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Supporting Playful Rehabilitation in the Home using Virtual Reality Headsets and Force Feedback Gloves

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Abstract

Virtual Reality (VR) is a promising platform for home rehabilitation with the potential to completely immerse users within a playful experience. To explore this area we design, implement, and evaluate a system that uses a VR headset in conjunction with force feedback gloves to present users with a playful experience for home rehabilitation. The system immerses the user within a virtual cat bathing simulation that allows users to practice fine motor skills by progressively completing three cat-care tasks. The study results demonstrate the positive role that playfulness may play in the user experience of VR rehabilitation.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices

1 Introduction

Rehabilitation encompasses a range of rehabilitation services, such as assessment, prevention, intervention, supervision, education, consultation, and counselling that are delivered via information and communication technologies in lieu of in-person clinical visits [28]. The COVID-19 pandemic and related containment measures, such as quarantine, social distancing, and self-isolation, have catalyzed the widespread use of rehabilitation at home and it is believed that this new normal for rehabilitation services will continue after the pandemic [44]. The shift provides an opportunity to explore VR rehabilitation as an alternative method for people trapped at home alone without access to immediate facilitation. VR is considered a promising delivery vehicle to lessen the impact of an interruption in rehabilitation services while retaining pre-pandemic, in-person activity gains [10, 53].

Even during normal times, the proportion of eligible patients who successfully complete a rehabilitation program remains low due to 1) transportation issues that lower the convenience for patients, especially those living in remote areas, to access hospitals or rehabilitation centers [38]; and 2) the tedious and meticulous nature of conventional therapies, such as moving a hand back and forth dozens of times in a single rehabilitation session, which quickly results in patients' loss of interest in rehabilitation programs [1]. Prior studies on VR rehabilitation have primarily targeted the first issue—the delivery of functional and purposeful therapies to rehabilitate cognitive and functional abilities of target users through exposure to simulated "real-world" or analog tasks at home [56]. For example, prior research has deployed VR in-home rehabilitation to help stroke patients regain functional use of their bodies, such as for upper-limb mobility [62, 63], gait speed [37, 41], and ADL (activities of daily living) outcomes [6, 16]. Yet research investigating the mechanisms of designing and evaluating motivating contexts to tackle unappealing rehabilitation procedures is insufficient to guide practitioners to develop related systems and programs. Considering that there is not enough evidence to reach the conclusion that VR approaches are more beneficial than conventional therapy approaches in improving patients' body functions [29], we suggest more attention to be paid to the incorporation of ludic and motivating features into VR rehabilitation that help users to actively engage in playful rehabilitation programs.

Playfulness, defined as an individual's tendency to interact spontaneously, inventively, and imaginatively with the system [64], has been emphasized in some research regarding pediatric rehabilitation [46, 49, 55]. We take the stance that playfulness may be important for user groups of VR rehabilitation since it promotes motivation towards the accomplishment of self-imposed goals and tendencies towards active involvement, which are vital to the successful completion of treatment courses in general [1, 18, 54]. Presenting meticulous and tedious rehabilitation procedures in a more playful way can potentially increase users' motivation during the therapeutic process.

In this paper, we investigate how *playfulness* can be used as a driving force in designing rehabilitation systems and corresponding experiences for potential users. Our proposed system uses a VR headset in conjunction with force feedback gloves to present users with a playful experience for home rehabilitation. The rehabilitation is conveyed through a virtual cat bathing task, creating an abundant, engaging, and feedback-rich scenario for users in need of upper-limb rehabilitation solutions.

This paper makes three contributions. First, we present a novel playful VR rehabilitation system that integrates engaging game mechanics design with mechanical force feedback to trigger pleasurable interactions and positive experiences. Second, we discuss playfulness as a driving force for designing VR rehabilitation solutions. Third, we evaluate the system's potential in terms of playfulness in two user studies and discuss the implications of the system itself and the wider issues around introducing playfulness in VR rehabilitation.

2 Related Work

2.1 Virtual Reality for Rehabilitation

VR brings the complexity of the physical world into the controlled environment of the laboratory, allowing for precise control over multiple physical variables that influence behavior while recording and documenting users' physiological and kinematic responses [5]. By designing virtual environments that do not only look like the real world but also incorporate real-life challenges, the ecological validity of rehabilitation methods can be enhanced, which is a shortcoming of traditional clinical rehabilitation methods which have long been criticized [50]. There are several other additional benefits afforded by VR rehabilitation over conventional methods: stimulus control and consistency, real-time performance feedback, response modifications contingent on users' performance, self-guided exploration, gaming factors to enhance motivation, and duplicability [50, 51].

These distinctive advantages of VR make it a promising medium to convey rehabilitation tasks. In fact, VR has been promoted by laboratories for psychosocial interventions and physical rehabilitation

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since the early 1990s [25]. The main discussion in the literature has centered on how VR can be developed to address impairments and disabilities [52]. VR-based upper limb and hand function rehabilitation systems are of particular interest and are closely related to our work. For example, Jack et al. [21] developed a PC-based desktop VR system for rehabilitating hand function in stroke patients. Rinderknecht et al. [48] introduced a novel robotic device combining tendon vibration and virtual reality based on a touchscreen computer for neurorehabilitation of hand function. Postolache et al. [42] applied VR and Internet of Things (IoT) for remote monitoring of physical rehabilitation, facilitating effective communication between patients and physical therapists.

