RehabCity: Design and Validation of a Cognitive Assessment and Rehabilitation Tool through Gamified Simulations of Activities of Daily Living

Athanasios Vourvopoulos
Madeira-ITI,
Universidade da Madeira
Funchal, Portugal
athanasios.vourvopoulos@m-iti.org

Ana Lúcia Faria
Madeira-ITI,
Universidade de Coimbra
Coimbra, Portugal
ana.faria@m-iti.org

Kushal Ponnam
Madeira-ITI
Funchal, Portugal
kushal.ponam@gmail.com

Sergi Bermudez i Badia
Madeira-ITI,
Universidade da Madeira
Funchal, Portugal
sergi.bermudez@m-iti.org

ABSTRACT
Worldwide, more than one in three adults suffers from a cardiovascular disease. According to the World Health Organization, 15 million people experience a stroke each year and, of these, 5 million stay permanently disabled. The current limitations of traditional rehabilitation methods push towards the design of personalized tools that can be used intensively by patients and therapists in clinical or at-home environments. In this paper we present the design, implementation and validation of RehabCity, an online game designed for the rehabilitation of cognitive deficits through a gamified approach on activities of daily living (ADLs). Among other findings, our results show a strong correlation between the RehabCity scoring system and the Mini Mental State Examination test for clinical assessment of cognitive function in several domains. These findings suggest that RehabCity is a valid tool for the quantitative assessment of patients with cognitive deficits derived from a brain lesion.

Author Keywords
Serious Games; Virtual Reality; Game Design; Stroke rehabilitation

ACM Classification Keywords
J.3 [Computer Applications]: Life and Medical Sciences - health; K.4.2 [Computers and Society]: Social Issues – assistive technologies for persons with disabilities

INTRODUCTION
Cognitive deficits are a major factor for loss of autonomy and independence in the performance of Activities of Daily Living (ADLs) [1]. These deficits comprise limitations in attention (focusing, shifting, dividing or sustaining attention), executive functions (planning, organizing thoughts, inhibition, control), visuospatial ability (visual search, drawing, construction), memory (recall and recognition) and/or language (expression and comprehension). The high incidence of these deficits results from the current increase in the incidence of neurological diseases [2]. Every year, 15 million people suffer a stroke, 7.7 million are diagnosed with dementia and 10 million are affected with traumatic brain injury [3]. The loss of autonomy of the victims together with the burden of mortality and morbidity that these conditions impose on society represent a pressing public health problem. The direct costs are estimated to be more than US$800 billion per year [3].

Traditional cognitive rehabilitation methods typically entail a cyclical process involving: 1) assessment of the patient deficits through objective (questionnaires and scales) or/and subjective (clinical observation) tools; 2) goal setting, to define realistic and attainable goals for improvement in the patient's performance of ADL; 3) goal oriented training through the repetitive training of ADLs [4] and resolution of paper and pencil cognitive tasks; and 4) reassessment, to evaluate recovery [5].

The limitations of traditional rehabilitation methods evidenced the need of personalized tools that can be used more intensively by patients and therapists, in clinical or at home environments. One recent approach is the use of gaming to train motor, cognitive, and social abilities [6]. Gaming in rehabilitation has great potential for today's and future health care, and there is increasing evidence that gaming positively contributes to the recovery process of stroke[7]. Rehabilitation through computer based gaming capitalizes on motivation to engage in rehabilitation and the personalization of training [8]. Moreover, gaming enables online monitoring of performance and the possibility to provide immediate feedback in controlled settings, making it suitable for at-clinic or at-home rehabilitation [6]. Besides monitoring the performance and progress of the player, training through gaming allows the use of rehabilitation principles such as goal setting, feedback, reinforcement and

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self-efficacy. Finally, improvements in gaming have been found to transfer to real task performance [9].

Some well-established computer-based approaches replicate standard paper and pencil tasks in a computer environment, lacking the use of gaming elements. For instance, the REHACOM system is widely used in clinical environments and it targets training of several cognitive domains [10]. Some newer approaches such as the IREX GestureTek [11], the Neurorehabilitation Training Toolkit [12], the Dance2Rehab3D [13] and the TheraGames [14] are games that support sophisticated tracking, orienting and signaling systems for impaired people. Nevertheless, their focus is mostly on motor training game tasks that are not directly related to ADL.

