Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 December 2020 doi:10.20944/preprints202012.0331.v1

Article

Rapid Prototyping of Virtual Reality Cognitive Exercises in a Tele–Rehabilitation Context

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Abstract: In recent years, the need to contain healthcare costs due to the growing public debt of many countries, combined with the need to reduce costly travel by patients unable to move autonomously, have captured the attention of public administrators towards tele-rehabilitation. This trend has been consolidated overwhelmingly following the Covid-19 pandemic, which has made it precarious, difficult and even dangerous for patients to access hospital facilities. We present a platform devoted to the rapid prototyping of Virtual Reality based, cognitive tele-rehabilitation exercises. Patients who experienced injury or pathology need to practice a continuous training in order to recover functional abilities, and the therapist need to monitor the outcomes of such practices. The Virtual Reality exercises are designed on Unity 3D to empower the therapist to set up personalised exercises in a easy way, enabling the patient to receive personalized stimuli, which are crucial for a positive outcome of the practice. Furthermore, the reaction speed of the system is of fundamental importance, as the temporal evolution of the scene must proceed parallel to the patient's movements, to ensure an effective and efficient therapeutic response. So, we optimized the Virtual Reality application in order to make the loading phase and the startup phase as fast as possible and we have tested the results obtained with many devices: in particular computers and smartphones with different operating systems and hardware. The implemented platform integrates in Nu!Reha system®, a tele-rehabilitation set of services that helps patients to recover cognitive and functional capabilities.

Keywords: Blender; Cognitive exercises; Nu!Reha; Tele–Rehabilitation; Unity3D; Virtual Reality;

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1. Introduction

The attention to bring services operated remotely has grown in the last years. The pressure on health related services prompted for simple and fast solutions for tele-rehabilitation in several fields. Those services were conceived as reliable and routinely services (not only pilot tests)[1], and are nowadays even more important to provide continuous and efficient health services.

Cognitive rehabilitation is a branch of the whole rehabilitative treatments, and is devoted to all patients who need a continuous training of cognitive functions because of injury (Traumatic Brain Injury, Stroke, Cerebral Palsy, etc) or pathology (Alzheimer's disease, Multiple Sclerosis, etc), which are affecting the Central Nervous System (CNS).

We need to stimulate several functions, such as attention (i.e.: sustained attention, divided attention), memory (i.e.: spatial memory, auditory memory, working memory) and executive functions in general (i.e. Planning, Categorization, Flexibility, Inhibition).

In general terms, cognitive training consists in a number of different and well focused exercises whose results can be logged and tracked by the therapist, in order to tune the subsequent phases of the therapy. The routinely practice is carried out with the help of a therapist who monitors the execution of activities, which can be either based on paper and pencil or software tools.

Pilot cognitive tele-rehabilitation practices are reported in literature[2]: they report relevant advances for patients and their families, both as objective results as well as perceived comfort. However, some barriers have been identified for the proper routinely adoption of the remote treatment modality. The main aspect relates to the availability of dedicated hardware (Operating System compatibility, type of touch screen, medical grade if requested) which should be supplied by the health institutions to patients and caregivers. Because of the cost of these apparatuses, the number of users that can use it is very limited. In most cases, a limited number of the available standardised exercises reduces the motivation of neurological patients to continue the practice. Furthermore, these exercises lack of contextual personalised stimuli and seems to limit the personal motivation, inhibiting long term application to the proposed tele-treatment.

On the basis of these experiences, new concepts have recently become established. First of all, the opportunity and the importance of applying the "Bring Your Own Device" (BYOD) approach, using the network and the devices owned by the family of the user. Furthermore, we have to consider the problem of selecting, among the activities that we can propose to improve the rehabilitation practice, those most suitable for the patient and with a better chance of success. Finally, we must stress the importance of the customization of these activities by means of cognitive contextual stimuli that reinforces the patient's motivation.

The NU!Reha system[3] is based on all these considerations and allows to rapidly realise user–engaging activities to support cognitive functions. The system is based on a series of devices created ad-hoc for the recovery of cognitive functions (Nu!Reha Desk) and a web based environment that allows the patient to carry out more complex, game-based and endearing experiences, implemented in a virtual reality environment.

Since several software components may be reused in different exercises, we provided a number of pre-programmed software elements (assets) to speed-up the development of new exercises, transforming this tool in a powerful Rapid Application Development (RAD) system devoted to the realisation of cognitive exercise.

Since the patient can practice using a web browser, the user will benefit of the BYOD approach.

2. Related works

Rapid prototyping work is often linked to agile production paths[4] that are arising in recent years as a way to respond promptly, easily and with high degree of customisation to the "customer expectations", considered in wide sense. In general terms, it is intended as an approach toward a fast development cycle from Software Requirement Specification to Software Prototype Testing, including the chance to produce automatically documentation for the expected Quality Requirements, with respect to the production framework.

With specific reference to programming, the idea to simplify the access to programming tasks historically sources from different needs:

- to let introduce a larger audience to programming activities for educational purposes (algorithmic mindness, problem solving) [5];
- to speed-up repetitive operations, mostly in industrial environment, allowing an automatic control of syntax and speeding-up tests;
- to support easily customisation of programs, as for as adaptation of user interface and behaviour.