2.2 Playfulness of VR Rehabilitation

Playfulness is a complex variable encompassing individuals' pleasure, physiological stimulation, and interest [8]. It is associated with characteristics including motivations towards the accomplishment of self-imposed goals and tendencies towards active involvement [18, 54]. Reid [47] developed an integrated model of playfulness in virtual reality, in which he concluded based on previous work that playfulness can be determined within any transaction by evaluating for the presence of three elements: intrinsic motivation, internal control, and freedom to suspend reality. The playfulness of an activity can be modified by the level of user engagement, reflection, imagination, collaboration, and exploration through interaction [43]. If the activity is challenging, absorbing, matched to a user's skill level, and provides clear goals and unambiguous feedback, then participants will experience a flow state [7].

VR rehabilitation at home has gradually become technologically and practically feasible but leveraging informed professional input on system design to positively influence users' affective states and motivations is under-explored. Reid [46] examined the effects of virtual play intervention on the level of playfulness of children with cerebral palsy and produced insights useful for creating new VR applications for children with disabilities. Paraskevopoulos et al. [40] proposed a holistic VR-based framework for participatory design of serious games for rehabilitation, facilitating mapping game mechanics to playful therapeutic exercise games. Lin and Yeh [33] explored users' acceptance of VR-based mental-rotation learning and the results showed that higher levels of perceived playfulness were found in motion-control training.

Despite efforts to bring affect and emotion concepts into user acceptance studies, most research assumes that users are rational and behave based on logical thinking [66]. The affective aspects are often less central in the design or evaluation of rehabilitation systems compared to other attributes, such as effectiveness and usability. Due to the limitations of current studies, it is unclear how significant the role of affect can be in increasing users' motivation for continuous usage of VR rehabilitation systems.

2.3 Haptic Feedback in VR Rehabilitation

Haptic feedback has been identified as a significant signal for improving a user's performance in difficult tasks and is vital for the construction of a multidimensional and multisensory virtual environment, thereby enhancing immersion and enabling a richer user experience. Prior research has demonstrated that haptic feedback enhances the interactivity and immersiveness of VR games and further improves the performance of participants through enhanced realism [4, 27].

The past two decades have seen the emergence of rehabilitation treatments using VR as an alternative to some of the traditional rehabilitation approaches. Jack et al. [21] used force feedback gloves in their VR rehabilitation system, allowing more systematic manipulation of training and offering an individualized motor learning paradigm. Shing et al. [57] reported some specific benefits of adding haptic information to a 3D pick and place task. Giannopoulos et al. [17] evaluated a haptic device that simulated human handshakes in a virtual environment. Lee et al. [31] examined the synergy of associating out-of-body illusory tactile sensation with different visual feedback to improve the user experience for interacting with augmented virtual objects. Yeh et al. [65] developed a haptic-enhanced VR system to simulate haptic pinch tasks to assist the recovery of stroke patients in the chronic stroke phase.

However, in general, the integration of haptic information in rehabilitation remains under-explored, despite numerous potential benefits in terms of immersion and enjoyment. The majority of VR rehabilitation systems only provide an audio-visual interaction process due to the technological complexity and high cost of haptic-integrated solutions [57]. Less attention has been paid to how haptic feedback influences the emotion of participants within a virtual reality environment, even though participants' engagement and perception can be significantly altered by haptic feedback [26].

3 System Description

To explore the feasibility and efficacy of force feedback, VR immersion, and game mechanics in rehabilitation program design, we have developed a VR system that allows users to rehabilitate their fine motor skills in an enjoyable atmosphere through a cat-bathing task.

3.1 Conceptual Model

According to a model of playfulness and flow proposed by Reid [47], *playfulness* can be determined by intrinsic motivation, internal control, and freedom to suspend reality. Drawing on this playfulness model, we present a conceptual model (see Fig. 1) to elucidate how playfulness is made to manifest itself through the combined effect of three key drivers in the interaction process of the rehabilitation program: 1) VR immersion that suspends reality and realizes the framing; 2) force feedback that enhances the sense of presence [58, 60] of the virtual experience and amplifies users' internal control of the outcomes of their actions; and 3) appropriate game mechanics that provide clues for users to follow and thereby increases users' intrinsic motivation during play, and, ultimately, ensures an experience of flow. An increased experience of flow in VR can in turn intensify emotions elicited from the gameplay, leading to changes in heart rate, blood pressure, and cortisol levels [30]. Thus, we pay particular attention to the creation of an atmosphere and a control of rhythm to properly manage playfulness, avoiding potentially harmful effects resulting from intensified emotions.

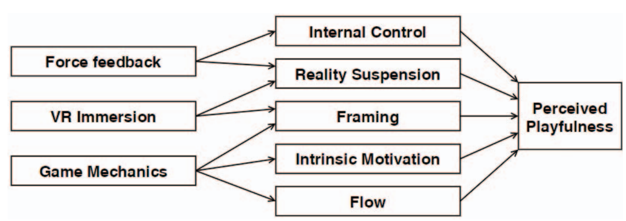

Figure 1: The conceptual model elucidating how playfulness is made to manifest itself through the combined effect of three key drivers in the interaction process of the rehabilitation program: 1) VR immersion; 2) force feedback; and 3) game mechanics.

3.2 System Composition

We implemented a VR system called *VRCatBath* with all virtual scenes developed in the Unity3D game engine (2020.3.18f1c1) using the relevant device SDKs. The system (see Fig. 2) was run on a PC with an Intel Core i7-10750H, 16 GB RAM, and a GeForce RTX 2060 6G dedicated graphics card. The PC is connected to an Oculus Quest 2 head-mounted display (HMD), with an 1832 $\times$ 1920 pixel resolution per eye and a refresh rate of 90Hz for the

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Figure 2: The Oculus Quest 2 HMD, Dexmo gloves, and laptop used in the study.