The main goal of rehabilitation is to re-enable people with impairments to perform effectively their ADLs [15], hence numerous systems were developed with the purpose of simulating the ADLs in a Virtual Reality (VR) environment. For example, the Virtual Action Planning - Supermarket (VAP-S) [16] trains individuals to plan a purchasing task in a virtual supermarket; the Virtual Street Crossing System [17] recreates a real scenario of a city, for players to navigate in the presence of distractor stimuli (cars, traffic lights, sounds); and a system by Gamito et al. [18] simulates various ADLs like morning hygiene, meal preparation, dressing, etc. Although these VR simulations are more ecologically valid than the computerization of paper and pencil tasks, these systems focus only on training specific ADLs in an isolated context. The AGATHE project followed a more holistic approach, integrating ADLs in a valid context [19]. This system consists of a virtual neighbourhood with several landmarks (town, studio, post office, supermarket), each of which is used to train specific ADLs. Although it is configurable, upgradable and able to provide personalized therapeutic training, the system lacks a gaming approach and a quantitative evaluation with end users.

By merging a gaming and an integrative ADLs approach we propose RehabCity, an online deployed game for the rehabilitation of cognitive deficits. A simulated city populated with streets, sidewalks, commercial buildings, parks and cars, has been created to provide an ecologically valid environment, where some common ADLs are executed. In the RehabCity game, the player has to perform several sequential tasks that require navigation in the city. RehabCity uses short-term goals and frequent feedback on progress to increase the sense of self-efficacy and, as a result, the motivation and engagement to work towards the next goal. Furthermore, RehabCity goals can be customized and personalized to each player, as well as the level of difficulty assistance provided by the game. In this paper we present the design, implementation and validation of the Rehabcity.

METHODS

Design

RehabCity has been designed based on a participatory approach [20] as an attempt to actively involve stakeholders (e.g. health professionals and patients, in our case) in the design process of the game to ensure that the result is usable and meets the user's needs.

The process started by collecting standard paper and pencil training tasks widely used in clinical environments. Subsequently, together with a rehabilitation physician, we selected 12 tasks considered to have more impact in the successful performance of ADLs. In addition, 20 health professionals experienced with brain-injured patients (physicians, occupational therapists, speech therapists, neuro-psychologists and physiotherapists) provided input on how to operationalize the difficulty, memory, executive functions, attention and language demands of each task. Finally, tasks that could be integrated through the performance of common ADLs were implemented in RehabCity, such as visuospatial orientation, attention and executive functions.

Implementation

Improving the ecological validity of Activities of Daily Living (ADLs)

Although paper and pencil training allows for a very controlled and specific intervention in one or several cognitive domains, it lacks of an ecologically valid context. Real life activities usually involve interdependency of multiple cognitive domains. The main goal of RehabCity is to provide an integrative and engaging cognitive training experience that, not only simulates ADLs, but it tries to do so in an ecologically valid context. Thus, we recreated in VR a simulated city neighborhood of 386x358m^2 to integrate the cognitive training tasks derived from the participatory design process and to deliver them, in a very controlled manner, in the context of real life ADLs. RehabCity is organized in a quasi-regular grid structure of streets with sidewalks, containing over 200 realistic buildings, several parks and moving vehicles. In this simulated city, four of the most commonly visited places by patients have been reproduced: a supermarket, a post office, a bank, and a pharmacy. Further, to increase the ecological validity, all of these places display billboards and products of real spaces and trademarks that are commonly found in Portugal. This helps the patient in relating the in-game goals to the real world.

