

Reh@City v2.0: a comprehensive virtual reality cognitive training system based on personalized and adaptive simulations of activities of daily living

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Abstract—Cognitive impairments are among the most common age-related disabilities worldwide. Literature has shown that cognitive training using Virtual Reality (VR) systems can be a valid and effective solution for cognitive rehabilitation. Virtual environments can be easily customized to deliver very specific training by controlling the presentation of stimuli and keeping track of the user responses. Reh@City (RC) is a virtual reality simulation of a city where patients can train a variety of cognitive skills while performing simulated activities of daily living. An initial prototype of this city with four environments was clinically validated with a stroke sample, and the encouraging results motivated further iterations and improvements in the RC, in terms of its tasks, interaction with the content, and task adaptation. This paper presents the efforts of creating RC v2.0, a VR-based software system for cognitive rehabilitation that presents different cognitive training tasks that take place in 8 realistically modeled 3D environments, that are personalized to the patient clinical profile and also implements automatic difficulty adaptation.

Keywords—virtual reality, cognitive rehabilitation, stroke, activities of daily living, software development

I. INTRODUCTION

VR-based solutions offer the possibility to simulate Activities of Daily Living (ADLs) while stimulating motivation and enjoyment. VR has been considered to be a practical solution to be used both in physical and cognitive rehabilitation [1]–[4]. VR-based technologies allow the customization of the environment and presentation of stimuli and enable it to be adapted to different profiles [5].

A multitude of virtual environments have emerged during the latest years and have been studied and validated for cognitive rehabilitation [1], [3]. However, little information is provided concerning the design process of such VR systems leading to improved clinical effectiveness in terms of cognitive outcomes. For instance, Gamito and colleagues introduced a VR-based program for cognitive rehabilitation following stroke [6]. Their tool allows patients to interact with VR scenarios while simulating ADLs such as morning hygiene, eating breakfast, or buying items on a supermarket. Later, the authors used a very similar system in a posterior study with stroke patients [7]. However, no information was provided to know if the VR software went through improvements or not. Similarly, Klinger and colleagues presented the Virtual Action Planning–Supermarket (VAP-S), a VR-based tool developed with the aim of assessing cognitive planning skills [8]. Their tool consists of a virtual supermarket where instructions are given

to the patient with a list of items to be bought. The same tool was studied over time with patients with cognitive deficits related to different pathologies [9]–[11]. However, little information is provided concerning how the system evolved over time and based on what type of knowledge gained through the different studies. We believe that providing information on how and why a system changes over time, whether visually or functionally, is important as it is part of an iterative design process, but also is a necessity since they are essential to interpret the outcomes of studies carried out with different versions of a software tool.

The initial prototype of the RC (RC v1.0) was developed and studied with stroke patients [12], [13]. Four commonly frequented places of daily life were reproduced in the RC v1.0 integrating cognitive training of attention, visuospatial orientation, and executive functions. Results of a longitudinal trial with 18 patients showed that training with the RC v1.0 had a larger impact than a control group cognitive training using puzzles, calculus, problem resolution and shape sorting [13]. Also, usability tests of the initial prototype reported good levels of usability and satisfaction. However, this initial version had little variety of tasks, mostly used 2D graphical elements and lacked a quantitative and automatic training adaptation procedure, a key ingredient to keep the patient motivated to achieve better rehabilitation outcomes [14]. In this paper, we present the design and implementation process of the upgraded version of the RC (RC v2.0).

The RC upgrade had four main goals:

- 1- Increase the ecological validity of training through improving the overall visual realism of the city and existing tasks;
- 2- Implement automatic and dynamic difficulty adaptation mechanisms based on an existing framework developed for paper-and-pencil cognitive tasks [15];
- 3- Increase the repertoire of cognitive training tasks and the existing set of locations;
- 4- Improve the User Interface (UI) and interaction with the system.

II. INCREASING THE ECOLOGICAL VALIDITY

The RC was implemented using the Unity 3D game engine (Unity Technologies, San Francisco, USA). All user and game data are saved in CSV and XML files which RC loads in future sessions, keeping, therefore, the user progress.

RC went through a multiple-iteration cycle over one year and a half. A multidisciplinary team including clinical psychologists, occupational therapists, software engineers, and designers, with expertise and experience in the field, led the design decisions. During the development lifecycle, multiple pilot tests occurred both with end-users and with healthy testers to inform the implementations. The overall appearance of the virtual city was improved. Decorative elements such as trees, statues, bus stops, and street ads, were added to make it look more like a real city. Buildings of the main streets were decorated with different types of stores and restaurants using realistic 3D models and images. The locations' such as supermarkets or banks were transformed to look like known Portuguese brands. This was achieved by using actual visual elements present in those locations in Portugal. The reasoning is that this way patients can recognize them more easily and relate them to the real world. This relatedness and resemblance to real-world elements and places are very important to increase the ecological validity of cognitive training. Fig. 1 shows the comparison of the two versions of the RC.



