GAME-ASSISTED REHABILITATION FOR POST-STROKE SURVIVORS

A Dissertation Presented

by

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ABSTRACT

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August 27, 2019

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Stroke is a leading cause of permanent impairments among its survivors. Although patients need to go through intensive, longitudinal rehabilitation to regain function before the stroke, patients show poor engagement and adherence to rehabilitation therapies which hampers their recovery. As a means to enhance stroke survivors' motivation, engagement, and adherence to intensive and longitudinal rehabilitation, the use of games in stroke rehabilitation has received attention from research and clinical communities. In order to realize this, it is important to take a holistic, end-to-end research approach that encompasses 1) the development of game technologies that are not only entertaining but also rehabilitating or monitoring the functional/impairment level, 2) the quantitative evaluation of the clinical efficacy of the technologies, and 3) the deployment of the technologies in real-world clinical settings to understand if the

anticipated clinical efficacy is achieved and how the technologies affect the interaction dynamics among patients, therapists and the technologies.

In this dissertation, we introduce our approach to this holistic, end-to-end research for the development, validation, and understanding of real-world use of games in stroke rehabilitation. Towards that end, we designed and developed *Neuro-World* that can enable accurate, longitudinal assessment of patients' cognitive function outside the clinical setting. The analysis results in the controlled setting show that the proposed approach can accurately assess patients' cognitive function without the help of therapists. While it remains as a future study to deploy *Neuro-World* in stroke survivors' free-living environments and study the system's impacts on patients' engagement patterns, we use another game platform (i.e., *RAPAEL Smart Board*) to demonstrate our efforts to understand the real-world interaction dynamics. We investigate the use of the games in the actual hospital setting where the system has been adopted as part of stroke survivors' routine upper-limb motor rehabilitation therapies. Our findings reveal patients unexpected engagement patterns, therapists critical roles and challenges in maintaining patients' engagement and therapeutic value. These findings enhance our understanding of the impact of serious games on the patients' engagement to rehabilitation therapies and provide us with insights into potential directions leading to the development of more effective games for stroke rehabilitation.

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CHAPTER 1

INTRODUCTION

Stroke is one of the leading causes of permanent disabilities in the stroke survivors' motor and cognitive function [16]. Each year, in the United States alone, nearly 800,000 individuals suffer from a stroke. Approximately 75% of them experience long-term motor impairments with their upper-limbs, which are marked by reduced strength and dexterity [16]. Moreover, 17% of the survivors suffer from long-term cognitive impairments, such as deteriorated memory and attention [78]. Such deficits significantly affect stroke survivors' performance in the essential activities of daily living [54] and their health-related quality of life [37, 48]. In the conventional rehabilitation setting, stroke survivors go through an iterative rehabilitation process, in which therapists assess patients' impairments, identify attainable goals for potential recovery, design and administer rehabilitation therapies to help patients achieve the identified goals in the hospital setting [96]. Research results support that patients can achieve greater recovery when they participate in intensive (i.e., more hours of therapy) and challenging (i.e., engaging in more difficult therapeutic exercises) rehabilitation therapies for a longer duration in the hospital setting [50, 74] due to brain's capacity to reorganize its synaptic connections (i.e., neuroplasticity) [42, 87]. Despite such acknowledged importance of intensive, longitudinal rehabilitation, research and clinical communities attempt to reduce the cost of overall stroke rehabilitation by discharging patients from rehabilitation hospitals early [113] and engaging the patients in rehabilitation therapies in their home setting [97]. However, patients exhibit poor engagement and adherence to rehabilitation therapies, especially in the residential setting [139] when they have limited access to therapists, who are responsible for motivating and encouraging patients to engage to more effective therapies [177].

