D7.1 ReHyb Interaction Scenario Development

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The REHYB Consortium consists of the following partners:

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3	Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna (SSSA)	IT
4	Össur hf (OSS)	IS
5	TECNALIA Research & Innovation (TECN)	ES
6	Imperial College London (ICL)	UK
7	Institute for Bioengineering of Catalonia (IBEC)	ES
8	Technical University of Denmark (DTU)	DK
9	Stelar Security Technology Law Research UG (STELAR)	DE
10	Schön Klinik Bad Aibling SE & CO. KG (SK)	DE
11	Congregazione Suore Infermiere dell’Addolorata (VALDUCE)	IT

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Executive Summary

The development of digital health solutions grounded on science-based principles is fundamental for the design and validation of novel interventions for stroke recovery that can be deployed to the patients' homes and can adapt to individuals' needs.

Our goal is to identify all the requirements needed for the optimal design of interactive gaming scenarios and their subsequent mapping into a personalized treatment plan for the rehabilitation of stroke patients. We aim to use principle-based rehabilitation paradigms and serious games to promote post-stroke motor and cognitive recovery for at-home use. We want to enable stroke patients to operate in a gamified environment and promote a sense of empowerment and a positive mind-set to engage with the rehabilitation system. To do this, we will develop and test gamified scenarios using Virtual Reality and Augmented reality technologies interfaced via the Rehyb interaction engine to the Rehyb robotic system. The training scenarios will be developed considering the user requirements or "personas." The training environments are designed to integrate the users' inputs via adapting the training recommendations to the users' internal states . This will ensure that the system adapts to individual needs. Our scenarios capitalize on a series of empirical results to target experience-dependent cortical plasticity to promote the acquisition, retention, and generalization of motor and cognitive skills. The motor and cognitive programs we develop here, on the one hand, take into consideration the feedback from clinical partners and the requirements from the different modules of the project; on the other hand, generalize to the Activities of Daily Living (ADLs) and introduce the users to a wide range of exercises, tasks and movement ranges. The Rehyb system will adapt the training recommendations to ensure that the user takes charge of the training strategy via the user's inputs and performance.

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1 Introduction

This section provides the introduction to the report, highlights its key objectives, and outlines the report structure.

1.1 Objectives

The ReHyb[1] Project Deliverable 7.1 is a report on Task T7.1 focused on developing virtual reality (VR) and augmented reality (AR) based interactive scenarios designed to be used as training protocols for the rehabilitation of stroke patients. These protocols are grounded on clinical expertise and the requirements of the identified "personas" and previous research conducted by the consortium members on the recovery of motor and cognitive function after stroke. The rehabilitation scenarios developed in this task will capitalize on the Rehabilitation Gaming System (RGS), previously developed and validated at the Institute of Bioengineering of Catalonia (IBEC). In a collaborative effort, the IBEC's group SPECS Lab and the Technical University of Denmark (DTU) are now exploring new solutions for gamified rehabilitation protocols targeting Activities of Daily Living (ADLs). The use of VR and AR interfaced to robotic exoskeletons and digital twin technologies intends to help and empower the users/patients toward their motor and cognitive recovery. In the following chapters, we will describe the use cases, the technologies, and the methodologies used to address our objectives and the results obtained so far.

1.2 Structure of the Deliverable

Following this introduction, in Section 2 we will provide an overview of all the activities and an introduction to the terminology and theory used in this report, such as neurorehabilitation principles, learned non-use, recovery, etc. (section 2.1). Additionally, we will briefly describe the technology used in this project, including augmented and virtual reality, serious games, and the digital twin (section 2.2).

According to the objectives of D 7.1, section 2.3 focuses on the selection and definition of the RGS-based scenarios. To achieve this task, a set of rehabilitation protocols were proposed and selected. Based on the results of the demo at Villa Beretta (VB), together with the feedback from the clinicians (Valduce, SK) and the needs of the different "Personas" (WP2), The selected protocols are explained in more detail under section 2.4 together with their specific motor and cognitive components. Section 2.5 illustrates the process of tailoring the rehabilitation scenarios to the patients or "personas", based on WP2.

In Section 3, we provide a detailed description of the Serious Gaming scenarios, their functionality, technical implementation, and how they relate to the set of Activities of Daily Living proposed in work package (WP2), and specific individualization proposals (3.1-3.4). In addition, section 3.5 references the ReHyb project's KPIs that relate to the work within the interaction scenarios and how there are going to be accomplished.

Finally, in Section 4 we describe the development process and technical implementation of these protocols in VR and AR technologies, together with future steps to be conducted during the months of April and May, 2021. We finalize the report with the conclusions and future work, in Section 5.

The report includes a full list of references , and two appendices:

- Appendix I provides more images of the Serious Games.
- Appendix II reports a full list of definitions, acronyms, and abbreviations used along the report.

[1] https://rehyb.eu/

2 Overview and Activities Description

This section describes the problem statement and background that support the choice for the design of our VR and AR-based interactive scenarios:

1. Activities of Daily Living (ADLs), what they are, and their relevance to maintain quality of life during aging and after suffering a disease such as a stroke.
2. Learned non-use (LNU), a phenomenon that affects motor function after stroke in which the movement of the paretic limb is suppressed due to failure of attempted movements during activity performance. Later, we describe the meaning of recovery and the theory which supports the evidence-based design of the training scenarios.

After that, we describe the technologies and paradigms we use to address these challenges, namely:

1. VR and AR-based technology and gamification and the rationale behind them to develop scenarios for rehabilitation post-stroke.
2. Robotics interfaces.
3. Digital twin and modularity paradigms for continuous advised support and monitoring.

2.1 Problem Description and Investigated Paradigms

The socioeconomic burden of stroke will increase in the coming years due to the global aging of the world's population (Wafa *et al.*, 2020). Additionaly, the COVID19 situation, together with limited resources at healthcare facilities, has caused a tremendous strain on stroke care and denied stroke patients the necessary rehabilitation care (Rudilosso *et al.*, 2020). This situation calls for remote interventions and digital health strategies that can face up the challenge. The development of digital solutions based on scientifically-grounded training paradigms becomes then fundamental for the near-future design of novel interventions for stroke recovery that can be deployed at the patients' home and adapt to individuals' needs (WP3 – Cognitive Architecture).

2.1.1 *Activities of Daily Living (ADLs)*

Activities of Daily Living (ADLs) refer to tasks typically performed at home for self-care and functional living. [Katz et a. 2013] One's ability to independently complete ADLs can be used as a measurement of self-sustainability and is an important target for rehabilitation activities after physical and neurological damage. Individuals that suffer from neurological disorders can have diminished abilities to complete ADLs. The degree of functional independence while performing ADL is not only an important factor for the quality of life of the patients. Still, it is also used as an operationalization process to assess motor recovery. As such, some of the clinical scales commonly used in clinical practice measure the capability of the patient to perform these activities without external assistance (Wolfe et al., 1991; Mayo et al., 2000). Indeed, conventional rehabilitation techniques, such as Occupational Therapy (OT), focus on helping patients regain independence in performing ADL. However, the extent to which functional gains result from the recovery of lost motor patterns and/or the development of compensatory movements and how rehabilitation influences these processes are unclear. In other words, conventional approaches that focus on promoting patients' independence in ADLs might result in compensatory behaviors and not "true" recovery of motor patterns (Levin, Kleim, and Wolf, 2009). Although one could argue that being able to perform the ADL independently should be the goal of recovery, compensation might not be the right strategy to achieve it. It is suggested that therapy should focus on changing impairment and not on modulating function, performance in ADL or quality of life because reducing impairment more likely reflects true biological repair mechanisms (Krakauer et al., 2012). Also, suppose the patient can compensate for a lost function instead of being animated to restore it. In that case, the impairment will continue to be present and could interfere with long-term functional outcomes.

Moreover, silent motor and cognitive deficits might go unnoticed because the patient appears to be fully functional in ADL (Hylin et al., 2017), impeding adequate therapy. However, clear evidence that compensation impedes a return to normal neurological functioning is still missing (Kwakkel, Kollen, et al., 2004). The goal, thus, is to enable the patient to regain the same or close to the same pre-stroke movement patterns while as far as possible controlling for compensation.

2.1.2 *Learned Non-Use (LNU)*

A common issue in post-stroke recovery is that some patients worsen their motor function once discharged from hospital facilities (Van De Port *et al.*, 2006). Taub (Taub *et al.*, 2006) proposed the concept of "learned non-use" to account for part of the persistent limb motor deficit after certain types of neurologic injury. Concretely, LNU can be defined as the discrepancy *between residual functional capacity* and *reduced use* of the affected limb (Hirsch *et al.*, 2020). In other words, the patient could be using the arm but does not. As such, learned non-use could be seen as a specific form of compensation, as the patients could be successful in performing ADL, however, by relying on the healthy limb for doing so.

It is thought that LNU might arise through the combination of an initial suppression due to increased cost and neurological changes and a learning mechanism through unsuccessful attempts of any activity performed with the affected limb over time. Although the affected limb regains functionality, the continuous suppression of use might lead to a decreased neural representation, which constitutes a vicious cycle of function deterioration. Importantly, it has been suggested that the use of the paretic arm beyond a certain threshold might lead to increased neural representation, which in turn facilitates the spontaneous incorporation of the arm in future actions (Han, Arbib and Schweighofer, 2008). This is stated as the "*Use it and improve it or lose it*" dogma in motor recovery and emphasizes the need to promote activity at the home of the patients (Hidaka *et al.*, 2012).

Some approaches try to reverse the LNU vicious cycle by forcing the patients to use their affected limb. For instance, in Constraint-Induced Movement Therapy (CIMT), this is achieved by constraining the use of the healthy arm together with intensive training of the paretic arm to counter-condition the non-use (Kwakkel *et al.*, 2015). However, recent studies provide novel alternatives to bias the effector selection through a less demanding reinforcement to the patients. This is the case of Reinforcement Induced Movement Therapy, where using virtual reality, the visual amplification of the actions performed with the affected arm shift the decision-making processes of arm use and promote functional outcomes of the patient (Ballester & Maier et al., 2016, Ballester et al., 2015)

Hence, the goal of our rehabilitation scenarios is to positively promote the use of the paretic limb during ADL to counteract learned non-use and prevent further deterioration. This is achieved by building training scenarios in VR and AR that reinforce the use of the paretic limb during goal-oriented actions inherent to ADL. The use is reinforced through various gaming mechanisms (or principles of neurorehabilitation (Maier, Ballester and Verschure, 2019)) that are incorporated in each training scenario. For instance, we will incorporate embodied practice from a first-person perspective, which provides implicit feedback, rewarding successful movements with the paretic limb, which provides explicit feedback, adjusting the difficulty of the training to the ability of both the paretic and non-paretic limb, fostering bimanual movements during goal-oriented actions. One of the reasons for using VR and AR-based solutions is that these neurorehabilitation principles can be better implemented and more controlled in virtual than physical reality (Maier *et al.*, 2020).