In terms of educational resources, several solutions have been developed starting from authoring tools produced for educational purposes: presentation, interactive exercises, algorithm exploration, problem solving activities and more recently pet-bots (including also Lego robotics) control for social educational games. In this, the prevalence of Block Programming solutions, simplified the approach to small app generation through a graphical syntax rule control[6]; the success story of such approach[7] has brought to a large community using similar solutions for development of single purposes/simple applications running in different OSs[8].

In the field of industrial automation and control as well as in designing virtual instrument solutions, the main reference is constituted by Labview Graphical Programming environment[9]. The virtual connections between constructs and statements build up programming logic, simplifying development and debugging of the application. The main application is intended in interfacing complex and re–configurable hardware and software systems (starting from the origin: testing and virtual instrumentation) speeding-up the deployment while in the field, which is a key factor in industrial production chains. IIOT (Industrial Internet of Things) and IOT in general are revamping some experiences in RAD already developed for firmware development. In case of MCU (Micro Controller Unit), the chance to rapidly land on proto, means also the possible advance in hardware interfacing problem solutions, significantly reducing the overall time of design process [10]. More recently, IOT and hardware application based on building blocks launched several MCU/MPU functional boards, that can be programmed with a multi-level approach, starting from RAD (mostly based on block programming concepts), as for as Microbit projects [11].

All solutions, coming from the educational and industrial environment, could be usefully applied to user interface adaptations/configuration as well as for specific applications in AT (Assistive Technology) solutions. The variability of human functional profile, as it referred to ICF (International Classification of Functioning, Disability and Health)[12], brought to apply RAD solutions to assure prompt response to users needs in several fields of application. Our experience, started some years ago with the development of software to support and monitor exercises of occupational therapy for neurological patients (i.e. stroke and traumatic brain injury survivors, multiple sclerosis, etc.)[3]. As the complexity of solutions to assure efficiency and efficacy included concepts coming from a gamified approach to learning, introducing to "serious games" [10], a multi-layered software structure has been adopted: a Labview based layer to address all routinely functions of rehabilitative application embedding single purpose software app realising each specific exercise. Each app develops a functional exercise and it is part of a library that can be configured by the therapist, even at distance as in the case of tele-rehabilitation modality.

Tele-rehabilitation is an emerging method of delivering rehabilitation services that uses technology to serve clients, clinicians, and systems by minimizing the barriers of distance, time, and cost [13]. Tele-rehabilitation was first documented in 1959, when interactive video was first used at Nebraska Psychiatric Institute in the delivery of mental health services, but the term tele-rehabilitation born only in 1997 when the "Department of Education's National Institute on Disability and Rehabilitation Research" of United States proposed the field of "tele-rehabilitation" for the new rehabilitation engineering research center [14].

Tele-rehabilitation has developed strongly to improve and optimize the rehabilitation services and patient's outcome, allowing to continue a rehabilitation path at home. The aim is not to replace traditional services but to strengthen and maintain them over time.

Tele-rehabilitation originated for motor rehabilitation; only later was cognitive rehabilitation introduced. The impairment of certain cognitive abilities can depend on a number of factors and circumstances, some of which are linked to ageing, such as dementia, vascular problems, head injuries, chronic psychiatric illnesses or internist pathology. Only after a careful and thorough neuro-psychological evaluation that highlights the presence of cognitive deficits, it is possible to carry out neuro-psychological rehabilitation cycles to improve cognitive functioning, stabilize deficits, stimulate residual cognitive abilities and slow down the course of decay.

Currently, there are three theoretical-practical currents of thought underlying the rehabilitation of neuro-psychological deficits:

- the first one proposes to address the rehabilitation of cognitive processes through non-specific stimulation;
- the second, on the contrary, suggests that recovery must necessarily pass through specific stimulation of the disorder. This type of intervention can be differentiated into: restorative approach (recovery) or substitution approach (compensation) [15].

 doi:10.20944/preprints202012.0331.v1

- the third does not deal with the specific disorder but proposes to stimulate the residual abilities, in order to overcome the difficulties and inhibitory effects, guaranteeing the greatest possible autonomy.

The importance of a neuro-psychological rehabilitation intervention derives from the evidence that exposure to a stimulus-rich environment, learning and cognitive stimulation promote brain plasticity, allowing recovery after brain injury or slowing down the progression of a degenerative disease[16].

Physiotherapist Trevor Russel, University of Queensland, showed how the contemporary technologies described in tele-rehabilitation literature can be classified [17] as:

- Image-based technologies, which have been used in videoconferencing or for monitoring and diagnosis purposes.
- Sensor-based technologies, which use tilt switches, accelerometers or gyroscopes to sample and quantify three dimensional space movement.
- Virtual environments and virtual reality, which use virtual environments to elicit specific movement from the patient.

These studies are the foundation of Nu!Reha platform giving a scientific basis to the effectiveness of performing cognitive exercises. Nu!Reha Service is a digital platform for cognitive rehabilitation that allows to train cognitive functions such as memory, attention and executive function, changing the difficulty of activities according to the patient's abilities. This characteristic determines a flexibility service that allows a customization of rehabilitation path [3,18–28]. This flexibility implies a great variety and number of proposed activities, because its initial package is constantly expanded and upgraded, but even professional users can gradually add and get richer the platform, making new exercises. The target users can be divided into three categories of patients:

- Neurological, in the context of brain injuries, with the aim to recover impaired cognitive skills and / or enhancing residual ones.
- Geriatric, not only for pathological but even physiological aging, in order to preserve the functions.
- Minors, with disabilities in education and rehabilitation.