Fig. 1. Screenshots of one of the main streets of RC (v1.0 on the top and v2.0 on the bottom). The upgraded version shows the new added elements: trees, different types of shops, and city ads. Also, the UI elements have been improved. New navigation helpers of v2.0: a) shortest path, and b) city signs.

Similarly, the visual appearance of the 4 existing cognitive tasks was transformed using realistic objects or visual elements present in Portugal. Additionally, the shelves and most of the items were changed from 2D images to 3D models (Fig. 2).

III. DYNAMIC DIFFICULTY ADAPTATION

A framework for difficulty adaptation was implemented based on [15], providing 1) personalization of the initial set of cognitive tasks to the user and also 2) the adaptation of the following ones based on the patient's performance. This was

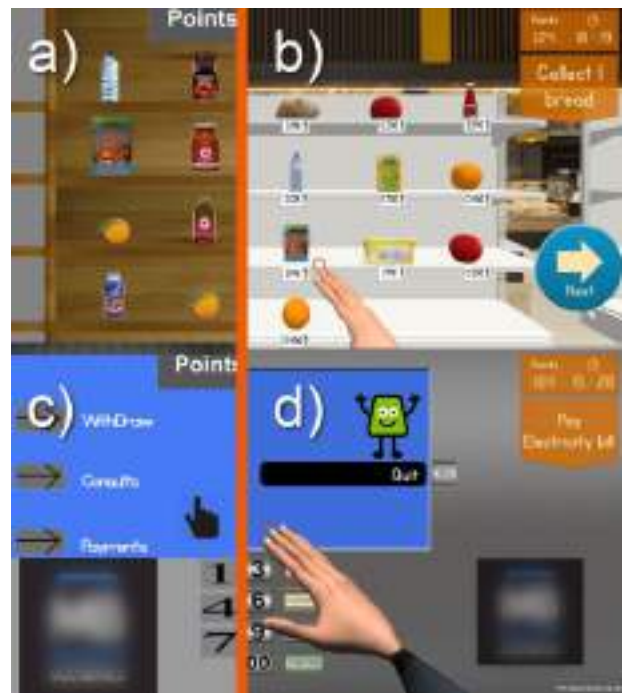


Fig. 2. Comparison of two of the initial cognitive tasks implemented in RC: v1.0 on the left and v2.0 on the right: supermarket (a, b) and bank (c, d).

implemented through user profiling, task instantiation, and performance assessment processes.

A. User profile

The user profile consists of an assessment of 5 different domains: attention, memory, executive function, language, and difficulty. Values range from 1 to 10 with 0.5 intervals. Levels of these parameters can be manually input or by inserting the patient's Montreal Cognitive Assessment (MoCA) sorted by cognitive domain: visuospatial, naming, attention, language, abstraction, delayed recall, and orientation. The delayed recall and orientation are used to obtain the memory score. Executive functions are obtained by summing the visuospatial and the abstraction scores. Language is obtained by the naming result. The difficulty parameter is obtained by the overall MoCA score. Fig. 3 shows the UI menu where the therapist can insert the MoCA values. The parameters are then recalculated to fit a scale that ranges from 1 to 10. The obtained values are then rounded to its closest value considering 0.5 intervals. The entered configuration is used to perform the initial task personalization to each patient.



Fig. 3. UI menu that allows inserting the MoCA results

Fig. 4 shows the sequential flow of the dynamic difficulty adaptation process. First, the user profile is created based on the results of the MoCA test. Based on this, the models are used to calculate the most suitable configurations for the tasks which are then instantiated in sets. The training starts by requesting the patient to go to a specific location, and then executing the cognitive task on that location. The process is repeated until the set is complete. After the set completion, the performance processor calculates the average of the performances which will then influence the user profile depending on the percentage obtained. The new set of tasks is then instantiated based on the models recalculated for the actual user profile.