Multiple auditory and visual feedback elements are used to support the player in the accomplishment of the in-game goals as well as to reward successful actions. Points are accumulated at each goal completion (+20) and at each intermediate task (+1), and points are subtracted (-1) whenever a mistake is performed or the player resorts to a so-called "map/objective" button for additional help. The game is designed as an open-ended experience, organized

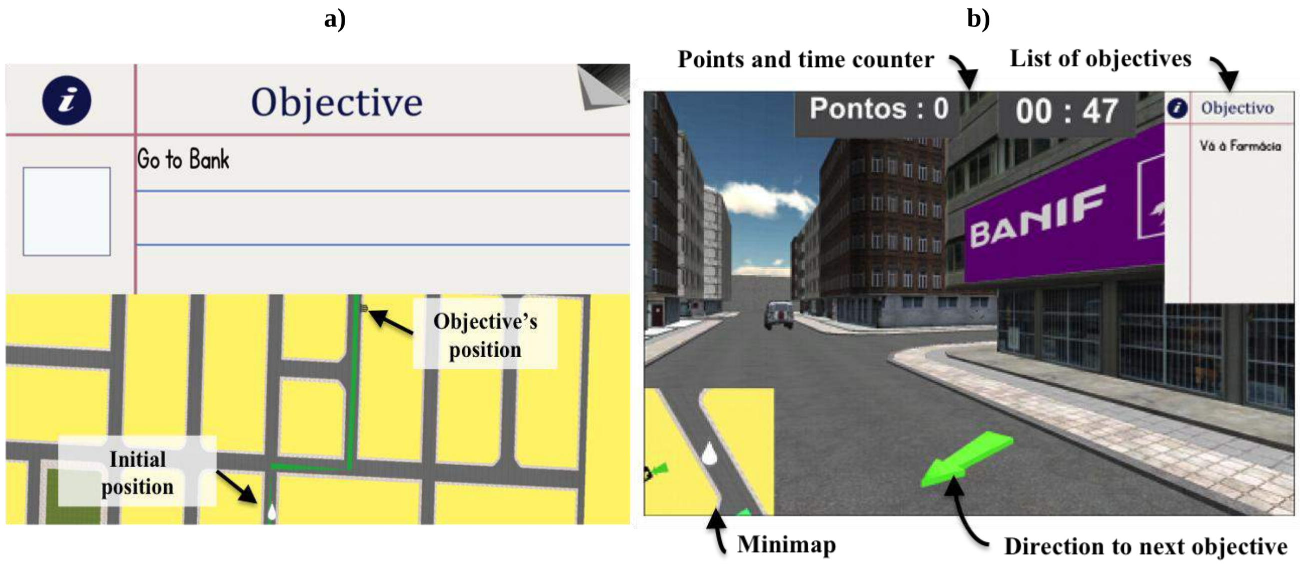

Figure 1: Navigation challenges in RehabCity. a) In-game goal instructions supported with a map indicating the optimal path (green line). b) First-person navigation in the RehabCity indicating the Points and Time counters, list of goals, mini-map and direction to the next goal.

in levels of predefined complexity. If a player finishes Level 1 successfully, he/she will continue onto Level 2, 3 and 4 until time is over. A final score of performance is not provided to avoid frustration and discouragement in case of negative feedback. Additionally, tasks are generated procedurally with increased difficulty to support replayability, meaning that multiple game plays with the same settings result in different game experiences.

In RehabCity we have created multiple in-game tasks, organized in difficulty levels that address the following cognitive domains: visuospatial orientation, attention, and executive functions.

Visuospatial orientation

All in-game tasks happen at specific locations in the city that are designed to reproduce real life tasks and environments. Thus, patients need to navigate through the city to go to the appropriate places for the in-game goals. Because we are dealing with patients of generally older age and low computer literacy, the city has been designed to have only square or rectangular building blocks and regular street intersections. This arrangement helps in memorizing the number of turns a player needs to take to get to destination, and allows us to control very precisely the difficulty of the task. RehabCity incorporates several in-game elements to support players with the visuospatial orientation tasks. When a goal is given to the player, a general map of RehabCity, showing in green the optimal path from the player's position to the goal, aids in the task (Figure 1a). These maps show only the player, streets and places, ignoring unnecessary details that can be overwhelming. A player can always use a "map/goal" button to bring up again this general map of RehabCity at the expense of in-game points. During the game, and depending on the player's needs, RehabCity can be configured to provide a mini-map in the lower half of the screen and/or a guidance arrow placed in front of the player (Figure 1b).