Based on the functional profile of the individual patient, the therapist can choose among activities that go to train:

- Attention, its role is to select, filter and activate relevant information for the goal, choose necessary activities and discard the useless ones that would only end up to saturate the cognitive system and waste efficiency. Specifically, you can find activities aimed at:
  - Selective attention, includes all those processes that involve the possibility of ignoring meaningless information and allow you to select only the necessary one, focusing on it.
  - Sustained Attention, allows you to pay attention for an extended period of time.
  - Divided attention, the ability to pay attention to multiple tasks and process information from two different channels.
- Attentional shifting, involves alternating between two attentional focuses: you don't have to pay attention to them at the same time, but you need to switch quickly from one to the other when the task requires to do it.
- Memory, a complex function by which subject is able to acquire, preserve and reuse knowledge. In particular:
  - Short-term memory, it is the ability to retain for short periods of time (10-30 sec.) the information just collected; it is characterized by capacity and time limits.
  - Working memory, it stores and processes information while performing cognitive tasks, so it allows us to keep information in memory and to manipulate it at once.

    - Long-term memory, it allows us to keep an indefinite amount of information for an equally indefinite time, therefore even for a lifetime.
- Executive functions, a set of related but distinct skills necessary for an intentional, targeted and problem-solving action [29]. In particular:
    - Categorization, ability to organize information by capturing the essential characteristics, sorting and giving a meaning to our experiences.
    - Inhibition, ability to inhibit previously learned responses and to control the interference effect of distracting stimuli.
    - Cognitive flexibility, ability to change behavioral patterns based on received feedback.
    - Planning, the ability to imagine how to reach a goal and what steps must be taken to get to it.
    - Emotional self-regulation, the ability to recognize and manage one's emotions.

NU!Reha Service offers to professionals and structures the opportunity to continue the work done in the presence even at the patient's home, in order to guarantee continuity and consolidate the results obtained. In this way, once the therapist has configured the activities to be carried out by his patient, he can monitor their progress at any time and on the basis of this, if necessary, propose a new plan. The execution of a personalized rehabilitation program at home is facilitated by the Bring Your Own Device technology, which NU!Reha is based on, since a dedicated hardware system is not required, but can be run on the user's device. All this can simply be done ensuring the accessibility: indeed, a simplified access method on a tablet has been implemented with no necessity of entering credentials, but only by focusing a QRCode by the device's camera. In addition, a group of exercises / activities have been designed to be carried out by the interface equipped with one or two sensors, so even users with poor or absent pointing or movement skills of the upper limbs can access the platform.

3. The relevance of VR Cognitive exercises

Virtual reality-based tele-rehabilitation systems use three-dimensional virtual environments to stimulate and obtain specific movements from the patient. The virtual environment can be viewed by the patient on the computer screen, or using fully immersive devices, like Head Mounted Display, 3D movement sensors and haptic devices. The use of such technologies allows physiotherapists to use and customize virtual environments to incorporate key rehabilitation concepts such as activity repetition, feedback and motivation in order to stimulate learning of impaired motor skills and then translate them into the real world. [30]

Virtual Reality based tele-rehabilitation systems include those using video games.[31–33]. Thanks to the development of technology, nowadays you can experience a virtual reality game very easily, given the availability of powerful and low cost devices. The created virtual environments reach such a level of realism and immersion that they have an important positive effect on tele-rehabilitation.

According to Willer and Corrigan[34], the recovery or learning of motor or cognitive functions in the environments where it will be expressed, is the ingredient to maximize the result of a good rehabilitation therapy. The immersion deriving from the use of virtual reality instruments is winning: the patient, through the use of instruments that allow the play-therapeutic experience in three dimensions, finds himself immersed in an environment as similar as possible to the real one. The patient thus exercises the desired functionality in an environment that reconstructs the scenes of the subject's life, in an absolutely familiar context.

Another strong point of tele-rehabilitation is the possibility of performing movements in a "dangerous but without danger" situation: this means that the creation and use of virtual environments capable of recreating the patient's entire life context allows the therapist to perform motor gestures and apply cognitive skills in everyday life situations, preventing and cancelling the individual risk factor. [3,30] This seems essential for recovery and for learning the compromised skills that are actually plausible but absolutely safe for the patient, where the margin of error in the execution does not generate further harmful effects for those who perform them.

 doi:10.20944/preprints202012.0331.v1

In conclusion, it is possible to assert that virtual reality applied to tele-rehabilitation has made it easier and more widely used because of its low cost and the wide diffusion of the necessary instrumentation. Moreover, through the game, it is possible to increase the therapeutic work time as the patient makes the necessary gestures for the rehabilitation intervention applying them in a playful context. This makes it possible to increase the effectiveness of the treatment and reduce the side effect of alienation linked to the sterile repetition of motor gestures for themselves.

4. The Architecture of Nu!Reha system

The architecture of Nu!Reha system, shown in Figure 1, is composed of two parts: the Back-end used by health professionals (i.e. psychologists, physiotherapists, speech therapists) that organized patient's therapy inserting the most appropriate exercise and the Front-end used by patients to perform the exercises.