Figure 3: In this game, players wear the force feedback gloves and control the movement and strength of their hands, conducting a series of interactions with the cat and necessary tools using gestures such as pulp grip, spherical volar grip, and transverse volar grasp.

visual embodiment in VR. The headset and its controllers provide full six degrees of freedom (DOF) movement tracking for both the head and hands. Hand motion capture and force feedback in VR were provided by Dexmo gloves, which are lightweight 11-DOF mechanical exoskeleton systems [19]—note that we used an updated version of Dexmo that supplies both variable force feedback and vibrotactile feedback [12]. With physically attached tracked controllers, the glove system supports the room-scale VR experiences that most headsets are capable of. A Dexmo glove weighs under 300g, providing good wearability vital to rehabilitation system users. Each glove is powered by an 1800mAh Li-Po battery allowing it to operate wirelessly for 8 hours while capturing the full range of hand motions and providing instant force feedback [12]. When users are touching or grasping virtual objects and the force feedback is activated, the glove exoskeleton forms a rigid body and exerts an opposing force to users' finger tips so that users can feel the size, shape, and stiffness of virtual objects. In combination with the immersive environment created by the HMD, a realistic sensation of interaction was provided by the system when participants carried out the cat bathing task.

3.3 Game Design

Three key elements can be considered as cornerstones of game design: 1) the context of the game that encompasses the storyline, the setting of the game, the goals, and the aesthetic information, which can significantly affect users' activities; 2) the activities that must be carried out in order to win the game, that is, functional information, such as what the user can do and how the game responds to the user's decisions; and 3) how well the game allows the user to understand what must be done, and how to actually accomplish it [15].

3.3.1 Context

Hand rehabilitation exercises are designed to test and practice certain abilities of individuals, involving applying task-oriented forces to hand areas to regain strength and range of motion [2]. The exercises included in our game are commonly seen in activities of daily living as well as in well-established exercises, such as the Jebsen Test of Hand Function (JTHF) [22], Box and Block Test (BBT) [34], and Sollerman Hand Function Test [61]. Considering the exacerbating mental health conditions of many people caused by the isolation during the pandemic, we integrate pet-related contents into a hand rehabilitation program in VR, aiming to provide users with companionship, provide a sense of purpose and meaning, reduce loneliness, and increase socialization [11, 32] while they are enrolled in the hand rehabilitation program.

3.3.2 Goal

In the game players wear force feedback gloves and control the movement and grasping strength of their hands, conducting a series of interactions with the cat and necessary tools to complete the bathing task.

The cat is designed to have the characteristics of real-life cats, such as curiosity and naughtiness. Most importantly, bathing is not its favorite activity. Thus, players need to "bribe" the cat with food treats before the bath and keep it in a relatively relaxed mood when placing the cat in the basin. Immediately after the bath, players must blow-dry the cat with a hair dryer since it does not feel comfortable being wet. During the entire exercise, gentle petting of the cat is regularly required to soothe its emotions. Players will win the game if they successfully complete all procedures for the cat bathing task. Too many mistakes or inactivity will irritate the cat and will lead to failing the game.

3.3.3 Aesthetics

Aesthetic experience is more than superficial sensations—it is a play experience producing "fun" in its fullest sense [39]. In this game we manage playfulness by carefully manipulating the portion of "hard fun" (challenge) and "easy fun" (immersion in the game), subdividing playfulness in a more comprehensive way into "aesthetic" components of sensation, narrative, and challenge. Concrete sensory pleasures arise from visual, auditory, and tactile elements of the play experience, such as the classic color combination of blue and white, which makes a bathroom look smart and clean; warm lighting, which gives the players a welcoming feeling while brightening up the space; the cute visual appearance and behaviors of the cat, which increases intimacy; the sounds of the cat, which reflect its emotions; tactile sensations, which adds a sense of reality, etc. The narrative for this game is linear, corresponding to the procedures normally required before, during, and after bathing. Each subtask contains a few goals that need to be achieved by the user through certain steps, which lead to the unlocking of the next subtask. Although challenges exist in the game, the overall atmosphere is relaxing and encouraging for players to fully enjoy the playfulness without bringing any burden to win the game or cause intense emotions during play.

3.3.4 Procedures

The three tasks involve fully articulated hand interactions with virtual objects of different sizes and shapes. They are designed to facilitate the exercises of three canonical hand-grips: pulp grip, spherical volar grip, and transverse volar grasp (see Fig. 3). The former pattern is a type of precision grip that focuses on dexterity and sensitivity while the latter two belong to the power grip category, which have an emphasis on security and stability [9].

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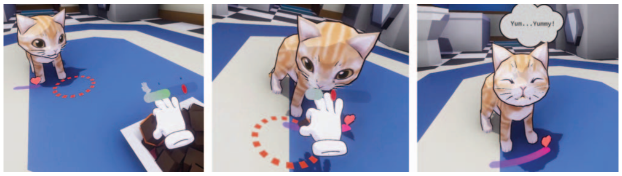

Figure 4: The game starts by preparing the cat for the bath psychologically through food treats.

Figure 5: In the second task, the user cleans and massages the cat with appropriate force.

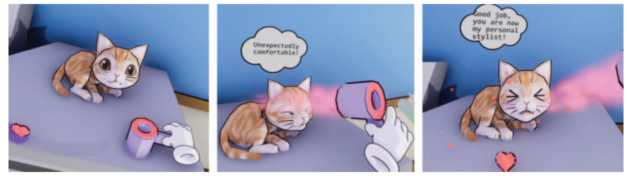

Figure 6: In the final scene, the user blow-dries the cat with a hair dryer.