Attention

RehabCity incorporates attention-training tasks related to relevant ADLs in different scenarios (supermarket, post office, bank, and pharmacy). The implementation of these tasks sits in between the more traditional paper and pencil cancellation tasks – tasks where patients need to cross out target elements among distractors – and real tasks where target and distractors are embedded in the real 3D environment (Figure 2a). This implementation enables us to have full control over the elements that determine the difficulty of training - such as the number and nature of target objects, number of distractors, their sizes and spatial arrangement - while avoiding navigation and interaction difficulties that can result from the exposure of patients to hyper-realistic 3D models of those places. The task parameters are then configured according to the patient's training needs, enabling the possibility to personalize training and provide both very simple and very demanding attention tasks.

a) b)

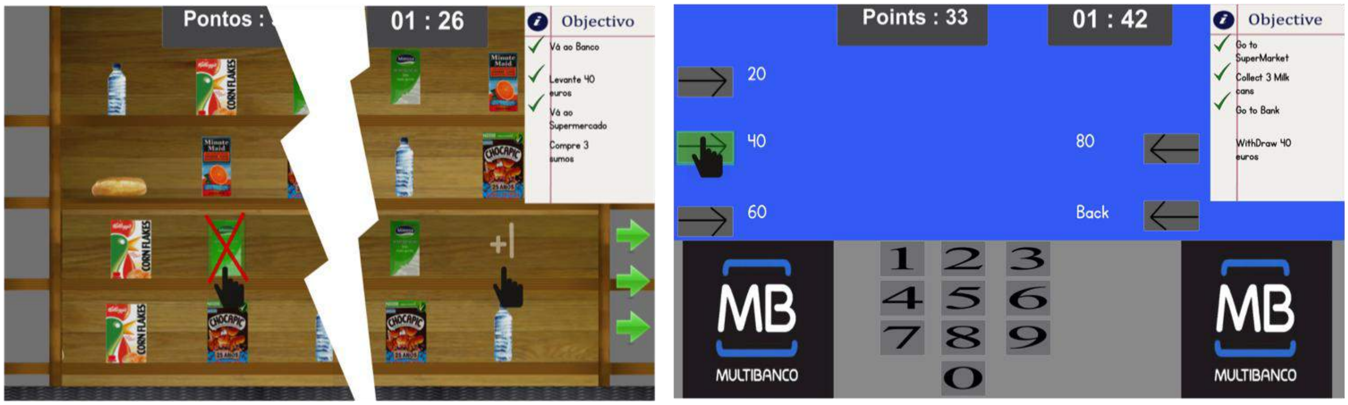

Figure 2: Examples of attention and executive function training scenarios. a) Simplified supermarket scenario displaying grocery products organized in shelves showing a wrong selection (left) and a correct selection (right) of an item of the goal's list. b) In-game reproduction of a cash machine. The layout, button arrangement and options correspond to those of a real Portuguese cash machine (Multibanco).

Executive functions

Executive function is a generic term that is used to designate the regulation of cognitive processes, including working memory, reasoning, problem solving and calculation, among other [21]. RehabCity is designed to pose challenges in those domains by defining a list of goals that the players have to accomplish. Goals can be simple elementary instructions – "go to the supermarket" –, a list of them – "go to the supermarket", then "buy bread and milk", etc. – or problem solving tasks of different levels of complexity – "withdraw 50 euros from the cash machine" or "get some food for breakfast" (Figure 2b). The later ones require the player to solve intermediate tasks that are not explicitly expressed in the goals, such as successfully selecting the right options in the cash machine or figuring out what type of food is appropriate for breakfast.

The game goals are presented initially in a list that occupies the upper-half of the screen, together with the RehabCity map, that minimizes to the upper-right corner (Figure 1, Figure 2). This list supports the player by displaying the current goal and recently completed goals. The visibility of the list is configurable but the player can always access it using the "map/objective" button at the expense of game points. Through the configuration of the visibility of this list we can require the player to focus on the task at hand or to have to memorize the sequence of in-game goals.

