliers, medians were calculated for both groups (Table 2). Performance within the VE indicates that most participants underestimated the true distances towards all targets which is in line with previous studies [27]. Distance judgments in the real environment were mostly accurate.

Generally, mental maps of our sample of neurological patients appeared to be consistent across both, real environment and VE. However, dimensions of these maps differed considerably so that mental maps based on VEs were reported to be smaller compared to their real-world counterparts. Results of this study add further support to the validity of VE-based data for cognitive assessment. As in previous studies [20,21] the gathered data is of such complexity that further evaluations are necessary to fully benefit from the complex virtual scenarios which can be created with modern computer technology. Realizing the proposed workflow for VE-development builds the foundation for extending this approach to several applied fields. Yet, it is the quality and quantity of produced data which need to be further investigated before patient-centered VEs become accepted tools in rehabilitation.

IV.   CONCLUSION

Cognitive rehabilitation is dealing with the individual background and deficits of each patient. A context-sensitive approach to rehabilitation has already been proposed [1] and described in detail [28]. Virtual reality technology has also gained momentum over the last decades [2], especially in the area of rehabilitation. However, given the labor-intensity of creating VEs, the use of these tools is still not common in a context-sensitive rehabilitation approach. Creating individual VEs for each patient to provide a relevant training scenario requires the cost-effective, timely production of these tools. This current study describes the workflow to achieve realistic, to scale models of real environments. The development process has been demonstrated in a random sample of four complex virtual rooms, each taking less than 6 hours to complete. The finished environments were realistic enough for users to recognize and to associate with their real world counterparts. Virtual tasks in several cognitive domains have been implemented within the VEs for use in therapy or training. These tasks are of high ecological validity and enable patients to train in meaningful environments that are based on the personal circumstances of the brain-injured individual. Enhanced fidelity and personal relevance of VEs are the basis for clinicians to make more accurate decisions about individual performance outside of the rehabilitation setting. In a recent study, five out of 39 patients have gained awareness of their cognitive deficits through the transparent, realistic nature of a VE-task [20]. Such awareness is of central importance for the rehabilitation outcome. However, in these situations it is necessary that VE-based training and assessments are accompanied by experienced clinicians to avoid frustration and distress of the patient.

Results of preliminary validation studies [20,21] indicate that the virtual tasks produce complex data which provide differentiated information about the users' behavior. Comparisons to traditional neuropsychological tests are not straightforward as the complexity of gathered data easily surpasses the common dichotomy of correctly or falsely answered test items. Data of the present mental map task is of similar complexity, so that more sophisticated analyses tools are currently in development for datasets of all conducted studies.

In summary, it has been demonstrated that user-centered VEs are a viable option for cognitive rehabilitation, especially for a context-sensitive therapy approach. With a fast, cost-effective development process and sophisticated data collection capabilities, VEs provide a valid alternative to traditional tests and trainings. Future investigations need to explore the conceptualization of rich VE-based datasets and further evaluate the validity of all gathered data. The extended use of

individual VEs during cognitive rehabilitation will be probed in upcoming single-case studies.

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