Figure 7: The rules of the game are explained in the voice of the cat to add more fun.

Task 1: food treating (shown in Fig. 4). The game starts by psychologically preparing the cat for the bath through food treats. The user draws the attention of the cat with cube-shaped snacks taken from a plate in front of them. To successfully grab the snacks from the plate and steadily deliver them to the specified place (randomly assigned in the room and marked with a flashing red circle), the user needs to apply a moderate pinching force on the snack. The snack would then be either dropped on the floor or crushed depending on whether the force applied on it does not reach a lower threshold or exceeds an upper threshold. Thresholds vary for each single snack to increase the difficulty of the game and to increase variety. Feeding must be repeated several times until the cat is satisfied.

Task 2: massaging (shown in Fig. 5). The second scene will be unlocked after the food treating task. In this scene, the cat is sitting in the basin, impatiently waiting to be cleaned and massaged. The user needs to grasp its body to massage the cat and produce bubbles. The cat has different levels of sensitivity and force tolerances over its body. Massaging its head, back, or hip will trigger different reactions. The force to be applied for massage also has lower and upper thresholds similar to Task 1. A massage action requires the user to initialize a force and maintain it for at least 0.2 seconds to ensure the action is robustly recognized. The pause duration can be extended to further slow down this repetitive action, which may be preferable since joints of the hand and wrist are particularly vulnerable to the effects of aggressive rehabilitation [35]. Receiving massage with a mild force will relax the cat while using too much force will irritate it. The user is encouraged to perform slightly faster grasping actions over the cat's body with both hands when the user becomes more skilled and feels comfortable.

Task 3: blow-drying (shown in Fig. 6). In the final scene the user blow-dries the cat with a hair dryer. The temperature of the air flow depends on two factors: 1) the distance between the hair dryer and the cat; and 2) the power of the hair dryer, which is modulated by how hard the user squeezes the handle. During this process, the user has to apply a constant force to keep the hair dryer on. However, excessive power in the hair dryer causes more noise and heat that in turn makes the cat uncomfortable. Therefore, a balance should be sought between the distance of the cat and the hair dryer and the force exerted on the hair dryer's handle. Further, the flow of hot air should be correctly directed towards the cat by rotating the hand.

3.3.5 User Guidance

The rules of the game are explained in the voice of the cat to add an element of increasing fun. The cat's movements, sounds, and monologues serve to imply its requirements and provide feedback in response to the user's actions, as shown in Fig. 7. The playful mechanism ensures the user knows the actions needed at the current stage to achieve the goal. For example, a monologue, such as "*Giving me a bath? Impossible...unless you treat me well..*" is a hint suggesting that the user feed the cat as a way to ease its nervousness before the bath. When the cat is treated with enough snacks, it will wear a satisfied expression and tell the user "*You may give me a bath now*". "*Ooh, that does feel nice.*" is positive feedback affirming the user's actions; while "*Ouch, you are hurting me, you foolish human!*" is an example of playful negative feedback. The cat complains after the bath, "*Look at what you have done to me. I'm totally wet!*" The user receives compliments from the cat after blow-drying it: "*Good job, you are now my personal stylist!*" The states of the cat both serve as instructions to the users, helping them evaluate the effectiveness of their actions, as well as a vehicle to drive the plot of the playful experience.

3.3.6 Performance

Through interaction with the food and the hair dryer, as well as physical contact with the cat, such as petting and massaging, we hypothesize that users have an enjoyable experience practicing their motion control, such as dexterity, eye-hand coordination, in-hand manipulation, grasping and prehensile patterns, and bilateral coordination. The performance of a user is assessed from two aspects: 1) action quality; and 2) completion time. These measures are reflected in the cat's *friendliness* attribute, which is a variable with an initial value of 30 that captures the willingness of the cat to cooperate with the user in completing the bathing task. The value of *friendliness* decreases linearly over time. However, the user's engagement can both temporarily halt this decrease and increase *friendliness*. In this way the user's engagement directly influences the progress of the game. The game is won if the value of *friendliness* reaches 100 and the game is lost if it drops to zero (see Fig. 8). The hardware system measures the user's actions and provides physical guidance by applying force feedback to the finger joints of the user using the mechanical exoskeleton glove. Optionally, the measures can be used to grade and document the therapeutic intervention to support further treatment planning.

4 Evaluation

The eventual medical efficacy of any VR rehabilitation system necessitates carefully controlled and monitored longitudinal trials with patients under supervision of medical professionals. In addition to

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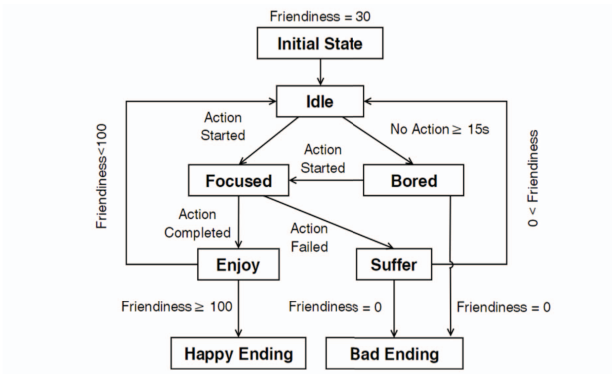

Figure 8: Users' performance is reflected in the *friendliness* attribute of the cat. The game is won if the value of *friendliness* reaches 100 and the game is lost if it drops to zero, as indicated in the flowchart.