2.1.3 *Neurorehabilitation Principles*

What is the evidence behind using the principles mentioned above of neurorehabilitation? A typical phenomenon observed after a stroke is the spontaneous brain network reorganization and increased responsiveness to enriched environments and training programs (Ward, 2017). Innate biological mechanisms such as forming new neurons and glia, axonal sprouting, or enhanced plasticity are nearly unique to the *damaged* brain. They are thought to be one of the main reasons for the recovery observed during early stages post-stroke (Zeiler and Krakauer, 2013). Building upon these mechanisms, novel approaches to neurorehabilitation capitalize on *experience-dependent* processes of cortical plasticity to boost recovery. Recent research provides a unification of the neuroscientific literature relevant to this recovery process, bringing together a set of neurorehabilitation principles that promote the acquisition, retention, and generalization of skills (Maier, Ballester and Verschure, 2019). These principles are based on a series of human and animal studies about motor learning and adaptation, and are listed in a comprehensible list below:

Massed practice, spaced practice, dosage, task-specific practice, goal-oriented practice, variable practice, increasing difficulty, multisensory stimulation, rhythmic cueing, explicit feedback/knowledge of results, implicit feedback/knowledge of performance, modulate effector selection, action observation/embodied practice, motor imagery, and social interaction.

For the aforementioned reasons, the design of the proposed protocols is strongly grounded on these neurorehabilitation principles to promote *true* recovery of motor and cognitive function. (Belén Rubio Ballester *et al.*, 2019; Maier *et al.*, 2020). By promoting the use of the paretic limb and increasing its functionality, we hypothesize that the patients can overcome compensation and reliance on the less affected limb, hence enhancing the performance in ADLs.

2.2 Technologies

Technology may serve as one of the enablers that facilitate implementing the above-mentioned principles in rehabilitation routines and thus support the post-stroke rehabilitation process. Below, the following technological concepts and approaches to technology are described: (1) Augmented and Virtual Reality (AR and VR) concerning stroke; (2) Serious Games; (3) Exoskeleton; (4) Digital Twin; and (5) Modularity.

2.2.1 *Augmented and Virtual Reality in Stroke Care*

Augmented reality (AR) and virtual reality (VR) are becoming increasingly used tools in health care and rehabilitation activities. [Yeung et al, 2021]. VR allows to create and enhance the sensorimotor and cognitive activity for a person in an artificially-created controlled virtual environment. AR is the overlay of digital information presented as a hologram on the real world in the users' environment, which allows for shared experiences. [Andrews et al. 2019] VR separates the user from physical reality into a virtual world. VR can offer an immersive and controlled environment where healthcare practitioners can regulate stimuli to achieve objectives such as coping with pain, overcoming fears, and rehabilitating cognitive and physiological impairments. The use of these technologies allows for the controlled application of neurorehabilitation principles in stroke therapy. (Maier, Ballester, Duff, Duarte Oller, & Verschure, 2019). Importantly, VR therapies that apply those (i.e., through the use of the RGS) show superiority over standard care (Maier, Ballester, Duff, et al., 2019) and that patients training with those therapies appear to be still sensitive to improvement even one year post-stroke onset (Ballester et al., 2019). This holds not only for the motor domain but can be generalized as a holistic strategy that enhances cognitive (Maier *et al.*, 2017) and language function (Grechuta *et al.*, 2019) over standard care. The content provided to patients in AR or VR as part of this project will be in the form of serious games or training scenarios to be conducted at home following these evidence-based notions.

2.2.2 *Embodied Practice*

In our protocols that use virtual or augmented reality, the patient embodies a virtual avatar and controls it from a first-person perspective. In all cases, the actions of the user are congruent with the visual feedback of the avatar. This choice was made because the visuomotor match of intended actions is one of the main factors influencing Body Ownership (BO) (Tsakiris and Haggard, 2005). Specifically, research from the moving Rubber Hand Illusion dictates a fundamental relationship between Agency (i.e., volitional actions from the participant) and ownership (Haggard, 2005) . Indeed, the sense of the body as being *one's own* depends on the processing of sensory and motor signals that accompany every bodily activity (De Vignemont, 2011). There is a general agreement that priors about different physical properties of the body also influence ownership towards artificial effectors. In other words, anatomical resemblance, peripersonal space, and spatial congruence are important factors in the emergence of BO (Tsakiris, 2010). For this reason, the virtual hands of the avatar are always human-resemblant and appear in a coordinates reference frame within the peripersonal proximity of the patients' body.

2.2.3 *Serious Games*

Serious games are games developed for the purpose beyond entertainment [Djaouti et al. 2011]. This does not mean they lack entertaining elements, as many are developed utilizing gamification techniques and are built using popular game engine platforms such as Unreal and Unity. Gamification of education and the use of serious gaming for learning stimulation is an increasingly common practice (McGlarty et al., 2012). In particular, serious games have gained recognition in healthcare, where they have been used to train healthcare professionals (Gentry et al., 2019; Wang, DeMaria, Goldberg, & Katz, 2016) to support patient rehabilitation (e.g., Koutsiana et al., 2020) and for the treatment of chronic diseases (e.g., Kharrazi, Faiola, & Defazio, 2009).

The key advantages of serious games include, among others, a) personalized experience, b) behavioral change due to increased engagement and motivation, and c) provide an appealing, context-based environment for training (McGlarty et al., 2012). This could mean, for example, allowing the user to practice everyday social situations without leaving home or adjusting the context of the training to one's interests or needs. In this report, we describe the development and design of serious gaming scenarios specifically targeting post-stroke rehabilitation at home to support the rehabilitation of both motor and cognitive functions. An important aspect of serious gaming scenarios is their adaptability to the user, allowing an individualized approach to the rehabilitation process (Nirme, Duff and Verschure, 2011). Individualization of rehabilitation programs has been previously shown to be a significant factor in reducing the length of treatment and the likelihood of re-hospitalization in the future, as well as increasing adherence to exercises (Clark, Catto, Bowman, & MacIntyre, 2011).

In addition, the use of distinctive clinical measures and biomarkers to predict recovery potential for individual patients has been shown to increase rehabilitation efficiency in patients after stroke (Stinear, Byblow, Ackerley, Barber, & Smith, 2017). In this sense, through the training scenarios interface, we log data from kinematics, game events (e.g., successful reachings), bilateral performance, difficulty parameters, physiological data (e.g., Empatica E4, eye-tracking…) to provide an enriched estimation of the user state and evolution. This will also help us better understand the phenomenon of learned non-use or compensation and aids in assessing the use of the paretic limb during ADLs. Thus, we consider adaptability and individualization essential to include when designing serious gaming scenarios, which is further explained in the subsequent sections of this report. Here we provide the building blocks that will be used to interface with other modules of the project. For example:

- The 3D coordinates of the virtual hands and targets are used to estimate user intention and inform FES and the powered Exoskeleton (SSSA, TUM).
- The difficulty modulators, together with the physiological data gathered through the Empatica E4, are used to estimate internal states such as cognitive, motor fatigue, or stress (IBEC).
- The difficulty modulators inform the cognitive architecture and the Digital Twin (see below) to adapt the environment based on patients' capabilities (DTU, IBEC).

Deliverable 7.3 dives into the real-time adaptability of the serious games to the patients' needs and the exoskeleton's capabilities. This adaptability will rely on the digital twin engine (developed for deliverable 3.5) to run simulations and create models for personalizing rehabilitation sessions and games' parameters to meet the patient's needs.

2.2.4 *Exoskeleton*

The exoskeleton developed by the ReHyb consortium partners is a modular and adaptive wearable robotic system to aid the stroke patient-user during rehabilitation and while conducting ADLs at home. The two types of exoskeleton, the active one, a powered version enabling robotic assistance, and the passive one, a spring-loaded version, are being designed with modular components that range from the shoulder to the hand and fingers [SSSA, IUVO]. These exoskeletons will have various sensors for recording data from the user as input to the serious games and digital twin engine. The movements of the user are also aided by Functional Electrical Stimulation (FES). This information is centralized in the exoskeleton processing unit and can be informed by data from the training environment, such as user intention measured as the discrepancy between the coordinates of the hand and the current target.

2.2.5 *Digital Twin*

A Digital Twin (DT) is a paradigm originally from the field of engineering which quickly spread into new domains such as healthcare, where it has gained a lot of traction. While DTs are a binary (virtual) replication of a physical object, it is the dynamic connection between the physical and digital models of importance [Bruynseels et al., 2018]. Changes to the physical model are captured and reflected in the DT's data repository. The digital twin engine is a machine learning system capable of conducting simulations against collated current and historic data.

In this project, stroke patients will interface with computers and robotics via wearables, an upper-limb exoskeleton, and the AR or VR head-mounted display (HMD). These devices serve as the interface for rehabilitation therapies as they allow for data to be collected from embedded sensors. Data from a wearable such as a smartwatch MiGo[2] or Empatica[3] E4 can be used to capture biometric data such as heart rate and temperature or even bodily movements. Advances in the development of HMDs, such as the Vive Pro Eye[4], for the use in research, has spurned the inclusion of sensors from accelerometers and eye-tracking to electromyography (EMG)[5]. The exoskeleton under development will be modular to provide a tailored solution featuring various sensors providing feedback to the digital twin on the patient's physical, psychological and biological state.

The modularity of the system enables the inclusion of FES and exoskeleton as assistive devices, together with HMD output, which permits visual and auditory manipulations to patients tailored by the DT. Wearables are additional interfaces to provide stimulation or information to the stroke patient since they can be worn throughout the day for continued monitoring and interactions. The training scenarios described in this document are prepared to adapt a set of parameters, such as the difficulty modulators, based on a series of inputs. These inputs will be controlled by the Cognitive Architecture (WP3) and can range from performance (coming from the training scenario itself), inferred internal states (inferred through the processing of kinematics and physiological data), or user information such as preferences (from the user profile in the DT).