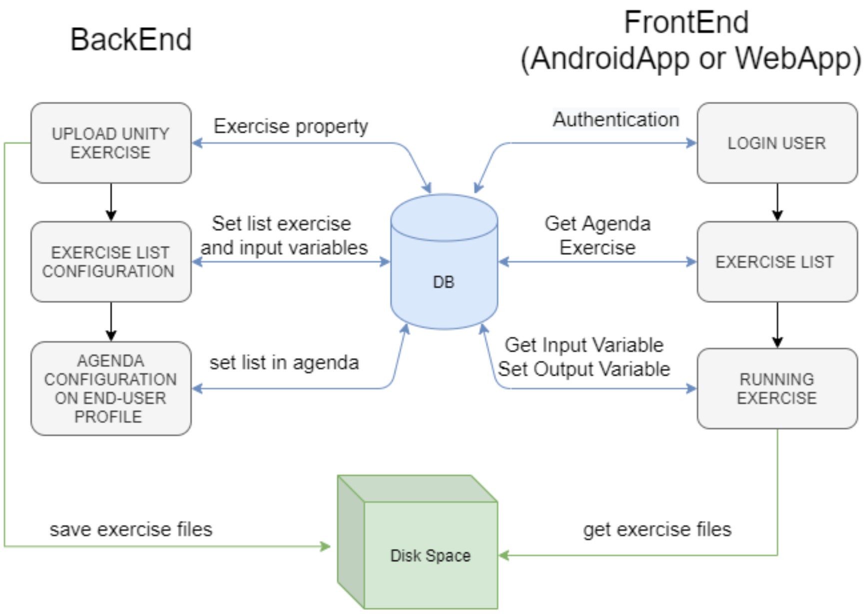

Figure 1. The architecture of Nu!Reha system

The main functions of the Back-end, are: upload the developed 3D exercises, list configuration composed by several exercises customized with input variables and the agenda configuration that allows to assign to a patient an exercise list for a certain period of time. On the other hand, the main functions of Front-end are: execution of personalized exercises inserted in agenda by the operator and variable saving that allows to monitor the progress and results of the therapy.

In order to integrate exercises implemented with Unity 3D in the architecture described above, ad-hoc web user interfaces have been created for:

- Upload HTML exercises on cloud and save input variables on database. The format exported by Unity is WebGL since it is fully integrated with web standards.
- Configuration and customization through input variables of previously loaded exercises to make a list.
- Execution of exercise with the possibility to manage input and output variable trough database connection. All exercises use a script that manage I/O variable, this script open a connection to the REST server of Nu!Reha via HTTP protocol. In the case of Input variables the connection gets results in JSON format, each tuple obtained is stored as an instance of a specially created class. In the case of output ones, all variables contained in exercise scripts are read and shown to the developer in the form of check-boxes to allow the selection and consequently the saving into the database through consecutive attempts in case the first one or subsequent fails.

5. Advanced Unity techniques

During the development of the software we took great care of all performance aspects. Our goal was to obtain the shortest application loading time to give to the users the possibility to immediately access the exercise that the therapist wants to manage. To do this we balanced various aspects, in particular we focused on how to obtain the best compromise among graphics quality, loading time and size in megabytes when the project is compiled in WebGL. Patients who will use the software may have outdated devices and this aspect actually requires to generate software which will require a minimum amount of RAM and VRAM while running.

Generally, outdated devices are rarely updated by smartphone manufacturers for major releases of the operating system, so we need to take advantage of APIs that allow us to obtain the highest percentage of market share even in the smartphone sector.

We have also considered that users may have slow and unstable connections, so it is important that the program should require them to download as little data as possible over the Internet.

5.1. Graphics Settings

To obtain the best possible performance we implemented as much as possible technical optimizations on the Unity project. First of all we analyzed the rendering techniques. The graphic settings related to the image quality that will be shown in the rendering phase on the device was manually calibrated by creating a custom profile in the Quality section of the Project Settings. The resolution of the textures has been set to "Full Res" thanks to the optimizations implemented with the techniques that will now be described, and there is no reason to further compress them. Anisotropic filtering and antialiasing filtering was disabled as well as the Soft Particles calculation engine, since they will not be used. We've also turned off the real-time reflections. The Texture Streaming feature has been enabled. This allows us to reduce the memory quality required for textures so that only small portions of mipmaps are loaded into memory. For this functionality we have set a maximum amount of VRAM memory that Unity can use equal to 512MB and a maximum of 1024 simultaneous input / output requests. As for the shadows, we used the Distance Shadowmask calculation method and render only the "hard" shadows on the scene, thus ignoring the calculation of soft shadows.

This calculation method allows us to obtain a realistic and fairly faithful graphic environment. To get a little bit lighter project, we could have set the rendering in shadowmask mode, but quality loss would not have been justified by the gained performance. Indeed, the project is contained and the rendering of the room is efficiently calculated anyway. The shadow resolution was set to a medium quality level.

The Forward rendering path was set on the Graphics card, which guarantees compatibility with the greatest number of devices compared to deferred mode. We describe now how the lighting system was configured, since it is well known that this is one of the aspects that most affects the rendering performance of a three-dimensional environment.