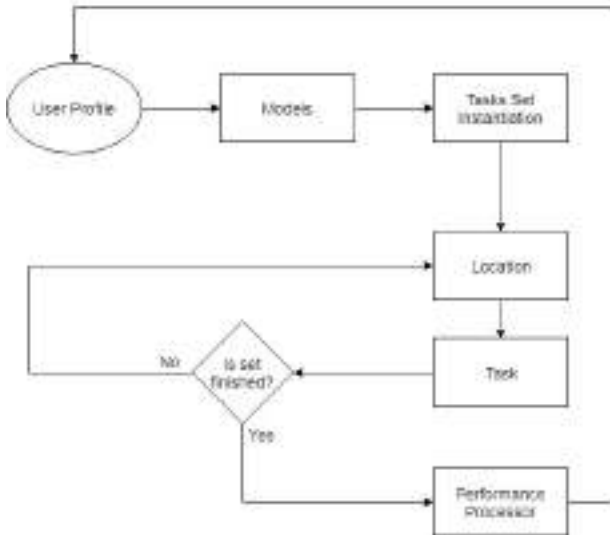


Fig. 4. Dynamic difficulty adaptation flow diagram.

B. Instantiation of tasks

The configuration of the VR tasks is based on the quantitative guidelines from Faria and colleagues [15]. This is implemented by a set of classes of type “Model” that implement the functions that receive the “UserProfile” levels as input and returns a set of task-specific settings that will serve as configurations for each VR task. Faria and colleagues framework proposed 11 different computational models to determine the parameters for the personalization of paper-and-pencil tasks based on mazes, cancellation problem solving, action sequencing, image pairs, categorization, memory of stories, numeric sequencing, comprehension of contexts, association, and words search. Of these 11 tasks, only the first eight could be easily operationalized in virtual reality in the context of ADL. The “TasksInstantiation” class is responsible for configuring each set of tasks to present to the patient, for this, it invokes the models by Faria and colleagues to obtain the right configurations based on each “UserProfile”. Tasks are then ordered by location depending on the distance between the player and the location where they take place. This order will vary according to the difficulty level. Tasks can be of three types: location, collection, and action. The location ones are related to the navigation in the city where the user is required to control a virtual character to reach a given location. Collection tasks are the ones found in the pharmacy, post office and supermarket. These tasks are based on cancellation tasks and require the patient to select a given set of targets among distractors. Action tasks can be found at home, bank, kiosk,

park, and at the supermarket, and implement the action sequencing, numeric sequencing, memory of stories, pairs of images, and problem-solving respectively. In Fig. 5 it is possible to see a diagram showing the classes involved in this process.

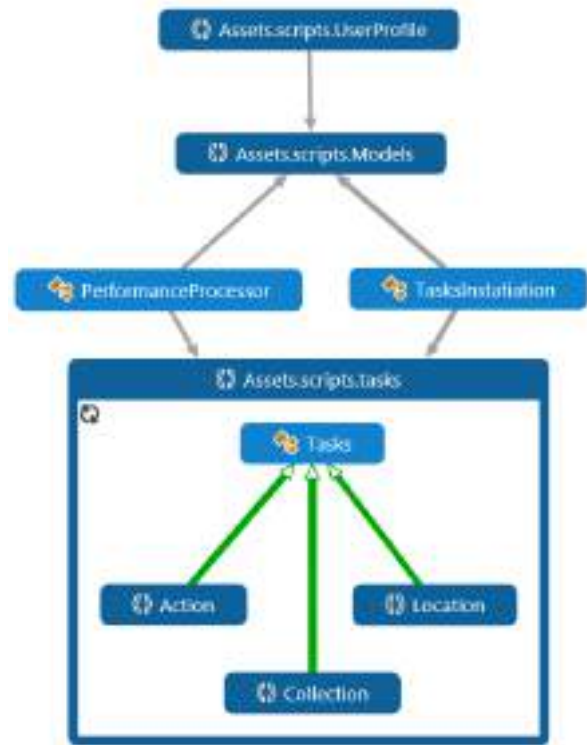


Fig. 5. Generic diagram of the main classes involved in the dynamic difficulty adaptation process.

C. Performance processor

At the end of each set of tasks, the user performance on each task is calculated by the “PerformanceProcessor” class (Fig. 4). Performance is measured in percentages of accomplishment of each task. Table I shows how performance is calculated for each implemented task. In some cases, performance can be negative if more mistakes than correct actions are performed. In that case, performance is considered 0%.

TABLE I. COGNITIVE TASKS PERFORMANCE CALCULATION.