2.3 RGS-based Serious Games Proposal

Before we dive into the serious gaming scenarios we are developing in this project, we present a short description of the Rehabilitation Gaming System (RGS), a computer-based rehabilitation system previously developed by IBEC (SPECS lab). RGS is a science-based ICT solution for the personalized rehabilitation of people suffering from the motor and cognitive deficits after stroke. RGS is based on integrating a wide range of ICT technologies, such as VR, AI, learning and adaptive systems, image and scene analysis, wireless technologies, multimodal interfaces, simulation tools, sensors, telehealth and information systems, and wearable physiological data sensors. One of the key features of RGS is the training adaptation to individual performance. This adaptation is done through an Adaptive Difficulty algorithm, which changes several difficulty modulators specific to each training environment based on patients' requirements (Nirme, Duff and Verschure, 2011). For instance, if a user presents difficulties in the range of motion of the paretic arm, parameters such as the space between targets or speed are more strongly modulated than other ones such as interval or size. This approach is based on the Yerkes-Dodson law, which poses an empirical relationship between the level of challenge and the user's arousal (Teigen, 1994). This approach is embedded in the rehabilitation strategies described in this document. Importantly, the system adapts to the performance, but physiological data will serve to optimize the environment based on the inference of internal states (WP3, Cognitive Architecture, IBEC, DTU) and to assist motor performance when needed (FES, exoskeleton, TUM, SSSA).

Some of the listed principles, such as social interaction (e.g., socially cooperative feedback), difficulty adaptation (e.g., Digital Twin Engine from WP3.5), explicit and implicit feedback (e.g., Cognitive

[2] https://www.flintrehab.com/product/migo/
[3] https://www.empatica.com/research/e4/
[4] https://www.vive.com/eu/product/vive-pro-eye/overview/
[5] https://www.emteqlabs.com/

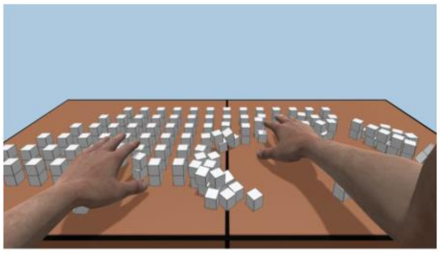
Architecture from WP3.1), multisensory stimulation, and embodied practice (e.g., exoskeleton interface) will become especially relevant in the ReHyb project.

Importantly, the promotion of experience-dependent cortical plasticity might lead patients to recover the function of their affected limb in opposition to the development of compensatory strategies, or "false recovery" (Jones, 2017; Krakauer, 2006). This also becomes relevant in the context of the ReHyb project. Instead of overtraining the patients on the performance of specific ADLs, we aim to promote the training of motor programs through evidence-based protocols that are later inherited in many daily life activities.

To develop the serious games in the ReHyb project, we started by presenting a set of RGS-based training scenarios tailored to promote motor and cognitive recovery in stroke patients. Thus, we presented a set of RGS-based games that focus on the motor and cognitive domains. These protocols were presented to the clinical partners (SK, VALDUCE) in the demo conducted at Vila Beretta to select those that better fit the requirements of the end-users.

2.4 RGS Protocols

This table contains a list of those RGS-based rehabilitation protocols that served to design the VR/AR scenarios developed for this project.

Arm Protocols	
Clean the Table 	Horizontally move arms over the table to clean up all white blocks (different table models and shapes). This protocol constitutes an evaluation of the range of movement for both arms. Its demands maximum flexion/extension of elbow and flexion/adduction of shoulder to cover as much surface Cognitive/muscle mechanics
Motor components	**Cognitive Components**
• Bimanual coordination • Whole-arm horizontal movement • Distal and proximal to the body execution • Shoulder/elbow flexion/extension • Promote the use of the paretic effector	• Coordination • Spatial awareness
Spheroids 	Bimanual task of capturing spheres and avoiding negative stimuli (e.g., Bombs). Planar movements over the table. The adaptive difficulty is lateralized (right, left) depending on each arms' performance. The RGS adaptation algorithm adapts the spheres' size, speed, and dispersion according to the user's performance for each arm individually.
Motor Components	**Cognitive components**
• Bimanual coordination • Planar movements with the whole arm • Elbow / Shoulder Flexion / Extension • Bilateral difficulty modulation	• Bimanual coordination • Spatial awareness • Attention (selective attention / inhibition)

Pinball	Dual-task training, divided attention, hemineglect rehabilitation, working memory training, attention and inhibition of movement (go/no-go)
	
Motor Components	**Cognitive Components**
• Bimanual coordination • Planar movements with the whole arm • Elbow / Shoulder Flexion / Extension • Bilateral difficulty modulation	• Bimanual coordination • Spatial awareness • Attention (selective attention / inhibition) • Prediction
Grasp and place	A series of coloured spheres approach from the horizon towards the user, who must grab and release them in the basket of the corresponding colour basket to get points.
	
Motor Components	**Cognitive Components**
• Bimanual coordination • Antigravitational movement • Power grasp • Release (fingers)	• Bimanual coordination • Spatial awareness • Attention (selective attention / inhibition)
Constellations	The patients are exposed to a star constellation in which a certain number of stars light up in a sequence. They must remember this subset of stars and reproduce it by touching the respective stars after a delay period
	
Motor components	**Cognitive Components**
• Bimanual or unimanual movements • Antigravitational movements of the arm • Movement precision	• Short term memory • Attention • Spatial awareness

Hand Protocols	
Bubbles	
 	Bubbles emerge from a lake. The user must intercept them with the hand open and palm facing down. Once the user has caught a bubble, he must close her hand to u it and get points. Fine movement, use of the Leap Motion sensor.
Motor Components	**Cognitive Components**
• Power grasp • Release • Fine pinch • Fingers coordination /precision	• Selective attention • Inhibition

2.5 Tailoring Serious Games Interfaces to the Personas

Based on the set of rehabilitation protocols already developed by IBEC, the Rehabilitation Gaming System (RGS) (see Chapter 2.2), four motor-cognitive tasks have been elaborated to address the deficit spectra of the persona defined in this project under WP 2.1. All the training scenarios allow for an implementation in VR and AR while incorporating assistive technology to provide adequate training. The main objective for selecting VR scenarios was that the training scenarios could be fully individualized to the persona's needs and capabilities. The current trend to reduce the length of stay in the hospital, and the increasing demand for efficacy in stroke care, emphasizes the importance of predicting outcome in terms of the ADLs, such as dressing, eating, and bathing to enhance a stroke survivors' quality of life. The selected tasks have been chosen, as their trained movement mechanics are thought to transfer to a variety of ADLs. Also, the gamification of the training scenarios is thought of for promoting enjoyment and adherence to the training regime and the use of the paretic limb.

Here, for each persona, we develop a table were we first group the functional impairments of the personas and link them with those training dynamics that we deem useful to fit their needs. This helped us to complete the design of the rehabilitation protocols, adding "New protocol mechanics", which are features of the system that were not included in the first proposal based on the specific needs from the description of the different Personas.

2.5.1 *Persona 1 (Alfred)*

Persona 1 presents mild hemiparesis in the right upper limb, good control of the proximal arm, capability to perform antigravity movements, and good control of the elbow flex-extension. He presents no major pain or spasticity. Mainly his wrist control and fine hand movements are impaired. The most suitable exercises for persona 1 would be the ones addressing the dexterity of the hand or fine movements of the fingers.

Table 1. Summary of the impairments, exercises, and VR scenarios proposed for Persona 1.

Impairment	Proposed exercise	Existing RGS-protocols and mechanics	New protocols and mechanics
Mild degree of spasticity	• Hand/Finger • Grasp and pinch • Flex-extension of wrist and Finger	No current protocol can address pinch, hence a new protocol should be developed. Final decision: expansion of the bubbles protocol to include a distinction between fine pinch / power grasp movements Bubbles: • Unimanual movements • Grasp and finger flexion training for precision and strength • Pronation and supination • Configured to hand control of patient • Sustained attention	• Unimanual/bimanual • Grasp and pinch training incorporating individual fingers for precision • Use of language through social interaction
Hemiparesis	• Antigravity movements • Training range of motion • Promote the use of the paretic arm	Grasp and Place • Bimanual movements • Horizontal movement training for range and speed against gravity • Precision • Divided visual attention / inhibition • Arm up and down, reaching movement, hand to body/mouth movement	Add rules and distractors for selective attention and extension to bimanual movements
Mild aphasia and cognitive deficit	Selective attention Visual attention	Constellations: • Executive function / inhibition • Short-term memory • Attention	Add enriched multisensory environment which includes verbal communication.

2.5.2 *Persona 2 (Luca)*

Luca is 75-year-old and lives independently at home with his wife. He arrived at the hospital 7 days after a left hemispheric ischemic stroke. He displays moderate hemiparesis on the right upper limb, moderate global control of the upper limb, weakness on antigravity movement, good control of the elbow flex-extension. He however, has no major pain or spasticity. He requires assistance to perform upper limb movements. His main impairment is pro-supination and fine movements of the hand. He further is moderately oriented in space and time, collaborative, able to respond and follow instructions. He displays a mild language deficit, mild attention and problem-solving deficit.

The main goal of his treatment plan is to improve global functionality of the upper limb in space exploration and for object managing as well as to increase social participation and improve language.

Table 2. Summary of the impairments, exercises and VR-scenarios proposed for Persona 2.

Impairment	Proposed exercise	Existing RGS-protocol mechanics	New protocol mechanics
Moderate hemiparesis, mild spasticity.	• Grasp and pinch Exercises • Flex-extension of wrist and Finger • Open and close finger, grasping • Pro-supination exercises •	No current protocol can address pinch, hence a new protocol should be developed. Bubbles • Unimanual movement • Grasp and finger flexion training for precision and strength • Pronation and supination • Configured to hand control of patient Sustained attention Final decision: expansion of the bubbles protocol that include a distinction between fine pinch / power grasp movements	Unimanual/bimanual Grasp and pinch training incorporating individual fingers for precision ADL-related training that includes the use of the paretic arm to perform activities such as eating, grasping and bringing drinks to the mouth
Mild language deficit.	• Language comprehension and speech exercises		Enriched multisensory stimulation that promotes the use of verbal language through social interaction
Mild attention and problem-solving deficit.	• Arm up and down, reaching movement, hand to body/mouth movement • Selective attention exercises • Problem solving Exercises • Space-time orientation exercises	Constellations • Bimanual movement • Space exploration • Movement control and coordination • Executive function / inhibition • Selective attention • Space and time interaction	Add rules and distractors for selective attention and extension to bimanual movements

2.5.3 *Persona 3 (Amaia)*

Persona 3 is single and lives in a nursing home. She has no kids but one very good friend. She arrived at the hospital 11 months after a right hemispheric ischemic stroke, and shows the following clinical condition:

- Motor: severe hemiparesis on the left upper limb, with general upper limb weakness. She is unable to perform antigravity movement and to perform flexion-extension of the elbow, no major pain or spasticity. She presents deficits in movement coordination.
- Cognitive: She is disoriented in space and time. Able to respond and follow simple instructions, with severe memory and attention deficits, and mild visual perceptive deficit.
- Functional: patient is highly dependent for all upper limb functional activities.

Based on this, the general expected results are to improve coordination, increase global functionality of upper limb and autonomy in ADL. Improve cognitive global functions.