Technical Implementation

RehabCity is multiplatform, it was implemented using the Unity 3D game engine (Unity Technologies, San Francisco, USA) and can be accessed online. RehabCity has been developed within the RehabNet framework, a software toolset developed for motor and cognitive neurorehabilitation that integrates a large number of commercial and experimental interface devices to enable patient-task interaction within VR [22]. This allowed us to record face position and orientation information (6 DoF) with a high-resolution webcam (FaceAPI v. 3.1.3, Seeing Machines, Tucson, USA) for investigating gaze behavior during game performance.

User study

The study took place in the Physical Medicine and Rehabilitation Unit of the Funchal Central Hospital. The recruited sample consisted on 10 patients (8 females and 2 males between 35 and 77 years old) with cognitive deficits derived from stroke, traumatic brain injury and mild cognitive impairment. Patients had between 2 to 12 years of schooling, and 4 of them had no previous experience with computers. The ethics committee of the Hospital approved the study and all participants signed a written informed consent.

Protocol

In order to assess how the cognitive profile of the participants relates to game performance and acceptance, all participants performed several evaluations prior to the game experience. They were evaluated with the Mini-Mental State Examination test [23], a well-established screening questionnaire that comprises the evaluation of orientation (time and place), attention (calculation), memory (immediate and delayed recall), language (naming, repetition and writing) and visuospatial capabilities (drawing a complex geometric figure). Additionally, the Stroke Impact Scale 3.0 – a self-reported questionnaire assessing 8 domains: motor strength, hand function, ADL's, mobility, communication, emotion, memory, thinking, and social participation – was used [24]. Training sessions with RehabCity are limited to 20 minutes to reduce fatigue, and the objective is to resolve as many goals as possible. After

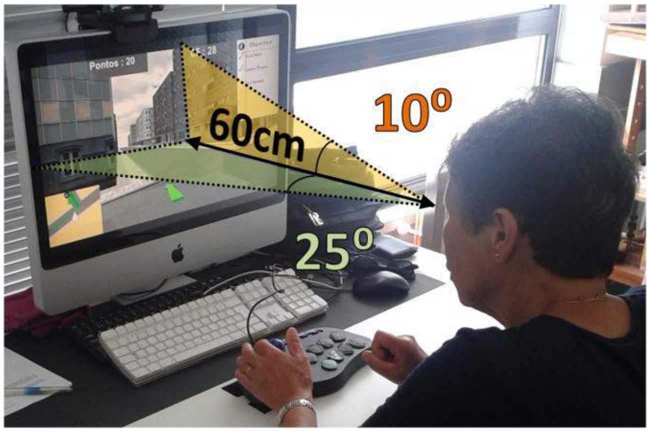

Figure 3. Patient positioned in front of the experimental setup during the user study. Face position and orientation is tracked by FaceAPI using the build-in webcam.

each session, participants rated their experience with the System Usability Scale (SUS) [25].

Experimental Setup

The experimental setup was composed by a desktop computer (OS: Windows 7, CPU: Intel core 2 duo E8235 at 2.80GHz, RAM: 4Gb, Graphics: ATI mobility Radeon HD 2600 XT) with a 24" LCD monitor, running both the RehabNet framework toolset and the RehabCity. For our testing we used an arcade type of joystick (Topway's Digi-usb Joystick Tp-usb670, China) with customized button colors corresponding to the in-game instructions. On each session, patients were placed approximately 60cm distance from the PC screen facing the center of it (Figure 3).

Data analysis

Face tracking data (captured through FaceAPI) and game data (task events and player data in RehabCity) were logged into a CSV file and parsed to Matlab (MathWorks Inc., Massachusetts, US) for later analysis. Face tracking data have been manually cleaned from artifacts and smoothed with a moving average filter (30 seconds window) for cutting-off all high frequencies and noise. Only head orientation data within the field of view of the monitor (±25° horizontal, ±10° vertical) was considered (Figure 3).