Research and clinical communities became increasingly interested in integrating games with stroke rehabilitation in both clinical and residential settings to motivate stroke patients to engage and adhere to rehabilitation therapies [180]. In order to develop and employ rehabilitation games in a way that can truly contribute to patients' engagement and their recovery in motor and cognitive function, it is essential to take a holistic, end-to-end research approach. Within this approach, researchers need to develop game technologies that go beyond merely entertaining players but could address the essential aspects of rehabilitation, such as stimulating the impaired function in accordance with therapeutic goals for individual patients, evaluating their functional/impairment level, and monitoring its change in longitudinal rehabilitation. The developed technologies, then, need to be quantitatively evaluated for their clinical efficacy to improve and/or assess the target impairments. Finally, the developed technologies that are often validated in controlled settings need to be deployed in real-world settings (e.g., clinic or patients' home settings) to understand if the anticipated efficacy can indeed be translated. More specifically, it is essential to qualitatively investigate the interaction dynamics among patients, therapists, and the deployed technologies in uncontrolled, real-world rehabilitation settings to truly understand the reasoning behind the observed clinical efficacy (or inefficacy) of the technologies. Despite the importance of such a holistic, end-to-end approach, research communities' efforts in game-assisted rehabilitation have been largely disjointed. For instance, clinical research communities at large are interested in investigating the therapeutic benefits of game-assisted rehabilitation [150, 167]. However, reported results are often based on the changes in patients' motor/cognitive functions after they engaged in game-assisted rehabilitation in controlled settings, and thus provide limited information regarding whether the improvement in motor/cognitive functions are due to the enhanced patients' engagement by using games [106]. On the other hand, human-computer interaction research communities in general are interested in developing games/interfaces and evaluating their impacts on patients' engagement. However, such studies often do not attempt to rigorously evaluate the clinical efficacy of the proposed games/interfaces on improving or monitoring patients' motor/cognitive functions [4, 5, 12].

In this dissertation, we demonstrate how we take a holistic, end-to-end research approach for the development, validation of games, and understanding of their use in real-world stroke rehabilitation. Towards that end, in collaboration with Woorisoft Inc., we designed and developed *Neuro-World*—a set of six mobile games—which allows stroke patients to self-administer accurate, longitudinal assessment of their cognitive function even outside the hospital setting. *Neuro-World* was designed to stimulate visuospatial short-term memory and selective attention since they are known to be able to explain the various aspects of human cognition according to neuropsychological findings. Furthermore, we proposed a novel machine-learning approach to translate patients' performance during self-administered *Neuro-World* game play into the Mini-Mental State Examination (MMSE)—a widely-accepted clinical measure—, which highlights the translational impact of the system in real-world settings. We collected game-specific performance data from 12 post-stroke patients at baseline and a three-month follow-up, which were used to train supervised machine learning models to estimate the corresponding MMSE scores. The results presented herein show that the proposed approach can estimate the MMSE scores with a normalized root mean square error of 5.75%. We also validate the system's responsiveness to longitudinal changes in cognitive impairment level and demonstrate the system's positive usability in cognitively impaired individuals and their willingness to adhere to the longitudinal use. Despite the promising results, it is yet to be investigated if the proposed approach can indeed enhance patients' engagement to rehabilitation in uncontrolled, real-world settings. While the real-world deployment and investigation of *Neuro-World* is left for a future study, we leverage *RAPAEL Smart Board*—a commercial serious game platform developed for upper-limb motor rehabilitation—to demonstrate our endeavor to understand the impact of using serious games on the interaction dynamics among patients, therapists, and games when games are employed during routine rehabilitation therapies in the real-world clinical setting. For that, we established a partnership with a rehabilitation hospital where game-assisted rehabilitation was routinely employed over two years. We then conducted an observational study, in which we observed 11 game-assisted therapy sessions and interviewed 15 therapists who moderated the therapy who had been engaged in upper-limb motor rehabilitation on a daily basis using *RAPAEL Smart Board*, a commercially available game-assisted rehabilitation that is designed specifically for gross-arm rehabilitation in stroke survivors. Significant findings include 1) the different engagement patterns of stroke patients in game-assisted therapy, 2) the imperative roles of therapists in moderating games and the challenges therapists face during game-assisted therapy, and 3) the lack of support for therapists in delivering patient-centered, personalized therapy to individual stroke patients. Furthermore, we discuss design implications for more effective rehabilitation game therapies that take into consideration both patients and therapists and their specific needs.

This dissertation makes the following contributions.

1. We developed *Neuro-World*, a set of six mobile games, based on the neuropsychological study results that a small number of basic cognitive processes (i.e., memory and attention), can explain various of aspects of human cognition. Furthermore, we indirectly validated such premise through the experimental results reported in this dissertation.

2. We demonstrated for the first time that we could accurately estimate patients' cognitive impairment level in a clinically well-established measure (i.e.,

the MMSE) based on their game performance while self-administrating *Neuro-World*. As previous empirical studies showed that the MMSE is strongly correlated with other tests, such as the WAIS [75], the MBT [49], and the MoCA [172], our proposed approach has the potential to generalize to accurately estimating more comprehensive, standardized instruments.

3. We revealed stroke patients' different engagement patterns during game-assisted therapy sessions and therapists' orchestrating roles in administrating personalized treatments (via game-assisted tools), as well as practical challenges that therapists faced during game-assisted therapy. These findings enhance our understanding of the impact of using serious games during routine upper-limb motor rehabilitation in the real-world hospital setting.