Persona 3 is not addressed directly through the training scenarios due to her severity but some of the exercises could be useful for her to do in the hospital. Due to her severeness, she might not profit as much from the current training, although the principle-based design of the protocols should work for her too. In these cases, a special focus on the interaction with the exoskeleton for assisting intended actions (WP4) should be considered.

Impairment	Proposed exercise	Existing RGS-protocol mechanics	New protocol mechanics
Pinch	• Grasp and pinch Exercises • Flex-extension of wrist and Finger • Language comprehension and speech exercises	No current protocol can address pinch, hence a new protocol should be developed. Bubbles • Unimanual movement • Grasp and finger flexion training for precision and strength • Pronation and supination • Configured to hand control of patient Sustained attention	• Unimanual/bimanual • Grasp and pinch training incorporating individual fingers for precision • Use of language through social interaction •
Wrist position Pro-supination Grasp and release Selective attention	• Flex extension of the wrist • Pro-supination exercises • Open and close finger, grasping exercises	Bubbles • Unimanual movement • Grasp and finger flexion training for precision and strength • Pronation and supination • Configured to hand control of patient Sustained attention	
Antigravity arm movement Trunk control support	• Reaching and Hand to body Movement • Allowing trunk control	Constellations • Bimanual movement • Space exploration • Movement control and coordination • Executive function / inhibition • Selective attention • Space and time interaction	
Mild language deficit.	• Language comprehension and speech exercises		Enriched multisensory stimulation that promotes the use of verbal language through social interaction

3 Detailed Description of the Serious Gaming Scenarios

In the following section we provide a detailed description of the training dynamics of the proposed protocols, a table on the current and planned technical implementation of the training scenarios, and an overview on how the trained mechanics can translate to ADLs. A critical question in any rehabilitation therapy is whether gains generalize to untrained tasks (Dipietro *et al.*, 2009). In other words, how the reductions in *impairment* (i.e., restitution) (if any) achieved during the rehabilitation therapy transfer to *function*, or independence during ADLs. Some results, such as the fact that patients undergoing RGS-based training score higher in scales that measure functional independence (i.e., Barthel, CAHAI), than those undergoing standard care (OT) provides promising insights on this issue (Belen Rubio Ballester *et al.*, 2019). We identified for each serious gaming scenario the motor and cognitive mechanics that are trained and map them to the mechanics that underlie ADLs that were defined as essential in the WP2 (TUM).

In addition, we establish how each serious gaming scenario could be adapted to the individual impairments of the patients, and how they relate to other modules that can be used.

3.1 Star Constellations

3.1.1 *Description of the functionality*

The Star Constellations scenario is a visuospatial short-term memory task (Maier et al., 2020). The training fosters bimanual movements, space exploration, movement control, and coordination while training cognitive aspects. The patients are exposed to a star constellation in which a certain number of stars light up in a sequence. They must remember this subset of stars and reproduce the correct sequence by touching the respective stars after a delay period. Currently, the difficulty level of four task parameters can be adapted in this scenario.

Difficulty Modulators

1. The complexity and spatial extension of the constellations (seven levels) aim to train spatial attention and spatial memory. This parameter addresses the recommendation to offer a unique sequence of stimuli in each trial during working memory training (Westerberg et al., 2007), to progress from simpler to more complex tasks in executive function training (Chung, Pollock, Campbell, Durward, & Hagen, 2013) and to train the ability to detect and deploy attention to all sides of space (Loetscher & Lincoln, 2013)
2. The number of stars in a subset (Westerberg et al., 2007).
3. The time interval between their appearance should aid the training of working memory (Westerberg et al., 2007).
4. The length of the delay period progressively challenges memory delayed recall. This parameter aids the training of internal strategies (visual imagery) which are recommended for memory training (Cicerone, 2002).

3.1.2 *Technical Implementation*

Current implementation	New implementation
Virtual reality (desktop) and movement tracking via Kinect	Full immersive environment (augmented reality) using the HoloLens

Figure 3. Constellations protocol. Left. Implementation in a Desktop setup using a PC and the Azure Kinect sensor for tracking (Rehabilitation Gaming System, IBEC). Right. Adaptation of the constellations protocol using the HoloLens (Microsoft) (Augmented Reality, DTU).

3.1.3 *Transfer to activities of daily living (ADLs)*

Here we outline how the movement mechanics trained in the task map to the essential ADLs defined within the project. The color code indicates which movement/cognitive mechanic maps to mechanics underlying the ADLs' execution.

Table 3. ADLs transfer Constellations

Trained mechanics	ADL 1 – Eating and drinking	ADL 2 - Hygiene	ADL 3 - Dressing
Bimanual reaching movement (vertical and horizontal) Movement control and coordination Executive function / inhibition Selective attention Space exploration Space and time interaction	Grasp and place a glass Localization of glass Traversal movement from grasp to place position Hand and eye coordination for transporting glass Positioning of glass Grasp and place a tray Localization of tray Bimanual reaching for tablet Bimanual coordination for transporting/balancing tray Positioning of tray Place and hold food while cutting Sequencing of use of fork and knife Coordinated movement of fork and knife Open vessel Positioning of both hands	Open toothpaste, squeeze out toothpaste Sequencing of use of toothpaste and toothbrush Coordination between squeezing toothpaste and holding toothbrush Clip nails Focus on nail and clipper to avoid cutting themselves	Button up Coordinate between both hands Close a zipper Coordinate between both hands

3.1.4 *Individualization Proposal*

The expansion of the constellation can be adapted to the patient's reaching ability (depth) and the ability to do antigravity movement (height). This would also aid the training of neglect or difficulties with space-time exploration. Further the number of stars to be remembered and the speed with which the stars appear could be modulated according to the patient's cognitive status with respect to attention. The size of the stars could be modulated to foster more precise reaching. To facilitate the interaction for more severely impaired patients, a rotating chair could be used: this would allow the patient to perform the task in a sitting position, but still be able to rotate to explore the space around them.

3.2 VR Bubbles

3.2.1 *Description of the functionality*

The training scenario "Bubbles" specifically trains the dexterity of the hand including grasp and finger flexion, precision, strength and pronation and supination. Within the training, the participants see different types of bubbles emerging from a lake. The user must intercept them with the hand open and palm facing down. Once the user has caught a bubble, he must close the hand to explode it. For each successfully intercepted bubble, the participant is rewarded with a point. Currently, the difficulty level of four task parameters can be adapted in this scenario:

Difficulty Modulators

1. The angle of the grasp required to explode the bubbles. It determines how much the participant has to open the hand to be able to intercept it.
2. The interval of which the bubbles appear. This parameter determines how fast the participant has to transition the arm in order to reach the bubbles that emerge from the lake.
3. The size of the bubbles that appear in the virtual environment.
4. Addition of stimuli that patients have to avoid (inhibition).

The training scenario can be extended by adding rules on how the bubbles have to be destroyed. The color of the bubble can indicate the rules. For instance, if a red bubble emerges, the participant must pass it from one hand to another to intercept it, fostering bimanual training. Else, some bubbles could contain a second bubble, which needs to be destroyed too.

3.2.2 *Technical Implementation*

Current implementation	New implementation
Virtual reality (desktop) and movement tracking via Kinect	Full immersive environment (augmented reality) using the HoloLens

3.2.3 *Transfer to activities of daily living (ADL)*

Here we outline how the movement mechanics that are trained in the task map to the essential ADLs that were defined within the project. The color code indicates which movement or cognitive mechanic maps to which mechanics underlying the performance of the ADLs.

Table 4. ADLs transfer Bubbles Protocol

Trained mechanics	ADL 1 – Eating and drinking	ADL 2 - Hygiene	ADL 3 -Dressing
Grasp and finger flexion training for precision and strength Unimanual or bimanual coordination	Grasp and place a glass Fixation of holding glass stable Grasp glass	Open toothpaste, squeeze out toothpaste Grasp tooth brush and toothpaste	Button up Pinch grasp a button Pinch for slip button through button hole

Pronation and supination Executive function / inhibition Sustained attention	Apply force while transporting the glass Grasp and place a tray Grasp handles of tray Apply force to hold tray Place and hold food while cutting Grasp fork and knife Apply force to hold fork and knife Contra movement force Maintain attention during cutting Open vessel Enclose jar and lid with both hands (grip) Apply force to hold the jar and turn the lid in opposing directions Tilt wrist to run the lid	Control force to squeeze Tilt toothpaste Clip nails Grasp clipper with pinch Apply force to clip Pay attention where to clip	Close a zipper Pinch zipper and loose end of fabric Tilt wrist to glide zipper upwards

3.2.4 *Individualization Proposal*

Based on the current hand dexterity of the patient, the task parameters can be adapted to the patient's ability. For instance, the size of the sphere, which determines the aperture of the hand, could gradually increase in size to adjust to training progress. In addition, the range of spread of the appearing spheres could be based on the range of movement that the patient can perform, supporting an integrated movement control aspect.

3.3 Grasp and Place

3.3.1 *Description of the functionality*

A series of coloured spheres approach from the horizon towards the user, who must grasp and release them in the basket of the corresponding colour to get points. This protocol focuses on processing speed, coordination, finger flexion/extension, range of movement training, antigravitational arm movement, horizontal/cross-movement and movement inhibition. The cognitive component of the protocol (i.e., attentional shift, precision and inhibition) gets increased with the number of colors present in the virtual environments, where patients only get points if the spheres are placed in the matching-color basket. For each sphere placed in the corresponding basket, the participants gain a point.

Difficulty Modulators

1. Speed of the approaching object (left and right). It is noteworthy that in the grasp and place scenario, the different parameters can be lateralized, meaning that they can be adapted individually to the performance of the healthy and the paretic limb of the patient.
2. Size of the approaching spheres.

3. Dispersion: This parameter indicates the average distance between the left/right spheres in the X axis (horizontal) of the virtual environment. It has been shown to be one of the most influencing parameters in the RGS-based protocols when our adaptive difficulty algorithm is applied (M.S., S.B., E.D., & P.F., 2010). This encourages higher ranges of motion and horizontal cross/movements.
4. Height: This represents the average z-position of the target spheres in the virtual environment. This parameter encourages the performance of antigravitational movements. The spheres with lowest height would not require the patient to lift the arm from the table.
5. Position of the basket: The baskets can move or remain static during the performance of the game.
6. Aversive Stimuli: Introduces cognitive load and requires the patient to inhibit a certain number of targets.
7. Number of colors: Also introduces cognitive load and increases the load to visual attention.