To try to contain the required computational capabilities as much as possible, we have disabled the real-time rendering of the lights, preferring instead to calculate them at compile time. To do this we deselected the RGI (Realtime Global Illumination) and we activated the "Baked Global Illumination". This operation requires that the objects should be defined with the "Static" property. All the objects that are part of the setting was therefore set as "Static" and the light bulbs that illuminate the scene was set with "Baked" type of light. This lighting calculation methodology pre-calculates how the light will affect the objects and elements in the scene by saving the calculated information in the LightMap. In total we defined 4 lights in the scene: the sun, the light in the room, the lights coming from the left bedside table and the right bedside table. The lights in the room are all Point Light set with the Baked type lighting mode. The sun is mimicked via a directional light in Mixed calculation mode. This calculation mode allows to take advantage of the pre-calculation (baking) of the lighting that interacts with static objects but leaves the rendering engine the ability to correctly calculate the lighting of any moving objects.

The patient will find in the room several moving objects that once clicked will perform a short animation that provides the user with feedback on the correctness of the action performed. The number of Direct samples was set to 32 and the number of indirect samples to 128. Our tests showed these values are an excellent balanced set that allows to obtain a good graphic quality while consuming few resources. Furthermore, environmental occlusion was activated to further improve the visual rendering. The Lightmaps obtained therefore has a size of 9x32x32px and occupies a space of 144 KB of memory. To minimize the space it occupies, we compressed it to obtain a size of 48.5KB. Also on the Player tab of the Project Settings panel we needed to set the Graphics API in order to use WebGL 1.0 instead of WebGL 2.0. This operation let us further reduce the size occupied by the compiled project while maintaining a comparable graphic quality.

5.2. Polygonal complexity and texture

Then we worked and thoroughly analyzed how to optimize the objects that make up the scene. Each single object has been processed and analyzed one by one, in order to minimize the number of polygons, finding the right balance between polygonal complexity and graphic quality. This is an operation that cannot in any way be defined a priori and strongly depends on the type of object. For example, the cushions that are placed above the bed can have a very high compression, while the polygonal model of a shoe due to its shape and structure requires more definition to be appreciated on the screen.

Object compression was done using two technologies: the first is through the Blender software, the second is provided directly by Unity which allows by the Mesh Inspector to obtain a copy of the object model that gets compressed and directly saved in the project file system. To do this we did set the Mesh Compression and the Optimize Mesh for each object by calibrating the parameters one by one. Furthermore, following all these intermediate steps, we recalculated the Normals for each object by generating the individual UV LightMaps that tell the graphic engine how the light should interact with the shape in the scene.

We also paid great attention to the textures we wanted to examine and study. First of all, textures were chosen so that they could create a contrast with the background and did not overlap the colors with each other in order to improve accessibility for users.

5.3. Compiler Optimizations

The last optimization phase was dedicated to the final compression of the project and to the study of the techniques that allow to reduce as much as possible the waiting time for the loading and start-up phase of the project. Unity provides different ways to export a project to WebGL:

- Without any kind of compression, the project has a large memory occupation and requires a considerable amount of time and bandwidth to be downloaded. Because of this difficulty we decided not to choose this option.
- Gzip, the project is compressed using the famous algorithm designed by Jean-loup Gailly, widely used in Unix systems and published for the first time in 1992
- Brotli, a compression algorithm born in 2013 and developed by Google. This algorithm is particularly efficient when it has to compress texts.

It is also possible to choose between two ways to export the code that makes up the project:

- ASM, this is the "legacy" mode. The JavaScript code is optimized and exported in bytecode through the JavaScript interpreter.
- Web Assembly streaming, permits to export the code in binary format and does not require any parsing since it is ready to run. The code is also compressed to save additional space. Its execution speed is almost comparable to what we would have achieved natively using machine code.

 doi:10.20944/preprints202012.0331.v1

From the preliminary tests we observed that the best combination was WebAssembly Streaming with Brotli compression. To validate this preliminary result we analyzed and studied in depth how these technologies affect the size of a WebGL project and its start-up time, taking into account a wide variety of hardware. With this analysis we could precisely determine the best possible combination for our purposes.

5.4. The obtained results

In total we tested 17 different devices among smartphones and tablets. The devices which the software has been tested with belong to different brands, have different CPU and GPU architectures and have different operating systems, including Android, Windows, Linux, and MAC Os. This wide variety of hardware has made it possible to systematically compare several kinds of the most common used hardware so that we can have a clear idea of how the program behaves with the various compilation technologies and what type of experience the end user will get. Eight different projects, which used several combinations of technologies, was tested for every single device. These are:

- WebGL 2.0 with Gzip and Web Assembly Streaming
- WebGL 2.0 with Gzip without Web Assembly Streaming
- WebGL 2.0 with Brotli and Web Assembly Streaming
- WebGL 2.0 with Brotli without Web Assembly Streaming
- WebGL 1.0 with Gzip and Web Assembly Streaming
- WebGL 1.0 with Gzip without Web Assembly Streaming
- WebGL 1.0 with Brotli and Web Assembly Streaming
- WebGL 1.0 with Brotli without Web Assembly Streaming

We have summarized the results obtained in tables to make them easier to read. In table 1 we carry out the analysis for WebGL 1.0 platform and we tested the combinations of Gzip or Brotli, with and without Web Assembly Streaming.

In table 2 we carry out a similar study for the WebGL 2.0 platform. In the tables we reported the project's loading times.

Each device was tested by resetting and clearing the browser cache and using the anonymous navigation mode in order to have the most accurate test as possible. The loading times are reported according to the notation: *minutes:seconds:hundredths of a second*. Since most of the times the project compressed when Brotli and Web Assembly Streaming were active was faster, we produced a summary table 3 that shows the final results obtained comparing this type of compilation when using WebGL1.0 and WebGL2.0.