Task	Performance calculation
Navigation in the city (mazes)	$(\#nodes \text{ of the shortest path} - \#nodes \text{ crossed} - \#nodes \text{ of the shortest path}) * 100 / \#nodes \text{ of the shortest path}$
Pharmacy and Post Office (cancellation) Bank (numeric sequencing)	$(\#Correct \text{ items selected} - \#Wrong \text{ items selected}) * 100 / \text{total } \#Correct \text{ items}$
Supermarket (problem resolution)	Correct invoice selected = 100% Wrong invoice selected = 0%
Kiosk (memory of stories)	$(\#Correct \text{ answers} - \#Wrong \text{ answers}) * 100 / \text{total } \#questions$
Park (image pairs)	$\#Pairs \text{ found within the time limit} * 100 / \text{total } \#pairs$
Clothes store (categorization) Home (action sequencing)	$(\#Correct \text{ items selected within the time limit} - \#Wrong \text{ items selected}) * 100 / \text{total } \#Correct \text{ items}$

The rules for adaptation based on performance proposed by Faria and colleagues are the following. If the user's average performance is lower than 50%, then the difficulty level is decreased by 0.5, if it is higher than 70%, the difficulty is increased by 0.5. Otherwise, the difficulty level remains the same. The reasoning behind this adaptation is to avoid frustrating settings that result in very low performances but that the patient is always challenged.

IV. INCREASING THE REPERTOIRE OF TRAINING TASKS

The previously implemented tasks were inspired by ADLs and based on two paper-and-pencil cognitive tasks: cancellation (post office, pharmacy, and supermarket) and action sequencing (ATM at the bank). Since there were already 3 locations to train the cancellation, one of them (the supermarket) was improved to train the problem resolution task. This was implemented by presenting two invoices at the end of a shopping task, one with the correct values and the other one with incorrect ones. Additionally, we added a numeric sequencing task, the ATM at the bank, to simulate the action of entering the correct PIN number. Four new locations based on four different cognitive tasks were implemented in the RC v2.0. Three were created based on modified versions of an existing cognitive rehabilitation software tool: the Reh@Task [16]. This tool can present a set of stimuli aligned as a grid, and the user is required to select a specific number of target elements among distractors. The type of stimuli, the number of targets, the number of distractors, and the time to accomplish the task is defined programmatically.

less the time available to accomplish the task. Hints are displayed to facilitate task completion in case the patient is not able to accomplish the task within the allocated time.

B. The cloth store

This location was prepared considering a known clothing shop which can often be found in Portugal. This way patients would recognize and would relate to a real clothing store (Fig. 6c). On this location, a categorization task was implemented. A set of items is presented to the patient who is required to select the ones that match the given category (Fig. 6d). The number of items can vary from 2 to 45. 12 Categories were made available and include: baby clothes, footwear, glasses, handbags, hats, home décor, jewelry, men clothes, perfumes, swimsuits, underwear, watches, and women clothes. Similarly, as in the park, task time is based on the number of items to find and on the difficulty level.

C. The magazines' kiosk

A kiosk with newspapers and magazines was added to the RC as a new location (Fig. 6e). The inspiration for this cognitive task was the memory of stories training task described by Faria and colleagues [15]. A newspaper with text or image is presented to the patient, who reads it for as long as he/she needs (Fig. 6f). When finishing reading, the patient proceeds to a new task in a new location. After reaching the next location, a set of questions are presented concerning the text or the image previously presented at the magazines' kiosk, and the patient has to select true or false.



Fig. 6. The new implemented cognitive tasks at different locations: the park (a, b), the clothes store (c, d), the magazines kiosk (e, f), and the home (g, h).

A. The park

A new location was prepared at the heart of the virtual city to resemble a park with trees, garden benches, children playground, and picnic tables. This is an ideal place to socialize and play card games, which is a common activity among older adults in Portugal (Fig. 6a). The cognitive task implemented was inspired by a paper-and-pencil memory recall of pairs of images task. A set of cards facing down is presented on top of a table, and the patient is required to flip one by one to find matching pairs of cards. The content of the cards can be numbers, letters, and symbols, both in black or in colors. Matching pairs will remain visible, while the non-matching ones will flip down again and hide their content (Fig. 6b). The number of cards can vary from 2 to 20 pairs. The task time is calculated based on the difficulty level and the number of pairs to find. The higher the difficulty, the

D. Home

A 3D model of a house was placed in the virtual city with three different rooms implementing action sequencing tasks: living room, kitchen, and bathroom (Fig. 6g). A set of images is presented to the patient who is required to select each one on the right order. In Fig. 6h is displayed one example of the action sequencing task at the kitchen. Related content was attributed to each specific room. Different action sequencing tasks were made available at the different rooms (7 at the living room, 7 at the kitchen, and 4 at the bathroom). New action sequences can be easily added through external configuration files since the system was developed to be customized without the need for extra programming. The time to accomplish the task and the number of steps in each sequence of actions, which can range from 2 to 6, is defined by the difficulty level.