3.3.2 *Technical Implementation*

Current implementation	**New implementation**
Virtual reality (desktop) and movement tracking via Kinect	Full immersive environment (Virtual Reality) using Vive Pro Eye

3.3.3 *Transfer to activities of daily living (ADL)*

Table 5. ADLs transfer. Grasp and Place Protocol

Trained mechanics	ADL – eating and drinking	ADL 2 – Hygiene Hygiene	ADL 3 – Dressing
Bimanual movement Horizontal and antigravitational movement training Precision Divided visual/attention and inhibition Goal-oriented grasping	Grasp and place a tray Reaching to the handles of the tray Open hands to grasp handles Positioning fingers around handles Elevate tray Position tablet close to body Carry tray Put tray on intended place Release grip Place and hold food while cutting Open hand to grasp fork Apply force to grip Elevate fork Fixate food with fork Fixate food while cutting Release fork from food Place fork on table	Open toothpaste, squeeze out toothpaste Reaching to object Open Hand to grasp object Position finger around object Elevate object Move object to intended position Put object on intended place Release Grip Move back to N position Bring hands to face	Close a zipper Bring zipper upwards Coordinate between both hands Pinch zipper, pinch buttons Pinch buttons

	Release grip Move back to N position		

3.3.4 *Individualization Proposal*

Based on the current hand dexterity of the patient, the task parameters can be adapted to the patient's ability. Depending on the ability of the patient to perform antigravitational movements, the height of the spheres could be adapted, as well as the degree of assistance from the exoskeleton. Depending on the cognitive impairment of the patients, the parameters that control the cognitive load, divided attention, and inhibition, could be modulated accordingly.

Depending on the degree of spasticity of the patients, the protocol could just include colliders which don't require a grasping movement. On the other hand, for patients in need for dexterity the size of the sphere can increase the level of power/fine grasp necessary to grasp it and can adapt hence to the capability and performance of the user in this particular task. Ideally, information from other training scenarios (e.g., Bubbles) could be exchanged to deploy a bigger picture of the patients' capabilities (i.e., performance in fine grasping/releasing movements) and adapt other scenarios accordingly. This will help to build a user profile withing WP3 Digital Twin that is updated by the information of the rehabilitation games.

3.4 ReHyb Cafe

3.4.1 *Description of the functionality*

Under the scope of the ReHyb project, a special emphasis is given on the performance of ADLs and to promote the independence of patients in the realization of these activities. For this reason, we aimed to develop a serious gaming protocol that incorporates a set of these activities in a controlled, computer-generated environment. For this purpose, we created the "ReHyb Café" environment, which consists of a virtual café-like scenario where patients interact, providing a scenario with strengthened ecological validity (Tarnanas *et al.*, 2013) to accomplish a series of ADL tasks. Concretely, we selected a series of ADLs that are also defined under the work conducted by TUM (rehabilitation primitives, WP2) and set a battery of gamified activities based on those. These tasks are divided into different *experiences* which are designed to fulfill a set of specific goals. Some key reasons for the development of the ReHyb Café protocol within the project are listed below, which include fulfilling the requirements of clinical partners:

- Inclusion of ADL in training experiences. Computer-generated environment to recreate ADL in a gamified and controlled way.
- Under WP2 D2.1, the clinicians suggested the training of ADL-related movements **proximal to the body** (i.e., zipping up, eating, drinking, wearing clothes…). Importantly, this is a major limitation in the previously presented serious gaming protocols that implement a first-person perspective, such as Bubbles and Constellations. The challenge is that the motion tracking device currently used (Microsoft Kinect) struggles to track movements close to the body, which is why current training protocols do not require proximal movements. The usage of AR and VR technologies provides the capability to include tasks that require proximal movement mechanics.
- Inclusion of 30+ of ADL-related objects in the experiences.
- Provide socially cooperative feedback through the inclusion of a virtual avatar that guides the user through the different experiences. This allows us to introduce dyadic multisensory stimulation in the environment. This approach has been proven to help patients with aphasia (Grechuta *et al.*, 2019), which is common in the Personas description (target end-users).

A VR coffee shop is a controlled environment where stroke patients can move in an immersive space while they perform ADLs related tasks defined according to post-stroke recovery principles.

All the principles of neurorehabilitation that promote learning and are beneficial for recovery implemented within this environment are:		
Massed practice/repetitive practice Spaced practice Variable practice Explicit feedback/knowledge of results Goal-oriented practice	Controlled dosage/duration Increasing difficulty Implicit feedback/knowledge of performance Motor imagery/mental practice	Task-specific practice Multisensory stimulation Action observation/embodied practice Social interaction

Regarding the motor/action mechanics, the serious gaming protocol includes:

- Movements that are proximal to the body (i.e., bringing the arms to the mouth/trunk)
- Reaching to objects (e.g., getting a pastry, carrying a tray)
- Grasping objects (e.g., coffee cup, glass of water)
- Releasing objects (e.g., dropping sugar in a cup)
- Motor affordances typically used in ADLs.
- Valid (e.g., reaching from the top/side for a glass)
- Invalid (e.g., reaching from the top side for a jar)
- Attention or avoidance of stimuli
- Action observation, imagery (i.e., including a mirror in the virtual environment)

Altogether, the proposed experiences include the following mechanics:

Uni-manual Promote paretic limb movement	**Bi-manual** Promote motor coordination Synchronized vs. non-synchronized movement
Spatial Reaching/pushing/pointing Range of motion Horizontal movements	**Proximal to body** Self-care Movements against gravity Vertical movement
Gross Movements Compensation and synergy control Arm extension	**Dexterous movements** Fine finger movement (pinch/grasp) according to affordance Wrist movements
Cognitive Attention Executive Function	**Social** Language use Cueing

Regarding the cognitive and social mechanics, the serious gaming scenario includes:

- Language exchange with VR agents (i.e., dyadic multisensory integration), naming, reading, counting, etc.
- Audiovisual integration.
- Responsive to meaningful sensations (e.g., sound of participants' name, other known items/objects).
- Multisensory exposure to sounds, colors, textures.
- Enriched social environment and social relatedness.

Attention, short-term memory, cognitive load and cognitive functioning tasks

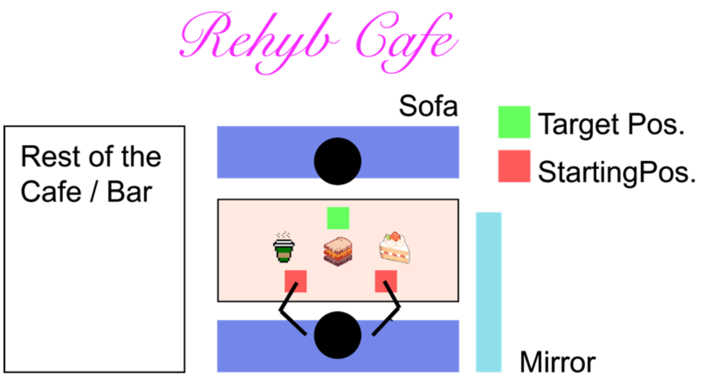


Figure 1. Schematic View of the ReHyb Café experience. The patient is sitting facing a virtual companion which guides the experience and provides feedback. During the whole game, there is a mirror positioned besides the patient for action observation. The reaching and target positions are predefined and pseudo randomly vary along the experience

For the development of the protocol, we explored the commercially available environment models[6] of a virtual café and object models to create a realistic and immersive environment. In the following paragraphs we describe the experiences within the training scenario ReHyb Café.

At the beginning of the VR experience (**Experience 1**), the patient sits by a table and can look all around the café. The patient might be prompted via a voice to grab the menu placed on the table and read the list aloud.

Figure 4 The patient is sitting by a table and can look all around the café, and might be prompted to grab the menu and read the list aloud.

In **Experience 2**, the patient might be prompted by the virtual companion to give him one of the items on the table, using verbal communication. The patient should grasp the object required and bring it to the target position (marked on the table). At the beginning of each round, the patient might need to bring both hands to the starting positions.

If after a given time (e.g., 30 seconds) the patients do not grasp the object, the command is repeated, with the word referring to the item appearing in the visual field of the user, and the object is highlighted to facilitate the task. The trial is considered unsuccessful if the time to bring the object exceeds a preset amount of time. The difficulty level is determined by the affordances, level of grasp required and time to perform the task. The use of the paretic effector is encouraged, by including items that require bimanual movements or suppressing the possibility of reaching with the non-affected limb. After a

[6] https://www.cgtrader.com/3d-models/interior/other/cafe-interior-c7aa99ac-e243-439a-881c-7ad2f014194e

successful trial (reaching the target position with the object), positive feedback is given by the virtual companion.

Note that, although in the current pictures we observe the virtual hands diconnected from the body of the patient (Figure 5), we are considering to include the arms in future implementations to satisfy the embodiment principles mentioned in section 2.

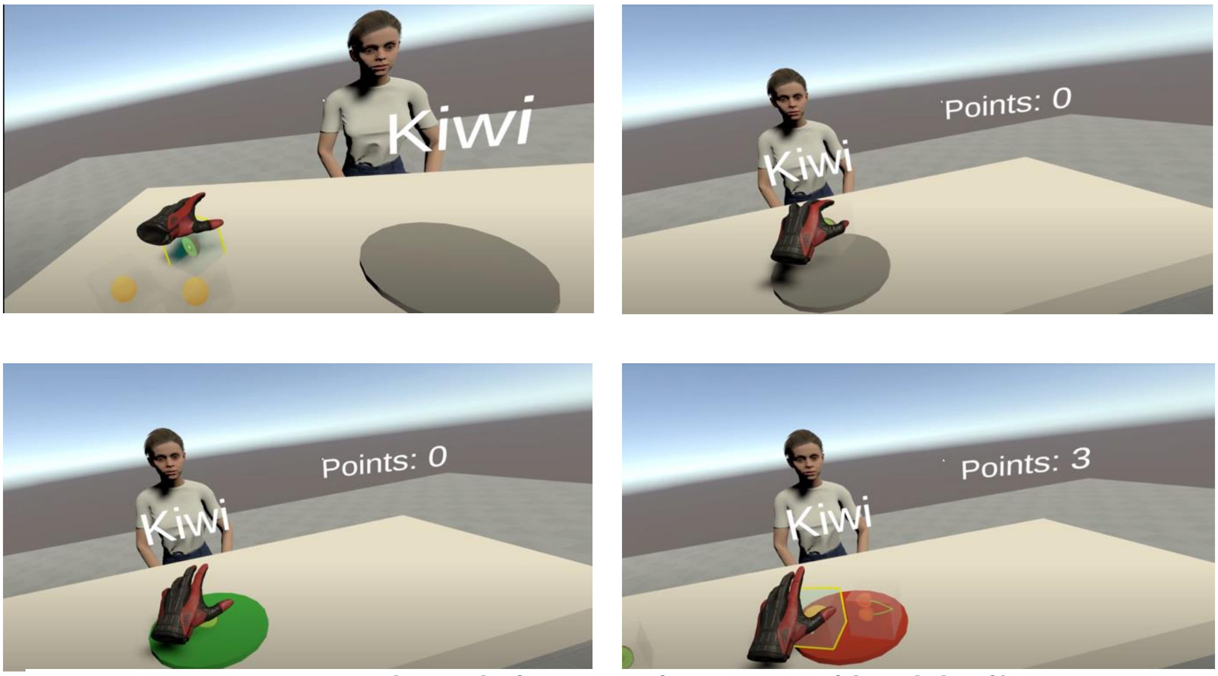


Figure 5 Mockup on the functioning of Experience 1 of the Rehyb café.