Figure 9: Participants equipped with a VR headset and force feedback gloves are experiencing the rehabilitation system in Study 1 and 2 respectively.

raising obvious issues with COVID-19 safety, such a comprehensive and careful study is a research project of its own and, as such, beyond the scope of this paper.

Instead, the objective here is to study the potentially positive and negative qualities induced by introducing playful game mechanics and mechanical force feedback into a VR rehabilitation system. At this early design stage, we opted to study this by first carrying out an indicative study with seven healthy adults (Study 1). We then improved the system design based on feedback from the first study and carried out a larger and more extensive study with 14 healthy adults (Study 2). The studies focused on two aspects: 1) the participants' attitude changes towards playfulness during the course of the game; and 2) the contributions of key drivers, such as VR immersion, force feedback, and game mechanics, to participants' sense of playfulness of the system. The quantitative evaluation of the system was supported by user interviews in the two studies. In addition, to complement this data, we invited three physical therapists to provide expert assessments on the system's feasibility as a VR rehabilitation solution. All studies in this paper had approval from the local ethics committee and informed consent was obtained from all participants.

4.1 Study 1

Study 1 served as a formative study involving seven healthy individuals. The main objective was to assess the feasibility of the VR rehabilitation system and collect design feedback for the next design cycle.

4.1.1 Method

We recruited seven participants (4 males, 3 females). Their ages ranged between 23 and 30. All participants had a medical background, such as being graduate students, researchers, or doctors in a medical faculty. One participant had prior experience with VR rehabilitation. Each session lasted approximately 30 minutes.

Upon arrival, participants were introduced to the research background and study procedure. Next, they were asked to complete a demographic questionnaire and a questionnaire probing their attitudes towards the system. Thereafter they were fitted with a VR HMD and force feedback gloves (see Fig. 9). The researcher explained the purpose of the study and the virtual scenario and participants were allowed to familiarize themselves with the equipment. A study session commenced when the participant was comfortable with the controls in VR.

The bathing task consists of three subtasks, which correspond to the procedures required before, during, and after bathing. After each subtask, the researcher helped the participants remove the equipment and instructed them to complete a questionnaire concerning their in-game experience. After all tasks had been completed, participants were asked to complete the attitude questionnaire again.

4.1.2 Measurements

We adapted established psychometric instruments to inform the quantitative part of the study. The Likert scale for most instruments was set to a five-point scale. The attitude questionnaire (Table 1) included six questions intended to explore three concepts: 1) users' attitudes towards using the system, adapted from Moon and Kim [36], with three pairs of antonyms describing the usage of the system as a bad/good, foolish/wise, unpleasant/pleasant idea; 2) users' intention to use the system, adapted from Dumpit and Fernandez [13], with two items asking participants to what extent they would like to begin or continue the game and recommend the game to others; and 3) the expected/perceived playfulness of the system. The in-game experience questionnaire (Table 2) included a total of 12 questions intended to explore the effectiveness of three key drivers of playfulness. The items for measuring force feedback were adapted from Slater et al. [59], and asked participants to what extent they felt glove control was easy to learn and whether any sense of reality/enjoyment was added to the game. In addition, participants were also asked whether they became so involved they momentarily forgot about the existence of the gloves. Eight items for measuring VR immersion and game mechanics were adapted from the Immersion Questionnaire developed by Jennett et al. [23]. In the VR Immersion part of the questionnaire, participants were asked if they lost track of time, how focused they were on the game, if they felt separated from the real-word environment, and if they became so involved they forgot about the fact they were using controls to play the game. In the game mechanics part of the questionnaire, participants were asked to what extent they felt motivated and what motivated them the most, if they were interested to see how the game events would progress, and if they were in suspense about winning or losing the game. Finally, all participants were asked to fill in the Simulator Sickness Questionnaire (SSQ) [24] to measure any sickness symptoms of the user. The complete questionnaire with all the above questions was paper-based and administered after the removal of the VR headset and gloves.

4.1.3 Results

Since this was a formative study we do not report statistical significances as there is no attempt to generalize to a population. All claims made in this section are with respect to the sample of participants engaged in the study.

In general, participants rated the concept highly by agreeing with positive descriptions, such as *good* (before the tasks: 4.54/5.00; after the tasks: 4.23/5.00), *wise* (before: 4.23/5.00; after: 4.23/5.00), and

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Table 1: Attitude questionnaire.

Items (5 point Likert scale, 0 = strongly disagree, 5 = strongly agree)
Attitude Towards Using
- Using this system is a (bad/good) idea.
- Using this system is a (foolish/wise) idea.
- Using this system is a (unpleasant/pleasant) idea.
Intention to Use
- To what extent would you like to begin or continue playing the game right now?
- To what extent would you recommend the game to others?
Expected/Perceived Playfulness
- How playful do you expect the game to be/did you think the game was? (0 = not at all; 10 = very)

Table 2: In-game experience questionnaire.