As it can be seen some very old and outdated devices such as Samsung Galaxy S4 are not compatible with WebGL2.0 while they are able to run the project with WebGL1.0.

The results obtained show that between the two versions WebGL1.0 is faster than WebGL2.0. Finally, in table 4 the size of the projects in MB is reported. As it can be seen the exported project using WebGL1.0 technology, Brotli and WebAssembly Streaming occupies 8,189MB, proving to be the lightest and most efficient combination for WebGL projects.

6. The Demo exercises

The Demo presented in this project represents an evolution for the tele-rehabilitation exercises already uploaded in the Nu!Reha Platform. It allows not only to further extend the potential of the platform, but also to extend the available possible practices, exploiting a three-dimensional setting and the possibility of creating quickly various scenarios through the use of rapid prototyping.

Demo A involves the patient, asking her/him to identify non-contextual objects within a room. The objects that have been chosen are simple and unequivocal, so as to be sure that the error is due to a difficulty inherent in the subject rather than due to the type of stimulus to be recognized or individual variables. The objective of this activity is to train the executive functions of the subject and more particularly his ability to categorize. In fact, the objects placed inside the room must firstly be

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 December 2020 doi:10.20944/preprints202012.0331.v1

Device	Year	Operative System / Browser web	*WebGL 2.0 Gzip no stream*	*WebGL 2.0 Gzip WAS*	*WebGL 2.0 Brotli no stream*	*WebGL 2.0 Brotli WAS*
Asus Zenfone 5	2018	Android 9 Chrome 85	*00:20.21*	*00:17.05*	*00:14.27*	*00:16.10*
Amazon Fire HD 8	2017	Fire OS 6 Chrome 84	*00:20.00**	*00:20.43**	*00:21.59**	*00:12.63**
Samsung Galaxy Tab E	2015	Android 4.4.4 Chrome 81	*No webGL2.0*	*No webGL2.0*	*No webGL2.0*	*No webGL2.0*
Huawei MediaPad M5 lite	2019	Android 8 Chrome 84	*00:45.36*	*00:45.67*	*00:42.54*	*00:28.87*
Samsung Galaxy S7	2016	Android 8 Chrome 84	*00:08.992*	*00:06.522*	*00:09.262*	*00:06.075*
Samsung Galaxy S4 Active	2013	Android 5.01 Chrome 85.0.4	*No webGL2.0*	*No webGL2.0*	*No webGL2.0*	*No webGL2.0*
DESKTOP CUSTOM	2014	Windows 10 Chrome 84	*00:02:440*	*00:01:980*	*00:02:830*	*00:01:650*
Asus GL502VM	2018	Windows 10 Chrome 84	00:02.900	00:02.138	00:02.776	00:01.818
Hp prodesk 400 g1	2013	Ubuntu 18.04 Firefox 79	00:03:040	00:02:640	00:03:480	00:02:230
DESKTOP CUSTOM	2012	Windows 10 Firefox 79	00:08:100	00:08:714	00:08:139	00:07:312
Redmi Note 8 Pro	2019	Android 10 Chrome 84	00:22:21	00:14:34	00:23:07	00:16:54
Acer Swift SF314-52	2018	Windows 10 Firefox 79	00:15:13	00:14:37	00:14:46	00:12:30
Honor 8	2016	Android 10 Chrome	00:19:20	00:19:09	00:21:26	00:15:17
HP-PC ProBook 450 G6	2018	Manjaro Chromium	00:11:78	00:10:16	00:09:45	00:09:01
ASUS H81M-D R2.0	2015	Mint 20 Mozilla Firefox	00:11:94	00:10:29	00:09:71	00:10:13
MacBookPro 14.2	2017	macOS 10.15 Safari	No webGL2.0	No webGL2.0	No webGL2.0	No webGL2.0

Table 1. WebGL1.0 comparison

recognized by the subject and secondly defined as belonging to the category "typical objects present in the bedroom" or not. Demo B, instead, requires the patient to remember a list, made up of a variable number of objects positioned in an unconventional way in a room. The two demos have several aspects in common, in fact both follow a very precise structure:

- explanation of the task that the user has to perform, both in a textual and auditory way.
- objects randomly appear in the room during the execution of the exercises, as shown in Figure 2; if the user correctly clicks on one of them, there is a positive audio reinforcement and the object rotates and disappears. Whereas only a negative audio reinforcement is returned if the object is in the right context, which means a user failure.
- feedback on the results are expressed with some stars and based on the ratio between the total number of clicks and the number of correct objects found. The score is expressed in such a way so that the patient does not feel frustrated even if she/he obtained a bad score. Moreover phrases have been added to encourage the patient to keep on doing exercises in order to improve.

In addition, input variables and output variables have been associated to both of them: the input variables are parameters that can be set by the specialist, in order to customize the activity according to the skills and needs of their patients.

The output variables instead, represent those parameters that are traced during the execution of the activity and that allow the therapist to monitor the rehabilitation path carried out by each patient.

Although they both share a common activity structure, the two demos present significant differences from a technical and clinical point of view.