V. IMPROVED UI AND INTERACTION WITH THE SYSTEM.

The UI in RC v2.0 was designed to provide a friendly and pleasant interaction. Large fonts and buttons were used to improve readability and usability. However, the most important improvement related to the actual interaction with the RC. RC v1.0 was controlled with a simple joystick with 2 buttons. Despite being usable and easy to understand, current research indicates possible benefits of the integration of motor-and-cognitive training in the context of post-stroke rehabilitation [17]. For this reason, different types of interfaces, ranging from a joystick, mouse to depth-sensing cameras were implemented and tested. After a study analyzing different interfaces, it was found that 2D Natural UI (2D NUI) using arm movements was the preferred option to be used by stroke patients in a rehabilitation context [18]. Hence, the whole interaction was redesigned considering that there could not be any keystrokes, mouse clicks or button presses during gameplay. Only the main menu requires to use a mouse and keyboard to enter the patient data, which is usually performed by a therapist or caregiver.

In RC v1.0, a 2D image of a hand was used as a cursor in the different cognitive training tasks where objects were required to be selected. In RC v2.0 a complete 3D model of a virtual torso, including both arms and hands were implemented. Interaction with virtual objects is now performed in the tridimensional space using arm reaching actions.

Improvements were also added to assist patients during navigation. One example is the indication of the closest path marked as green on the street floor (Fig. 1a). This path is dynamically recalculated whenever crossing a street. Another example is the city signs, located at each crossing node indicating the direction for each location (Fig1b). The trajectory path, the city signs, and the mini-map are considered helpers in the game mechanics and are disabled in higher difficulty levels. Particular attention was also given to the navigation control system along the virtual city streets. Past observations revealed that stroke patients had some difficulties controlling the virtual character navigation in a tridimensional environment, especially when using their affected arm. Therefore, we implemented in RC v2.0 a highly configurable navigation system that assists therapists in finding the best settings for each patient and allows patients to control the navigation through their arm movements on a tabletop surface. These movements are tracked with AnTS, a camera-based tracking software [19]. This 2D-NUI gives us information about the 2D position of the patient's hand that is then converted and mapped on the screen (Fig. 7).

For the navigation's configuration, a cursor can be made visible to show where the hand of the patient is located in the interaction space. Four different thresholds are used to define how navigation will occur in the virtual city. Those thresholds are represented as orange lines and the position of the hand as a circle (Fig. 8). The vertical lines represent the rotation thresholds and inform when the virtual player should rotate to the left or the right. This means, when the cursor crosses either the left or the right thresholds, it starts rotating in that direction. The top horizontal line represents the moving forward threshold. When the cursor is beyond this threshold, the virtual character starts moving. If it is in between the rotation thresholds, it will move forward. If it is in either the right or left quadrants, it will then rotate and



Fig. 7. User interacting with the system using the AnTS 2D-NUI.

move forward simultaneously. The bottom line represents the “stop completely” threshold, which will happen whenever the cursor is located below this line. The same behavior occurs if the cursor is in the middle section of the lines since it is not beyond the lines to rotate or move. These thresholds can be repositioned to facilitate interaction to each patient depending on the presence and specifics of their motor deficits. Two other important settings that enable adapting the navigation control: i) the speed when moving forward, and ii) the velocity increase mode - exponential, logarithmic, or proportional – depending on the distance between the cursor and thresholds.



Fig. 8. Street view with Navigation settings menu enabled.

VI. CONCLUSION

In this paper, we presented efforts towards improving a VR-based cognitive rehabilitation tool based on the experience gain through field studies with a stroke population. The first objective was to increase the ecological validity of training through improving the overall visual realism of the city and existing tasks. Considerable progress has been made concerning improving the existing city buildings and adding new decorative elements to make the city more visually appealing and ecologically valid. We also implemented automatic and dynamic difficulty adaptation mechanisms based on [15] that facilitate the training configuration and allow this training to be implemented with

minimal supervision, enabling its use at home. We increased the repertoire of cognitive training tasks by implementing four new city locations which provided a larger variety of cognitive activities and increased the variability of the navigation over the city. The existing locations and their respective cognitive tasks were highly improved by increasing their sense of realism and preparing them to accommodate new mechanisms for different cognitive tasks. The UI and the interaction were redesigned considering the advantages of combined motor-and-cognitive training and the limitations of the target population. Currently, the system is being used in a randomized controlled trial with 40 stroke patients, showing high acceptance and usability. In the future, we expect to report on the usability and clinical impact of the RC v2.0.

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