Principles	Difficulty Modulators (for WP3)
• Effector selection • Goal-oriented practice • Social interaction • Variable practice • Increasing difficulty	• Similarity of objects • Size • Reaching distance • Affordances (degree of power/fine) grasp required. Objects would be pre-classified to establish this metric

Similarly, in **Experience 3** patients will be prompted to interact with items of the virtual environment that require to perform movements proximal to the body (for instance taking a cup of coffee and drink from it).

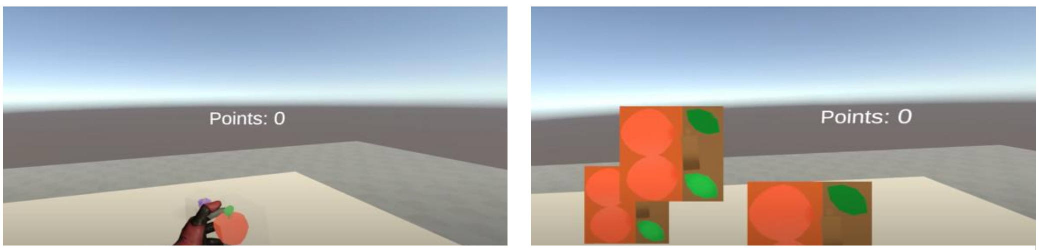


Figure 6 Mockup for the Experience 3 which consists on bringing food/drinks to the mouth of the patient

In this experience, a **mirror** is placed in front of the patient to promote action observation and imagery. Mirror therapy (MT) has been used to promote motor recovery for lower and upper extremity function in stroke patients, (Sütbeyaz *et al.*, 2007). In this strategy, a mirror is placed in front of the paretic arm and the patient is asked to perform movements with the healthy limb while observing the reflection of the movement on the paretic limb. MT has shown to be effective to improve motor impairments and sensations, visuospatial neglect, and pain after stroke. Although the use of a mirror in the virtual environment serves a different purpose in our case, future implementations could include adaptive mapping in the reflected image to manipulate the visual feedback of the actions and thus bias effector selection promoting the use of the paretic limb (Ballester *et al.*, 2015). At this first stage of the project, the mirror helps to visualize proximal movements that are difficult to achieve due to technological limitations (i.e., field of view).

Principles	**Difficulty Modulators (for WP3)**
• Effector selection • Goal-oriented practice • Variable practice • Embodied practice • Action observation • Embodied practice • Motor imagery • Implicit feedback	• Complexity of objects • Size of objects • Complexity of interaction (e.g., using cutlery vs. holding a glass)

For **Experience 4**, we propose a motor task that consists of cleaning the table. The patient sees that the table is dirty or something is spilled, and it needs cleaning. The patient gets a sponge/cloth and they should clean the table with the paretic or both hands. A possible caveat of this task is that patients might rely on compensatory strategies to achieve the goal, as gross movements of the whole limb are required.

The use of the paretic limb will be encouraged by dividing the workspace, e.g., half of the table has to be cleaned by the paretic limb. Alternatively, the patient might be prompted to use only the paretic limb to clean the table. IBEC is currently working with Valduce in the development of automatic compensatory detection techniques. This experience trains range of movement, bimanual coordination and precision. This task is based on the RGS protocol "Clean the table", and trains planar movements of the arm.

Principles	**Difficulty Modulators (for WP3)**
• Rhythmic cueing • Massed practice • Effector selection • Task-specific	• Range of motion, size of the table • Distribution of dirt • Size and type of the cleaning tool

For **Experience 5**, we propose a cognitive/motor task where the patient receives the bill. The patient sees the bill with the total amount and some cash to complete the payment. The patient needs to calculate the amount of cash necessary to pay the bill.

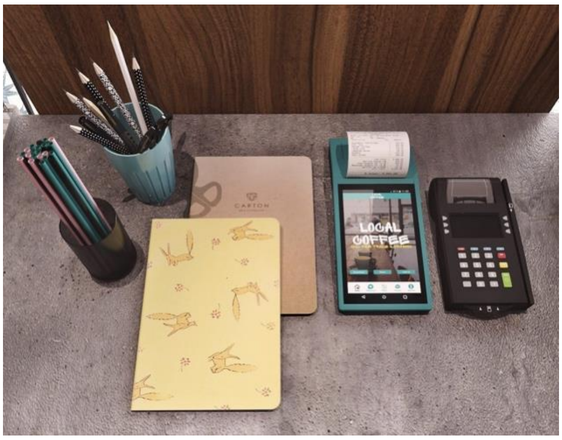


Figure 7 Mockup view of Experience 5

Principles	**Difficulty Modulators (for WP3)**
• Rhythmic cueing • Massed practice • Task-specific • Knowledge of results	• Complexity of the calculation (e.g., including decimals) • Type of cash provided to complete the transaction • Number of items in the bill

The ReHyb café protocol includes pauses for social interaction, where the patient receives different trivial comments about the day, the quality of the food/service, or the people surrounding them and the virtual companion.

To promote *adherence*, at the end of each interaction within the ReHyb Cafe, as **Experience 6**, the patient receives positive reinforcement in café loyalty cards, which unlock items for future iterations. This card might include information on the performance or accomplishments during the last/lasts sessions of training

Figure 8 Mockup view of Experience 6

3.5 Reference to KPIs

In this section, we briefly reference the ReHyb project's KPIs that relate to the work within the interaction scenarios and how those are or will be accomplished in the future.

Cognitive System for Sympathetic Human-Robot Interaction

1. Supporting more than 80% of the pre-defined use cases

We tailored the training scenarios to the needs of each of the Personas described under WP2. Those, in turn, reflect the needs of the end-users (stroke patients) who will be using the system in the project context.

2. Non-verbally interaction with a user in more than 70% of the pre-defined use cases

The protocols include verbal and non-verbal communication for providing feedback to the patient. Specifically, different game events trigger specific information, such as increases in punctuation, difficulty level, targets to inhibit, implicit feedback from the avatar movements, etc. The protocols also include multisensory integration of relevant stimuli and verbal social communication in the case of the rehyb café, to account for mild aphasia deficits. This will be described in more detail under T7.2 “Socially cooperative feedback design”.

3. Maintaining dyadic goal-oriented interaction for at least 70% of the tasks

This requirement is already satisfied. All the training protocols include goal-oriented tasks, as we used this requirement as one of the design principles. In most of them, this interaction consists of ballistic reaching or grasping actions (i.e., stars, grasping spheres, bubbles), which can be used to determine user intention for assistive modules. This holds for the ADL-like tasks defined for the experiences of the rehyb café.

4. Positive evaluation on the sympathetic interaction by more than 90% of the users.

Although the demo at VB provides promising results on this interaction, this needs to be tested in more detail when integrating the whole system. Furthermore, a bigger sample of users should be analyzed and specific evaluation metrics should be defined to test the interaction. An assessment of the solution (e.g., validation, usability tests) should be conducted and discussed with the clinical partners.

Socially cooperative interface for digital user twin

1. AR user status feedback displayed correctly in 90% of the pre-defined use cases

The integration of physiological sensors with the games engine is already being tested at IBEC using the Empatica E4. The display of user status will be discussed with DTU for T7.2

2. A minimum of 30 ADL related objects modeled in the (simulated) patients home environments

ReHyb café already satisfies this requirement.

3. Three or more serious gaming scenarios embedded in the rehabilitation exercises

In this document, we describe the development of 4 serious gaming protocols.

4. The serious gaming exercises positively evaluated by more than 80% of the users

This should be tested once the development of the serious gaming protocols is completed.

Link to KPIs and objectives:

https://docs.zoho.eu/ws/project/file/4137j1e52ad1d819b4383926533fe3193d4a9

4 Development Process (DTU)

Rehabilitation scenarios to be developed were selected based on efficacy validated in past studies and potential for immersive experience for patients. The Star Constellation scenario was selected as a demonstrator for the capabilities of the augmented reality and the Microsoft Hololens 2[7] in particular. The RehybCafe was designed to a full immersive experience and thus required the use of a VR technology such as the Valve Index[8] and the Vive Pro Eye[9]. Both the VR Bubbles and the Grasp and Place scenarios have the possibility to be developed as AR or VR games. Preliminary testing the prototypes with stroke patients will provide valuable insights into required improvements to the software design or technology capabilities. These lessons learned will influence the decision of how future serious gaming scenarios will be developed and which technology platforms will be utilized.

4.1 Technical Requirements Linked to Other Work Packages

The development of serious gaming scenarios must account for the requirement of the other work packages and technologies being developed. How the serious games communicate with the control system is of great importance. Currently, we are utilizing the User Datagram Protocol (UPD) as the standard communication protocol. Input data streams from multiple sensors will have to be fused and synced. To accomplish this, Lab Streaming Layer (LSL) is being implemented as an abstract layer in Unity to enable the management of a multitude of input and output streams while being source device agnostic. The implementation of LSL is meant to be modular to provide easy integration into all serious games and application across the ReHyb project. Output data streams from LSL can be fed to the historical data store for use in the Digital Twin or to the control system for manipulation of the exoskeleton and embedded sensors such as the FES

4.2 Benefits and Challenges of Technology

Today's Extended Reality (XR) technologies covers a broad spectrum of devices that includes but not limited to head mounted displays (HMD), trackers, and haptic devices to provide powerful array capabilities like precise hand tracking, gaze tracking, and biometric feedback to enable developers and researchers to create novel interfaces between the human and the computer as well as new methods of interacting in the augmented, virtual and mixed realities. For developers, these technologies offer the possibility to create immersive experiences, but just like any new tech, it has many challenges.