Device	Year	Operative System / Browser web	*WebGL 1.0 Gzip no stream*	*WebGL 1.0 Gzip WAS*	*WebGL 1.0 Brotli no stream*	*WebGL 1.0 Brotli WAS*
Asus Zenfone 5	2018	Android 9 Chrome 85	*00:14.72*	*00:17.92*	*00:13.57*	*00:09.51*
Amazon Fire HD 8	2017	Fire OS 6 Chrome 84	*00:18.75*	*00:12.51*	*00:20.07*	*00:12..62*
Samsung Galaxy Tab E	2015	Android 4.4.4 Chrome 81	*01:31.88**	*01:05.34**	*01:35.25**	*01:01.57**
Huawei MediaPad M5 lite	2019	Android 8 Chrome 84	*00:26.71*	*00:33.68*	*00:31.73*	*00:26.54*
Samsung Galaxy S7	2016	Android 8 Chrome 84	*00:09.473*	*00:06.699*	*00:08.421*	*00:05.708*
Samsung Galaxy S4 Active	2013	Android 5.01 Chrome 85.0.4	*00:18:570*	*00:15:860*	*00:24:320*	*00:15:650*
DESKTOP CUSTOM	2014	Windows 10 Chrome 84	*00:02:550*	*00:01:810*	*00:02:550*	*00:01:250*
Asus GL502VM	2018	Windows 10 Chrome 84	00:02.962	00:01.922	00:02.914	00:01.816
Hp prodesk 400 g1	2013	Ubuntu 18.04 Firefox 79	00:03:150	00:02:480	00:03:550	00:01:980
DESKTOP CUSTOM	2012	Windows 10 Firefox 79	00:08:371	00:07:560	00:06:921	00:05:620
Redmi Note 8 Pro	2019	Android 10 Chrome 84	00:18:37	00:12:02	00:11:30	00:19:08
Acer Swift SF314-52	2018	Windows 10 Firefox 79	00:11:57	00:10:36	00:11:50	00:13:32
Honor 8	2016	Android 10 Chrome	00:14:50	00:27:15	00:18:14	00:22:58
HP-PC ProBook 450 G6	2018	Manjaro Chromium	00:11:59	00:09:79	00:10:09	00:09:45
ASUS H81M-D R2.0	2015	Mint 20 Mozilla Firefox	00:10:28	00:11:57	00:08:92	00:08:54
MacBookPro 14.2	2017	macOS 10.15 Safari	No webGL1.0	No webGL1.0	No webGL1.0	No webGL1.0

Table 2. WebGL2.0 comparison

Demo A is not so structured from the point of view of programming, as the scenario remains fixed, whereas in Demo B the spatial exploration has been implemented and made possible by the use of directional arrows (the exploration is only permitted on the horizontal plane and not on the vertical one).

However, this technical difference also has a resonance on the clinical level because in the second case the user has to apply particular skills, such as visual-spatial orientation and eye-manual coordination. On the clinical level, finally, we choose to train different functions simultaneously. While in Demo A the patient primarily exercises categorization, in the other case we aim to train both the subject's mnemonic skills (working memory) and cognitive functions, with particular attention to cognitive flexibility.

The point is not only to remember what objects can be found inside a room, but also to be able to recognize them in an unusual perspective and position. We have chosen to insert a "HELP" key in the training screen: so the subject will be able to listen again to what objects she/he has to find inside the room. She/he can press the button and access the Help menu everytime it is thought to be necessary.

However, this kind of actions are recorded and taken into account when the final score is assigned. The target objects found, the time to complete the activity and the errors made are all traced and stored. These last output variables are traced in the Demo A as well. In this way, during the monitoring of the

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Device	Year	Operative System / Browser web	*WebGL 2.0 Brotli WAS*	*WebGL 1.0 Brotli WAS*
Asus Zenfone 5	2018	Android 9 Chrome 85	*00:16.10*	*00:09.51*
Amazon Fire HD 8	2017	Fire OS 6 Chrome 84	*00:12.63**	*00:12..62*
Samsung Galaxy Tab E	2015	Android 4.4.4 Chrome 81	*No webGL2.0*	*01:01.57**
Huawei MediaPad M5 lite	2019	Android 8 Chrome 84	*00:28.87*	*00:26.54*
Samsung Galaxy S7	2016	Android 8 Chrome 84	*00:06.075*	*00:05.708*
Samsung Galaxy S4 Active	2013	Android 5.01 Chrome 85.0.4	*No webGL2.0*	*00:15:650*
DESKTOP CUSTOM	2014	Windows 10 Chrome 84	*00:01:650*	*00:01:250*
Asus GL502VM	2018	Windows 10 Chrome 84	00:01.818	00:01.816
Hp prodesk 400 g1	2013	Ubuntu 18.04 Firefox 79	00:02:230	00:01:980
DESKTOP CUSTOM	2012	Windows 10 Firefox 79	00:07:312	00:05:620
Redmi Note 8 Pro	2019	Android 10 Chrome 84	00:16:54	00:19:08
Acer Swift SF314-52	2018	Windows 10 Firefox 79	00:12:30	00:13:32
Honor 8	2016	Android 10 Chrome	00:15:17	00:22:58
HP-PC ProBook 450 G6	2018	Manjaro Chromium	00:09:01	00:09:45
ASUS H81M-D R2.0	2015	Mint 20 Mozilla Firefox	00:10:13	00:08:54
MacBookPro 14.2	2017	macOS 10.15 Safari	No webGL2.0	No webGL1.0

Table 3. Synthetic comparison of the results

activities, the operator can distinguish if the subject has mainly got a working memory deficit or if he presents difficulties in both areas.