Items (5 point Likert scale, 0 = strongly disagree, 5 = strongly agree)
Force Feedback
- To what extent did you feel that the gloves control was easy to pick up?
- To what extent did you feel that the force feedback added a sense of reality to the game?
- To what extent did you feel that the force feedback added a sense of enjoyment to the game?
- At any point did you find yourself become so involved that you were unaware you were wearing gloves?
VR Immersion
- To what extent did you lose track of time?
- To what extent did you feel you were focused on the game?
- To what extent did you feel as though you were separated from your real-world environment?
- At any point did you find yourself become so involved that you were unaware you were even using controls?
Game Mechanics
- To what extent did you feel motivated while playing?
- What motivated you the most in the game? (write down the answer directly)
- To what extent were you interested in seeing how the game's events would progress?
- Were you in suspense about whether or not you would win or lose the game?

pleasant (before: 4.31/5.00; after: 4.23/5.00). Moreover, their intention to use the system was above a neutral rating and they expected the experience of the system to be fun. After engaging with the tasks, most participants expressed that the design and experience of the system met their expectations, which was supported by the average ratings of *expected playfulness* (7.60/10.00) and *perceived playfulness* (7.80/10.00). There were some drops in ratings resulting from dissatisfaction with the hardware that had some embedded flaws. Frequent mounting and dismounting of devices between tasks in order to complete the questionnaires was also seen as a nuisance and taxed participants' patience. In summary, it is reasonable to expect that participant's impatience is reflected in the attitude questionnaire in some way. However, with ratings largely beyond a neutral score, the participants' high recognition of the system's merits is clearly demonstrated.

During the study, participants were observed to be able to pick up the control of the gloves with less effort and experienced an increased sense of reality and enjoyment as the study proceeded. Participants also reported they were so focused on the game that they *lost track of time* (Task 1: 3.92/5.00; Task 2: 3.85/5.00; Task 3: 3.69/5.00) and *feeling separated from the real-world environment* (Task 1: 4.08/5.00; Task 2: 3.85/5.00; Task 3: 3.75/5.00). Unfortunately, although participants enjoyed the benefits brought by VR immersion and force feedback, the weight of the system failed to let them forget about the fact that they were *wearing gloves* (Task 1: 2.69/5.00; Task 2: 2.69/5.00; Task 3: 2.69/5.00) and *using glove control* (Task 1: 2.85/5.00; Task 2: 2.46/5.00; Task 3: 3.38/5.00) to a certain extent. Additionally, participants felt highly motivated by the game elements, such as the cute appearance and naughty behavior of the cat, the artistic scene design, instant force feedback during interaction, their desire to win, and the sheer novelty of the system. As the game proceeded, their motivation and curiosity towards the game naturally declined. Conversely, their desire to know the result of the game, that is, whether or not they would win or lose, increased as they devoted more time to the game.

Many interesting monologues of the participants were recorded during their interaction with the cat. Some of these were instructions given to the cat when it did not behave as the participants expected. For example, in Task 1 the cat was easily distracted and sometimes might run away from the participants if they failed to grasp the snack and caught the cat's attention. In this case, some participants tried to talk to the cat so that it could notice the snack they were holding towards it. They would give orders such as "*look here*" (P1, P4, and P6). Participants showed great patience with the cat's continuous requests for food and often replied with gentle words, "*Still hungry? All right, one more*" (P2). P7 was surprised by the reaction of the cat when he failed to accomplish a small goal,"*It just spat at me*".

In addition, no severe simulator sickness symptoms from SSQ were reported by participants (nausea: 23.17; oculomotor: 23.82; disorientation: 21.87; total (weighted sum): 27.78).

4.2 Study 2

The first formative study allowed us to conclude that playful VR rehabilitation has reached a state where it can be deployed and the initial results are promising. In addition, the study also allowed us to improve the system design and study procedure. In this study, we involve both participants in a user study and physical therapists in expert assessments to gain further insights.

4.2.1 Method

We used opportunity sampling to recruit 14 participants aged between 22 and 26 from a university campus (13 males, 1 female). Our sampling frame was limited this time around due to COVID-19 safety protocols and local restrictions. None of the participants had any prior experience with VR rehabilitation. Each session lasted for approximately 30 minutes. Following the study, we invited three experienced physical therapists (1 male, 2 females) from a local hospital to experience and evaluate our system from a professional rehabilitation perspective.

The feedback and insights from Study 1 resulted in four major changes to the study protocol and system design. First, we enriched Tasks 2 and 3 to maintain the interest and curiosity of participants while playing. In Task 2, we assigned different sensitivity levels and reactions to the cat's body parts. In Task 3, we added the distance between the cat and the hair dryer as a factor influencing the air temperature. Second, participants in Study 2 were required to keep the VR headset and gloves on between the tasks. Instead of filling out forms, participants told the researcher their answers to questions read out by the researcher. This saved time and effort for participants from (dis)mounting devices between task sessions, reducing their potential negative emotions resulting from such tedious operations. This also removed the need for context switching that would inevitably occur if the participant had to use controllers to fill out forms inside the virtual environment. Third, we adopted the latest version of the Dexmo mechanical force-feedback gloves, which used canvas gloves (as shown in Fig. 9 (right)) instead of rubber fingertips (as shown in Fig. 9 (left)) to attach the device onto users' hands. In addition, we added some minor features to the system based on the newer feature set of these gloves. For example, we introduced vibration alarms if the force applied on the cat was higher than the appropriate range.

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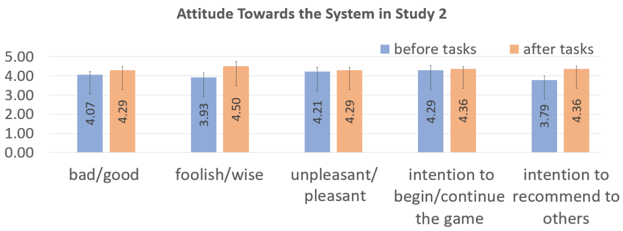

Figure 10: Participants' attitudes (mean values; error bars show standard error) towards the system, reported before and after all three tasks from Study 2.