	**Microsoft Hololens**
	Image Source: https://img-prod-cms-rt-microsoft-com.akamaized.net/cms/api/am/imageFileData/RWtxyV?ver=9e57&q=100&m=6&h=431&w=767&b=%23FFFFFFFF&l=f&o=t&x=901&y=280
	**Nreal Light**
	Image Source: https://roadtovrlive-5ea0.kxcdn.com/wp-content/uploads/2019/11/nreal-light.jpg

[7] https://www.microsoft.com/en-us/hololens
[8] https://store.steampowered.com/valveindex
[9] https://www.vive.com/eu/product/vive-pro-eye/overview/

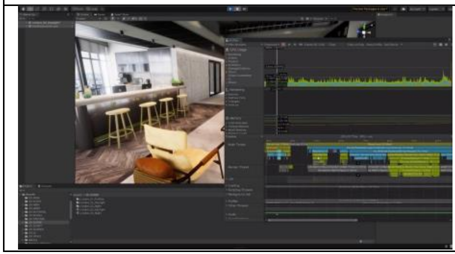
<table>
<tr><td rowspan="2"></td><td>Vive Pro Eye</td></tr>
<tr><td>Image Source: DTU</td></tr>
<tr><td rowspan="2"></td><td>Valve Index</td></tr>
<tr><td>Image Source: https://images-na.ssl-images-amazon.com/images/I/71ZgOpN805L._SL1500_.jpg</td></tr>
<tr><td rowspan="2"></td><td>Unity</td></tr>
<tr><td>Image Source: https://unity.com/sites/default/files/styles/810_scale_width/public/2020-05/unity-profiler-810x455%402x.jpg?itok=ti06jimy</td></tr>
</table>

Table 8 Technology Imagery

4.2.1 *Augmented Reality*

The Hololens 2 has very precise hand tracking sensors that enable intent-based interactions with the holograms in the environment. Playing a serious gaming scenario without any controller is a huge advantage when simulating real life interactions. However, as a standalone device, the Hololens 2 has some limitations regarding computational power, as well as a limited field of view compared to most VR headsets. Nevertheless, as the Star Constellation scenario does not use large-scale models and the processing of the collected data is done on another computer, the Hololens 2 is a perfectly suitable device for our purposes.

The Hololens has the advantage of being able to project holograms on top of what the user sees through the glasses, making the experience less overwhelming and more direct as there will not be any latency or distortion on the real-world image that the user perceives (in contrary to using VR with a video stream from external cameras). In addition, the internal 3D model of the Hololens is precise enough to perform depth perception tests on patient, as seen in the SPiAR[10] project. The Hololens, in the right light conditions, has an impressive spatial mapping feature, where it is able to recognize different surfaces in a room and tag them accordingly (couch, table, floor, walls, etc.). In addition, with access to those camera streams one can also implement machine learning algorithms to recognize objects in the room and add visual cues for the user. The gaze tracking is also good enough to estimate where and what the user is looking at but there is a lack of information such as pupil size and per-eye data for any in-depth eye research.

Future AR glasses will be reduced in size and resemble traditional eye-wear. Nreal[11] is one such company currently working future concepts and products. The Nreal Light utilizes traditional eye-wear form factor by offloading processing to Android smart phones[12].

4.2.2 *Virtual Reality*

[10] https://www.researchgate.net/publication/349058255_Spatial_Perception_in_Augmented_Reality_SPiAR
[11] https://www.nreal.ai/light
[12] Currently only the OPPO Find X3 Pro is compatible, but other models will be release soon.

Developing for VR on the Valve Index, creators can have control over the environment the user is immersed in. Tethered virtual reality HMDs, such as the Vive Pro Eye and Valve Index have access to greater computational power to create higher fidelity visuals and interactions or events that require the extra power to render as the application runs typically on a high-end computer. Standalone headsets, such as the Oculus Quest, have onboard computers that offer the freedom of movement and low cost to provide an avenue for the democratization of the technology. The Index controllers are a good alternative to the embedded hand-tracking sensors found in most HMDs, as they can simulate intent-based grabbing, pointing, and other interactions with high precision while providing other input methods for example the joysticks and pads typically used for locomotion, and buttons or triggers for activating interactions.

4.2.3 *Unity*

To develop all the serious gaming scenarios, we are Using the Unity[13] 3D game engine. It is a powerful tool that is especially efficient for rapid prototyping. In our workflow it is important to quickly implement features that can later be polished, or redesigned if needed. Unity also supports various XR plugins that abstract the hardware and provide an interaction-based interface. This makes our code easy to integrate with other VR headsets and controllers in the future too. Another advantage of the Unity engine is the community. The unity community provides a vast number of assets and code online as open source or freely accessible.

Lab Streaming Layer[14] (LSL) is a very robust open-source code library that is commonly integrated into Unity for synchronization of research data. It allows the collection of data from different sources, i.e. multiple sensors in the exoskeleton, wearables and HMD. The initial challenges include cross-communication between different platforms and programming languages, for example a C++ based plugin had to be run in unity which mostly uses C#, and the test stream data were sent via a python[15] script. Also, windows machines present problems with firewall rules, but other devices were easier to adjust. LSL’s is being implemented into the serious games as an abstraction layer allowing multiple channels to handle multiple simultaneous data streams.

4.3 Data

Management of the data produced during rehabilitation sessions is currently under discussion with project partners and will likely be discussed in more concrete detail in Deliverable 3.4 or 3.5 which focus on the digital twin architecture and engine. There will be some local storage available in the ReHyb system design, but transferring the data to a centralized data center allows for the data to be used by the digital twin and to provide analytics and visualization of the data that will serve as part of the deliverable 7.2, Socially Cooperative Feedback Design.

Raw data streams from sensors and devices will be output by the LSL into an extensible data format (XDF) format. This data can then be converted into other formats such as JavaScript Object Notation (JSON) or creating some local data visualization by utilizing Python. Handling of the data will need to be in legal and ethical compliance with national and European regulations. Data collected during the preliminary testing of prototypes will be under the control of the entity conducting the experiments.

5 Conclusion and Value

In this manuscript report, we describe the groundings for the design of principle-based serious gaming scenarios that can be deployed at the patients' home. These interventions are strongly influenced by a set of neurorehabilitation principles that promote the acquisition, retention, and generalization of skills. These interventions focus on experience-dependent cortical plasticity to regain motor patterns prior to the stroke onset. Previous studies using similar approaches using the RGS have shown more positive

[13] https://unity.com/
[14] https://github.com/sccn/labstreaminglayer
[15] https://www.python.org/

results than standard therapy in treating motor (Ballester *et al.*, 2015; Belén Rubio Ballester *et al.*, 2019) and cognitive (Grechuta *et al.*, 2019; Maier *et al.*, 2020) deficits, even at chronic stages.

We also describe how these protocols are specifically tailored to the necessities of the different use cases (Personas, WP2) in the context of the ReHyb project and how those and clinicians' requirements (SK, VALDUCE) guided the design of further strategies. Especially, the design of the ReHyb Café becomes a novel solution to account for a multisensory enriched environment that includes different ADL-based tasks while keeping the principle-based approach of the rest of the interventions.

This solution becomes especially relevant nowadays, where the pandemic has strongly affected stroke care at healthcare facilities (Rudilosso *et al.*, 2020; Zhao *et al.*, 2020). The serious gaming scenarios are designed to account for online manipulations based on individual needs. Some of those manipulations are achieved through the difficulty modulators described. However, the modular design allows for other kinds of interventions, such as avatar aspect, therapy intensity/duration, feedback delivery and more. These changes are guided by the information provided from the Digital Twin and will be described in more detail within WP3.

To achieve this, the serious games engine can centralize the information provided by physiological sensors using LSL and can output information useful to infer user intention, such as the spatial coordinates of the hand and the targets in the virtual environment. Shortly, DTU and IBEC will conduct tests together with TUM to study the data streaming from Unity to other modules. In particular, these pilots will evaluate the frequency rate of streamed data to fulfill the requirements of assisting devices (i.e., FES).

To the best of our knowledge, this is the first time the design of computer-based post-stroke rehabilitation interventions is tailored to adapt to the needs of participants in such detail. The development of these strategies will allow for remote treatment and monitoring of users' capabilities and states at the house of the patient. The use of different technological pathways, such as computer-based (RGS), VR and AR will allow for comparison of these strategies in stroke population. For instance, VR might become problematic in patients with cognitive deficits related to spatial awareness, who might be more prone to present motion sickness in such environments (Saredakis *et al.*, 2020).

5.1 Validation and future work

5.1.1 *IBEC and Schön Klinik – Physiological data integration*

Currently, IBEC is working on a pilot experiment with SK to infer the internal states of the patient while playing the serious gaming scenarios. This data will be used to inform WP3 Digital Twin and to adapt different parameters of the environment based on the level of fatigue or stress.

To do so, we are using the Empatica E4 to gather data from Electrodermal Activity (EDA) and Heart Rate (HR), which is synchronized using Lab Streaming Layer[16] to the different game events. Each patient will go through two experimental conditions, with a) fixed levels of difficulty which range from very easy to very hard, b) adaptive difficulty using a machine learning algorithm that takes the difficulty modulators to provide a desired performance (i.e., between 70-80% success rate). To do so, we are using a protocol developed at IBEC, which consists on a Pinball game that incorporates similar principles to the grasp-and-place one but does not require antigravitational movements.

[16] https://labstreaminglayer.readthedocs.io/info/intro.html

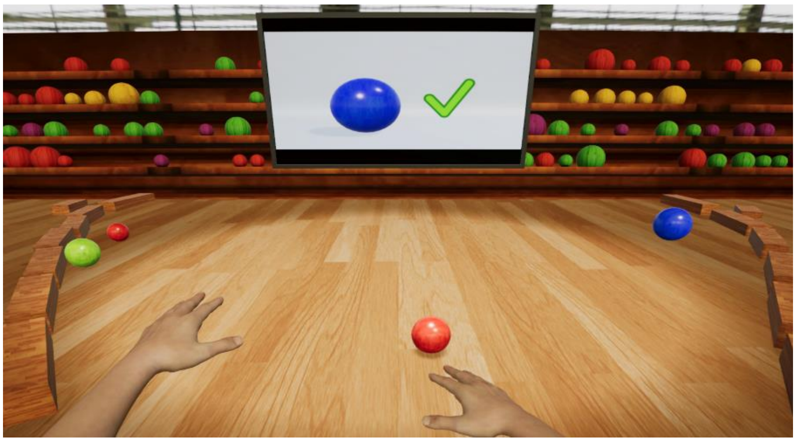


Figure 9. Pinball protocol for SK pilot on the inference of internal states based on Empatica E4 signals, game events and difficulty modulation.

To have a better estimate of the state of the user, we are using a modified version of the affective slider (Betella and Verschure, 2016), which is a validated tool for the self-assessment of affective states. This modification will include items from the NASA-TLX [17] questionnaire, to assess factors such as cognitive or motor fatigue, stress and perceived performance.

IBEC is also currently in conversation with VALDUCE to detect compensatory strategies from the RGS logs.