The exercises have a maximum duration, after that if the user did not find all the non-contextual objects, she/he will receive a negative score.

It is possible to add additional sentences linked to audio tracks. The text part will be displayed on screen while the corresponding audio will be played and, at the end of the audio, the program will automatically pass to the next sentence, loading its audio track. As soon as the explanation of the exercise is finished, another program is launched for randomly visualize the objects in the room. The program selects a series of coordinates inside the room and positions the objects one by one in the selected coordinates, taking them from the set of objects previously chosen by the doctor and checking that there are no overlapping objects or empty areas of the scene. This part has been developed to prevent the patient remembering a certain sequence of areas where to click, trying to stimulate his ability to promptly recognize which objects do not belong to the shown room context.

Each non-contextual object is linked to the scripts that allow the rotation, its disappearance and the expression of a positive reinforcement, while in the case of non contextual object it has been assigned a negative reinforcement.

 doi:10.20944/preprints202012.0331.v1

Project	**Size in MB**
WebGL 1.0 Gzip	9,965
WebGL 1.0 Gzip WAS	9,967
WebGL 1.0 Brotli	8,189
WebGL 1.0 Brotli WAS	8,189
WebGL 2.0 Gzip	10,454
WebGL 2.0 Gzip WAS	10,455
WebGL 2.0 Brotli	8,560
WebGL 2.0 Brotli WAS	8,564

Table 4. Size of the exported project

Figure 2. A screenshot taken form the Demo example representing the objects that will be randomly arranged in the room

The rotation script, as soon as the mouse click on the object is detected, rotates the object of 180 degrees, emitting a sound that express the correct execution of the exercise. Then, if the object is not contextual, the script that makes the positive reinforcement and remove the object from the scene will be activated. In this case we simplify as much as possible the understanding of the exercise by the patient, since the script removes from the scene the elements already discovered and facilitates the identification of the remaining ones.

7. Conclusions and future works

The present paper describes our recent activity devoted to the improvement of tele-rehabilitation exercises for patient affected by various types of impairments through a Virtual Reality environment based on an efficient combination of Blender and Unity3D components, which enables the therapist to use a rapid prototyping environment.

The described Demo exercises allows to train cognitive functions such as memory, attention and executive function. The therapist can customize the difficulty of the activities according to the patient's abilities and can enrich the virtual experience adding to the virtual scene objects that are familiar to the patient, reinforcing the positive effects of the exercise itself.

The virtual environment empowers the Nu!Reha Service with a series of rehabilitation exercises which can be rapidly deployed and customised according to the type of the patient's impairments.

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Figure 3. A screenshot taken form the Demo example

A careful and in-depth study was carried out to optimise the size of the applications developed in Unity3D so that these exercises can be run with excellent performance and graphic quality on any device on the market today. This is of great importance in order to allow the use of the Nu!Reha Service by the patient with a BYOD approach, which makes the execution of the exercises even more effective and friendly, thus increasing their scope and positive effects.

Our future work in this area is aimed at testing and optimising new pathways and technologies to make cost-effective, easy-to-use and, above all, effective tools available to patients facing post-trauma rehabilitation. Continuous collaboration with the team of rehabilitation experts is vital for us to focus the use of different technologies on overcoming specific patient problems.

8. Author contributions

Conceptualization, Martina Fortunelli, Riccardo Magni, Jessica Carloni and Osvaldo Gervasi; Data curation, Damiano Perri; Formal analysis, Martina Fortunelli, Riccardo Magni, Jessica Carloni; Investigation, Damiano Perri, Martina Fortunelli, Marco Simonetti, Riccardo Magni, Jessica Carloni and Osvaldo Gervasi; Methodology, Martina Fortunelli, Riccardo Magni and Osvaldo Gervasi; Software, Damiano Perri; Martina Fortunelli; Supervision, Riccardo Magni, Osvaldo Gervasi; Validation, Damiano Perri, Marco Simonetti, Martina Fortunelli and Jessica Carloni; Visualization, Marco Simonetti; Writing – original draft, Damiano Perri, Martina Fortunelli, Marco Simonetti, Riccardo Magni, Jessica Carloni and Osvaldo Gervasi; Writing – review & editing, Damiano Perri, Martina Fortunelli, Marco Simonetti, Riccardo Magni, Jessica Carloni and Osvaldo Gervasi. **Funding:** “This research received no external funding”

Acknowledgments:

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
AT	Assistive Technology
BYOD	Bring Your Own Device
CNS	Central Nervous System
CPU	Central Processing Unit
DOAJ	Directory of open access journals
GPU	Graphic Processing Unit
HTTP	Hyper Text Transfer Protocol
ICF	International Classification of Functioning, Disability and Health
IIOT	Industrial Internet of Things
IOT	Internet of Things
I/O	Input / Output
JSON	JavaScript Object Notation
MCU	Micro Controller Unit
MDPI	Multidisciplinary Digital Publishing Institute
MPU	Micro Processing Unit
OS	Operating System
RAD	Rapid Application Development
RAM	Random Access Memory
REST	Representational State Transfer
RGI	Realtime Global Illumination
UV	Represent the u,v graphic coordinates
VR	Virtual Reality
VRAM	Video Random Access Memory

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