RESULTS

Data from 10 training sessions were gathered. Face tracking data was used to measure gaze behavior - based on the face orientation (degrees) - into the four quadrants of the screen. The in-game data of RehabCity includes the overall score, task duration (in seconds), overall distance travelled, position and orientation of the virtual character and all the events within the tasks. This data, combined with the cognitive screening, enables us to quantify the relationship between the in-game data (patient's behaviors within the game), and real world measurements (gaze behavior, usability and cognitive evaluation).

Figure 4. Gaze heatmap based on FaceAPI tracking data, clustered in four quadrants.

System Use

To understand the usage of the on-screen game elements by the study participants we generated a low resolution gaze heatmap from the FaceAPI data averaged from all patients (Figure 4). To simplify the analysis and avoid inaccuracies from the data, we clustered gaze in 4 quadrants. Of those, the top-right quadrant - where the objective list is placed - and the bottom-left quadrant) - where the mini-map for navigation is located – are the most relevant. Data show that throughout the game, the top-right quadrant is the most active one (49% of time), confirming that users consulted the objective list frequently and relied heavily on it. On the other hand, users did not rely on the RehabCity mini-map (11% of time). This may suggest that the information provided by the mini-map was redundant with the directional arrow. A Pearson correlation analysis, however, revealed no relationship between the frequency of use of those two quadrants and the performance in the game. Moreover, we found no further correlation with age or computer experience. This indicates that the design of RehabCity can support both computer literate as well as for non-experienced users.

Patients reported a high System Usability Scale (SUS) score (M=77, SD=14.1), revealing good effectiveness, efficiency and satisfaction levels. However, we found a low correlation between SUS scoring and game performance ($r = 0.64$, $p < 0.05$), indicating that patients that had more difficulty in using RehabCity had also a lower game performance. A further analysis revealed no correlation between SUS scoring and computer experience.

Validating RehabCity as a Cognitive Assessment Tool

In order to understand how performance in the RehabCity can be used to monitor impairment and track changes during cognitive rehabilitation, we performed a correlation analysis of the in-game data with the demographics and cognitive profiles of patients (Figure 5). The in-game variables that we considered include: score, score progression over time (slope of the linear regression of

	MMSE	PC Exp.	SUS	Education	Age	Gender	Task List	Mini-map	Strength	ADL	Communication	Mood	Hand Function	Memory	Mobility	Recovery	Social
Score	0.81*	0.49	0.64*	0.67*	-0.84*	-0.5	-0.34	-0.14	0.2	0.42	0.19	0.75*	0.51	-0.03	-0.39	0.38	0.48
Regression Slope	0.46	-0.2	-0.32	0.2	-0.28	-0.057	-0.15	0.2	-0.37	0.08	0.55	0.46	0.14	0.38	0.13	0.57	0.3
Distance	0.65*	0.46	0.31	0.53	-0.82*	-0.36	-0.33	-0.23	0.34	0.5	0.18	0.46	0.58	-0.01	0.34	0.54	0.54
Nav. Time	-0.57	-0.36	-0.31	-0.78*	0.74*	0.36	0.19	0.3	-0.06	-0.36	-0.51	-0.72*	-0.38	-0.29	-0.36	-0.48	-0.56
ADL Time	0.56	0.35	0.32	0.78*	-0.73*	-0.37	-0.18	-0.3	0.05	0.35	0.5	0.72*	0.37	0.28	0.35	0.47	0.55

*p < 0.05

Figure 5. Correlation analysis between in-game data (rows) and patient data including (columns). Black boxes indicate a significant correlation (p<0.05) and gray boxes a tendency (p<0.1). See text for further information.

score vs. time), distance, % of time in navigation tasks, and % of time in simulated ADLs.