5.1.2 *Future work by DTU*

There are multiple research projects currently ongoing at DTU that could have an impact on the delivery and presentation of the serious gaming scenarios. In one such project, researchers are applying theories from behavioral psychology and design to improve the stroke patient's experience of home rehabilitation with the ReHyb exoskeleton. Their data set includes input from over 130 participants and the outcomes from their investigation could insights into how to improve factors that affect rehabilitation scenarios including but not limited to interface design, technology selection and implementation, long-term adherence to rehabilitation. A second project focuses on the design aesthetics of the interfaces and methods of interaction for stroke patient rehabilitation. This project currently has an ongoing study with Schoen Clinic Partners utilizing questionnaires and participatory design sessions with stroke patients and medical professionals to better understand stroke patients' capacity for interacting with technology for rehabilitation. Other upcoming potential projects will explore effect of embodiment and ownership in AR/VR and the design of user intention inference system to pilot the exoskeleton to assist during rehabilitation scenarios. Outcomes from these potential projects will have an impact on the design and framework for development of future serious games.

DTU is exploring the utilization of an existing platform for medical data currently being utilized at DTU by the Copenhagen Center for Health Technology (CACHET) called the CACHET Research Platform[18] (CARP). While this platform was originally designed for mobile applications, DTU will investigate the adaptability of this platform to the ReHyb project and its applicability for data management and visualization, or individual rehabilitation session performance data. The system provides capability for private data storage, user management, and other useful tools when designing a multi-user system.

The research by DTU is multifaceted and spans several different technology spheres. To address the challenges that are presented by the technology and integration into viable solutions for the ReHyb project and other affiliated or similar projects, DTU will begin remodeling of the GazeIT Laboratory. The newly remodeled lab, tentatively titled Smart Care Room, will allow researchers to simulate a

[17] https://humansystems.arc.nasa.gov/groups/TLX/downloads/TLX.pdf

[18] https://carp.cachet.dk/

patient’s home. Also, this new lab provides a dedicated space to prototype and test new rehabilitation scenarios and technology used to interface into the serious games. Additionally, the space will be fitted with sensors and furniture to design and develop a proof of concept of the digital twin which would encompass, the simulated home, user and the exoskeleton.

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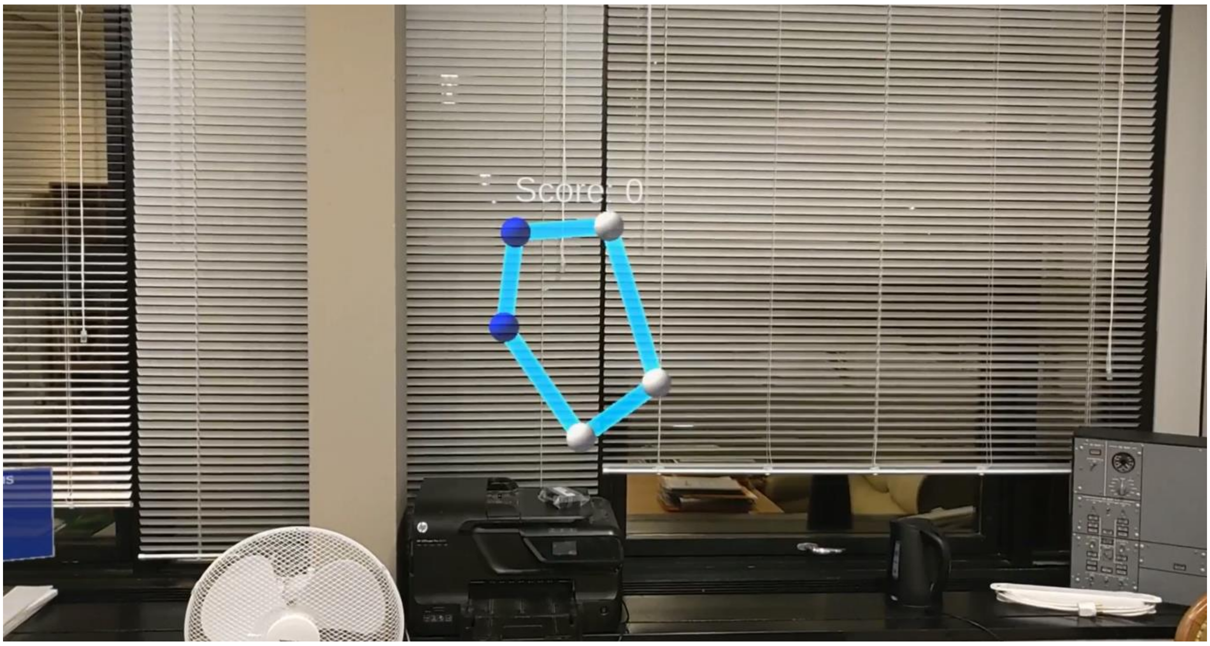
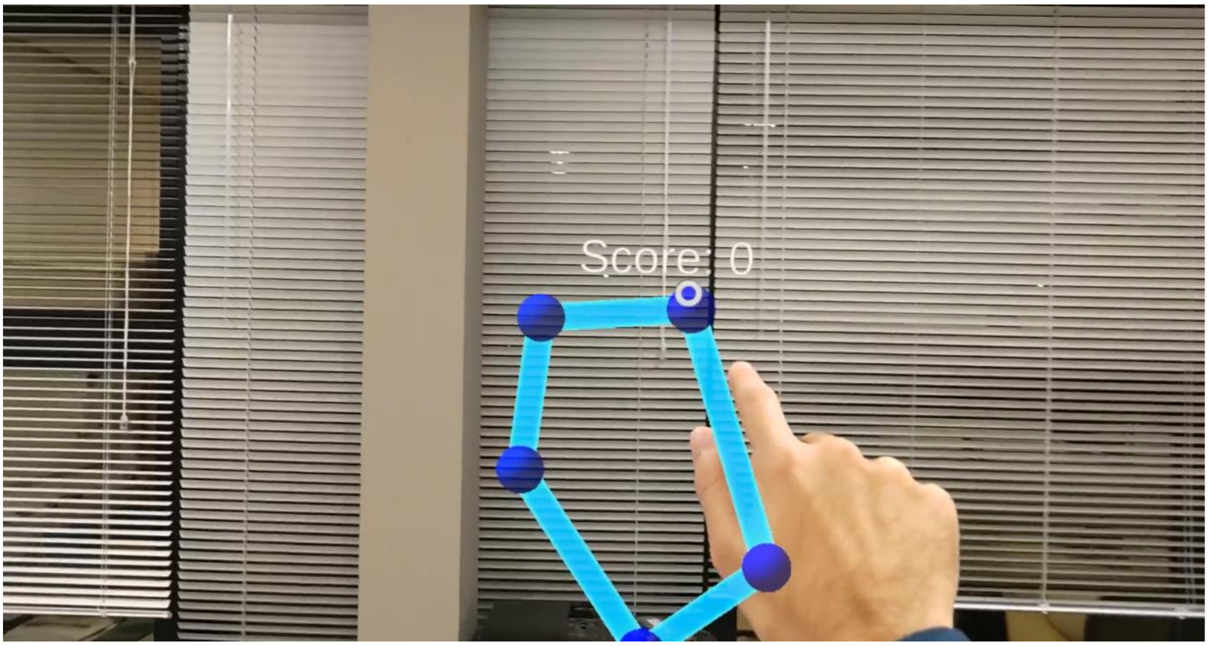
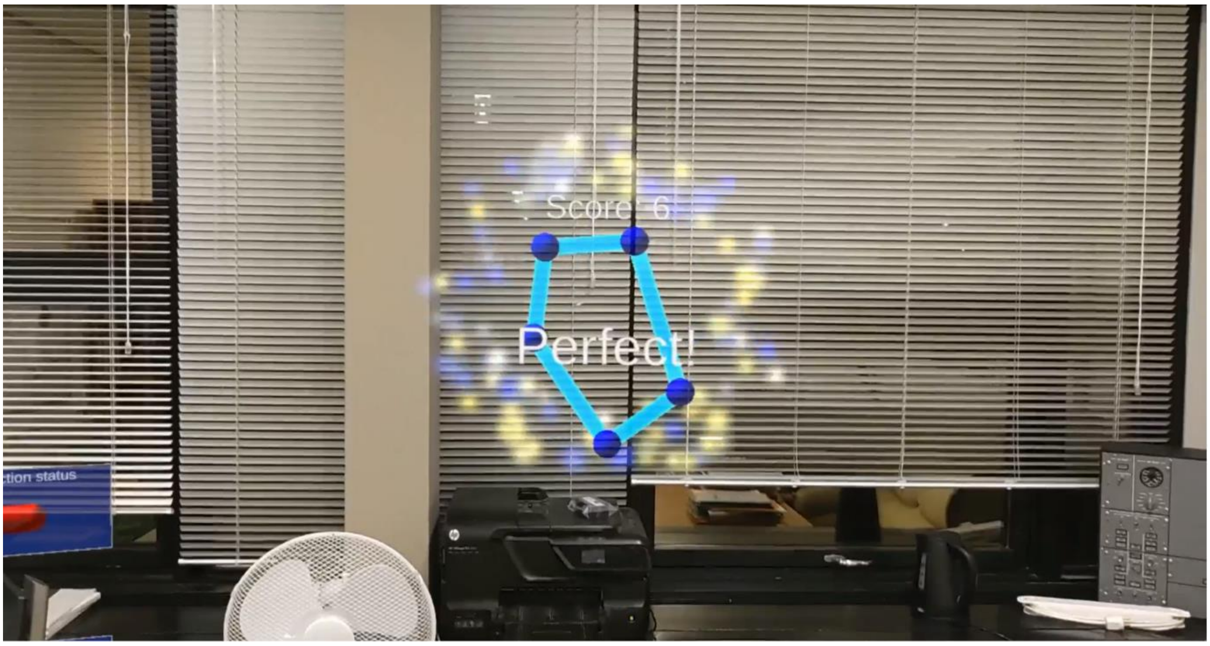
Appendix I. Images of Serious games






Score: 6
Perfect!


Kiwi


Ex 3


CAFE
Espresso
Coffee
Latte
Cappucino
Cafe mocha
Cortado

Appendix II. Definitions, Acronyms and Abbreviations

Acronyms abbreviations	Description
ReHyb	Rehabilitation based on Hybrid neuroprosthesis
OT	Occupational Therapy
MATE	Muscular Aiding Tech Exoskeleton
SoCCA	Socially Cooperative Cognitive Architecture
RGS	Rehabilitation Gaming System
ADLs	Activities of Daily Living
DT	Digital Twin
VR	Virtual Reality
AR	Augmented Reality
XR	Extended Reality
BO	Body Ownership
HMD	Head Mounted Display
UDP	User Datagram Protocol
LSL	Lab Streaming Layer
WP	Work Package
DTU	Technical University of Denmark
IBEC	Institute of Bioengineering of Catalonia
SPECS	Synthetic, Perceptive, Emotive and Cognitive Systems
VB	Villa Beretta