Finally, in addition to the questionnaires in Study 1, all participants were asked to report their perceived cognitive load using the NASA Task Load Index (NASA-TLX) [20].

4.2.2 Results

The results of Study 2 echo the original conclusions from Study 1 regarding participants' attitudes and experiences, indicating a consistent result in these aspects (see Fig. 10 and Fig. 11). In addition, likely due to the improved study protocol, the system induced a low perceived cognitive load and further reduced simulator sickness.

Participants' attitudes towards the system increased after playing the game. We used Wilcoxon Signed-Rank tests ($n = 14$) on the paired *expected/perceived* ratings to assess statistical significance. The level of statistical significance was set at an initial α-level of $p \leq .05$. The test results indicate the difference in the *foolish/wise* rating changed significantly ($p = .006$) before and after the tasks (see Fig. 10). This means participants felt the system was significantly wiser than they expected. There were no significant differences in any of the other ratings before and after the tasks. While increases in most ratings were marginal, we believe overall this is a promising result and a testament to the potential of the system in that it is able to maintain high expectations in users' attitudes during use.

Regarding the changes in in-game experiences during the study, a steadily increasing trend was observed for most of the mean ratings (Fig. 11), while the *lost track of time* and *unaware using controls* mean ratings experienced fluctuations around middle-to-high levels. We used Wilcoxon Signed-Rank tests on the paired *Task 1/Task 2*, *Task 2/Task 3*, and *Task 1/Task 3* ratings. Most significant differences were observed in *Task 2/Task 3* ratings, including *lost track of time* ($p = .048$), *unaware using controls* ($p = .037$), *unaware wearing gloves* ($p = .011$), and *focused on the game* ($p = .020$). In particular, we found significant differences in *unaware wearing gloves* and *focused on game* in the *Task 1/Task 3* ratings comparison with $p = .018$ and $p = .020$ respectively. These results imply that the participants were getting used to the gloves and became more immersed in the experience as the study proceeded.

In contrast to Study 1, participants reported lower mean SSQ scores (nausea: 1.22; oculomotor: 15.70; disorientation: 8.95; total (weighted sum): 14.16). Mann-Whitney U test results suggests the reductions in nausea and total scores were significant with $p = .039$ and $p = .042$ respectively. Moreover, Study 2 also assessed participants' perceived cognitive load. The mean NASA-TLX score among participants was reported to be 3.81 on a weighted 10-point scale, indicating that the overall workload of the task was relatively light.

4.3 Expert Assessments

To complement the ratings from the participants we engaged three rehabilitation professionals in order to solicit expert assessments. These three experts first experienced the system themselves in a process largely identical to the other participants in Study 2. During this process, and afterwards, they were encouraged to express their opinions about the solution, including its potential. Each interview session lasted about 30 minutes and the conversations were recorded.

The expert assessments were focused on the overall feasibility of the solution. We were encouraged by the three experts having relatively positive attitudes towards VR rehabilitation. They also did not raise any severe concerns about the proposition of the system presented in this paper, although there are several issues that would need to be tackled before the VR system could be used in a longitudinal study with rehabilitation patients. Expert 1 mentioned similar systems he had experienced in a medical research lab and agreed that integrating VR, as well as other haptic feedback, into the rehabilitation process was trending in this field.

However, the disadvantages were also obvious at the current stage of VR rehabilitation. For example, device weight was raised as a concern. Expert 1 pointed out that some patients who were still at the early stage of their recovery might require assistance from others to wear the devices. Expert 3 also mentioned that patients would likely find it demanding to complete a single therapeutic session (15–20 minutes) with the hardware used in this instance.

The high demand on the cognitive capacity of the users was considered as another potential obstacle for wider acceptance of the system since some patients may have both cognitive and physical impairments. Unlike the healthy adults in our studies, rehabilitation patients may find it challenging to pick up the controls or comprehend the game mechanism (Expert 2). All experts agreed that playfulness should be maintained at a moderate level to benefit patients because intense gameplay is likely to impose negative impacts on rehabilitation programs.

Expert 1 further stressed that the rehabilitation process was complex and may involve tracking interdependent body parts as well. Moreover, the design of rehabilitation programs would need to be customized according to the patient's health condition and living environment (Expert 1). There is a long way to go for the standardization and commercialization of VR rehabilitation applications.

5 Discussion

Recognizing the paramount importance of playfulness as a driving force in designing a VR rehabilitation system and improving the user experience, we identified four strands of lessons learned and future research directions for creating future VR rehabilitation systems, which we elaborate on below.

Strand 1: moderate pursuit of playfulness. Our interviews with rehabilitation experts suggest that essential but meticulous repetitive elements would inevitably be undermined, being replaced by more thrilling interactions, if we put primacy on playfulness during the development process of rehabilitation programs. There is a risk that this will not only weaken the therapeutic effectiveness of the rehabilitation program but also induce overly intensified emotions, thereby potentially introducing malign effects in the therapy. Thus, we stress that the pursuit of playfulness should be moderate due to the uniqueness of rehabilitation programs, as it is essentially a learning process requiring deliberate practice involving self-awareness to be in tune with performance. To set clear and rational goals for target users, we investigated existing rehabilitation programs at the early stage of this research to balance the challenges and skills required to meet those challenges in game design. Therefore, it was unsurprising to observe healthy adults in our studies accomplishing set goals with relative ease.