The RehabCity score accumulates the points during the 20 minutes long training session. Based on the reported correlation value, the strongest relationship we find is with the Mini Mental State Examination (MMSE) test. The MMSE is a well-established clinical instrument that assesses cognitive function in several domains. The high correlation (r = 81, p<0.05) indicates that the tasks within RehabCity address the cognitive functions as targeted in its design, and supports the idea of using it for cognitive assessment and monitoring tool throughout the rehabilitation process. Further, we also observed a high correlation value (r=0.75, p<0.05) with mood stability and control, as assessed by the Stroke Impact Scale (SIS). Patients reporting higher mood stability show better performance in the game.

With respect to patient's demographics, we found a negative correlation between score and age (r = -0.84, p<0.05), indicating that younger users achieve better scores.

Figure 6: RehabCity map displaying the trajectories of the study participants and locations of interest.

We also found a lower but still significant positive correlation with the number of years of schooling (r = 0.67, p<0.05). Nonetheless, there was no significant relationship with computer experience.

Users reaching higher scores in the game generally visit more ADLs locations, thus covering larger distances (Figure 6). However, the overall distance travelled is also related to the efficiency of the navigation task, being a more inefficient navigation in case of longer trajectories. This is supported by a positive correlation of the in-game distance travelled and the MMSE (r = 65, p<0.05), showing a similar but weaker relationship of distance with cognitive ability as found with score. A strong negative relationship of score with age is also found in the distance travelled (r = -82, p<0.05), meaning that younger patients perform better.

The time the player spends in the game is divided between navigation time and time in simulated ADLs. Interestingly, higher education levels in patients contribute towards spending more time performing ADLs (r = 0.78, p<0.05), whereas, age contributes towards older patients spending more time in navigation tasks (r = 0.74, p<0.05). This is mainly due to the automatic progression on the difficulty levels of the game, which makes "better" players face more difficult ADLs challenges. The time spent performing ADLs is also modulated by mood stability (r = 0.72, p<0.05). This trend is also consistent with the reported tendencies in cognitive, MMSE (r = 0.56, p<0.1), and social abilities of the patient (r = 0.55, p<0.1).

Finally, we also observed tendencies (p<0.1) in the data that suggest a relation between hand function and distance, perceived recovery with progress rate in the game, and social abilities with time spent performing ADLs (See Figure 5 for the complete correlation analysis).

DISCUSSION AND CONCLUSION

In this paper we presented the design, implementation and deployment of RehabCity, a novel online game for the rehabilitation of cognitive deficits through a gamified approach on ADLs.

We have evaluated the system with 10 stroke patients that reported high usability scores (*M*=77%) concerning effectiveness, efficiency and satisfaction. Through the analysis of gaze behavior we observed that patients relied more on the in-game provided goal list than on the navigation map.

We presented a quantitative analysis to validate RehabCity as training, assessment and monitoring tool, capable of addressing several cognitive domains. This is evidenced by a high correlation between RehabCity scores and the MMSE (r = 0.81), being thus the score an appropriate measure to assess the severity of the cognitive impairment. Results show that education level has an effect on score and time (both in navigation and during task performance) in interacting with a computerized system for ADL's and its content. Both the high correlations between cognitive functions and mood stability are consistent with previous studies [26][27]. Indeed, the cognitive impairment of individuals with depression has been shown to be consistent with a global-diffuse impairment of brain functions [28]. To sum up, we found that score is mainly determined by the integrity of cognitive functions, but that other factors that also contribute towards higher scores are years of schooling, lower ages, better mood and emotional stability.

Our results contribute towards the understanding of the design process for a complete gamified cognitive assessment and training tool for cognitive rehabilitation that cannot be found so far in the field of virtual rehabilitation. This information can help us move towards a RehabCity designed for patient profiling, as a tool for automatically personalizing training tasks to cognitive impairment levels, and recovery prognosis.

As future steps, RehabCity will incorporate virtual crowd behavior module, which is currently under development. Virtual agents will interact with the patient in real time, increasing the ecological validity of the city simulation. Finally, a multiplayer version of the game incorporated within the RehabNet social network [22] could enhance the rehabilitation process by enabling social interaction inside the virtual environment. The final goal of the RehabNet project is to build on the RehabCity to provide a complete virtual eco-system for a cost-effective, at-home cognitive and motor re-training, accessible by everyone, everywhere.

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