Strand 2: playfulness promotes engagement. In the two studies, user experience of *force feedback*, *VR immersion*, and *game mechanics* were rated highly among participants, which echoes the high *perceived playfulness* of the system. We conjecture that this high level of playfulness has the potential to alleviate one major issue inherent in conventional therapies—the tedious and meticulous nature of conventional rehabilitation programs. Further, the play-

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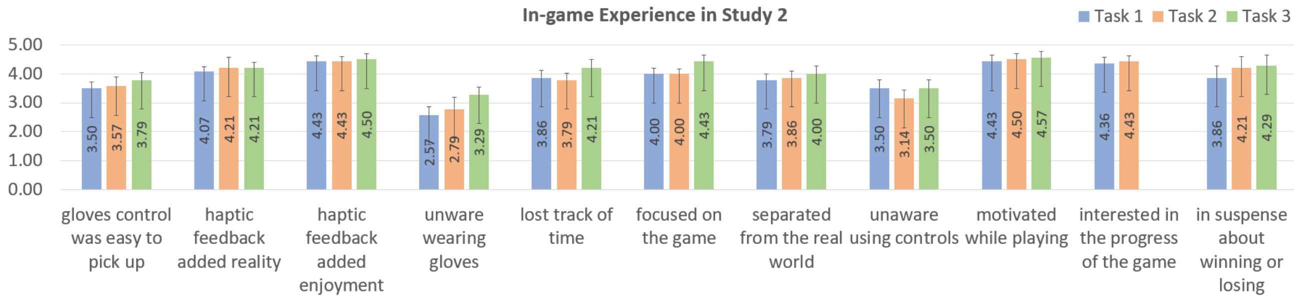

Figure 11: In-game experiences reported by participants after each task (mean values; error bars show standard error) from Study 2.

fulness of the game encouraged participants to actively engage in functional and hedonic experiences, creating an affective bond with the system. The engagement of participants was reflected in their tendency to express themselves verbally after they had developed a natural affinity with the cat.

Strand 3: mitigation of imperfect hardware. During the studies, participants raised issues, such as periocular pain, caused by wearing glasses and the headset simultaneously. Although it was not our intention to investigate the user experience of novel hardware in this study, the utility and playfulness of the VR rehabilitation solution were intrinsically influenced by the current state of hardware configurations available. Interestingly, we observed an incremental increase in the ratings for *unaware wearing gloves* and *unaware using controls* from Study 1 to Study 2, possibly indicating that it is possible to compensate for the weak spots of imperfect hardware to some extent.

Strand 4: potential of playfulness in VR rehabilitation. Both participants and experts saw great potential in VR rehabilitation due to its ability in creating numerous fascinating scenarios that are beyond reach in realistic settings and minimizing the impact of limited rehabilitation services provided by hospitals and clinics. This echoes findings described by Alankus et al. [3] and suggests that a promising direction of future work is to explore how patients can work with professionals to explore the suitability of various games and select appropriate ones that meet their individual rehabilitation needs. This may help them tolerate painful therapeutic procedures and potentially work as a palliative approach to combat mental stress.

6 Limitations and Future Work

Reflecting on the procedures and results of the two studies, we see two improvements that can be made to the experimental protocol for future studies. First, a researchers read questions out aloud to participants in Study 2 to save them from having to dismounting devices in between tasks. However, there is a risk that the voice from the outside world would affect the sense of presence of participants, which echoes findings from Putze et al. [45] and Erickson-Davis et al. [14]. Future work may want to consider embedding virtual questionnaire forms or using avatars to represent researchers in VR, which may be beneficial to help maintain the impression of a neutral experimental environment [14, 45]. Second, the canvas force-feedback gloves we used in Study 2 were relatively large and exceeded the average hand size of most females. Therefore, Study 2 was male-dominated and may lack sufficient insights from the female perspective.

Our study contains quantitative data with support from interviews with users and experts, which we believe is informative and fruitful for teasing out the positive and negative qualities of the system and to better understand the emergent design space of playful VR rehabilitation at the early stage of this research. It would be inappropriate to investigate any therapeutic effects of the system at this early stage due to both safety issues during COVID-19 and the fact that therapeutic effects in this area will require long-term assessments which invariably will involve additional factors, such as medication, change of personal circumstances, change of staff, and health condition variation over time. Thus, we focused on the playfulness aspects of a VR rehabilitation system. Therefore, we did not involve patients in evaluating the playfulness potential of this technology. Since there is no meaningful baseline to compare against our user studies primarily serve as a validation that the system is indeed usable and can induce positive attitudes and feelings of playfulness. This motivates further work involving patients at a later stage in the design process. Promising future work includes studying this and other future playful VR rehabilitation systems in controlled experiments to be able to distill design guidance that can generalize to the population. We believe this is a research trajectory that will demand a concerted effort of many research teams but the end-results may very well be worth it—potentially resulting in the ability to provide patients with much more engaging therapeutic experiences and thus demonstrating how VR can tangibly increase quality of life.

7 Conclusions

In this paper, we have presented a novel playful VR rehabilitation system that couples a VR headset with mechanical exoskeleton force feedback gloves. We took playfulness as the driving force of the system and manifested it through a combination of three key drivers: VR immersion, force feedback, and game mechanics. We evaluated the system in two user studies and with interviews of three experts. We found that all key drivers played a positive role in enhancing the perceived playfulness of the system, which could contribute to the participants' positive attitude towards the system and willingness to use it in the future. Based on these results, we identified four strands of lessons learned and future research directions, which we hope can contribute towards the establishment of more effective and enjoyable physical therapies that couple VR headsets with mechanical exoskeleton force feedback gloves.

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