4. We discussed different ways to enhance and maintain patients' engagement in a therapeutically more meaningful way, which provides insights into practical ways to integrate game-assisted upper-limb motor rehabilitation into a rehabilitation process. Furthermore, we suggested potential research and development directions to develop dedicated user interfaces and training to better support therapists' comprehensive roles, which will contribute to enhancing the quality of rehabilitation therapies.

The rest of this dissertation is organized as follows. Section 2 introduces readers to stroke, permanent impairments stroke leaves to its survivors, the conventional rehabilitation, its challenges, and the use of technologies to overcome such challenges. Section 3 explains a machine learning approach to estimate patients' cognitive function in MMSE based on stroke survivors' performance while they play mobile games and reports the evaluated performance of the proposed approach. Section 4 explains the investigation into the interaction dynamics between therapists and patients during the routine game-assisted therapy in the actual rehabilitation hospital setting. Section 5 concludes this dissertation by summarizing the contribution of the two studies and discussing the anticipated future extensions of the studies.

CHAPTER 2

BACKGROUND

2.1 Stroke and Permanent Impairments

Stroke, medically termed as a cerebral vascular accident, is a rapid loss of brain cells caused by a disturbance of blood supply to the brain [122]. This lack of blood flow can be caused mainly by two different reasons. The most common cause is the narrowed or blocked arteries (i.e., ischemic stroke), which accounts for approximately 87% of stroke incidents [62]. Another common cause is the rupture of arteries (i.e., hemorrhagic stroke), which accounts for about 13% of all strokes [62]. The damaged brain is then unable to function, which leads to the death of around 18% of stroke victims [186]. Even if the victims survive from a stroke, many are left with permanent impairments in their motor (e.g., diminished strength and dexterity) [44] and cognitive functions (e.g., reduced memory and attention).

Approximately 75% of the survivors experience impairments in upper-limb motor function [16]. The survivors have a weakness, diminished dexterity in their upper-limb, which makes it difficult to perform reaching, grasping, or manipulating movements [171]. While the motor deficit is the hallmark of stroke, approximately 17% of the survivors suffer from impairments in their cognitive function [78]. Cognitive impairments include declined memory, attention, orientation, and reduced language skills and executive function [3]. In addition, cognitive impairments are associated with depressive symptoms [120], reduced longevity [163], and greater institutionalization rate [131]. Furthermore, cognitive impairments negatively affect the engagement of stroke survivors in rehabilitation therapies [39, 88, 124], hampering the recovery of motor function [31, 119]. These impairments in motor and cognitive functions, in turn, can significantly affect the survivors' performance in their activities of daily living [54] and deteriorate their health-related quality of life [37,48]. Consequently, it is important to investigate ways to improve the quality of the rehabilitation process.

2.2 Rehabilitation, Therapists' Roles, and Challenges

Stroke survivors achieve functional recovery to some extent within the first few weeks after stroke (i.e., spontaneous recovery), then reach a stable, yet still improvable phase of recovery [17,178]. In order to regain and relearn the motor and cognitive skills that were affected by stroke and return to their normal life as much as possible, the survivors go through various rehabilitation therapies [96]. Rehabilitation therapies aim to improve patients' basic skills—such as joint range of motion and strength for motor impairments, and attention and memory for cognitive impairments—and help patients relearn functional skills for the activities of daily living [126, 147]. Recent studies suggest that repetitive, high-dosage rehabilitation exercises can contribute to the reorganization of synaptic connections of patients' brain (i.e., neuroplasticity) [42, 87] and regaining their motor and cognitive functions [36, 151, 165]. In conventional rehabilitation settings, therapists play substantial roles in personalizing rehabilitation therapies for individual patients [96]. Based on patients' motor and cognitive impairment level, therapists first identify the goals of improvement that patients are expected to attain. Therapists design and administer therapeutic activities while adjusting their difficulty levels that are challenging enough but yet attainable by individual patients [63,119,146] in order to maintain their engagement and ensure the therapeutic gain obtained by patients [177,182]. This is followed by an assessment of patients' progress towards the set goals. This process is repeated until patients are discharged [96].

Heavy reliance on therapists in the entire rehabilitation process poses critical challenges in the conventional setting. First, for assessing patients' functional and impairment levels, therapists employ clinically validated assessment tools. For example, MMSE [51] is commonly used to assess the cognitive function, and WMFT [149] is commonly used to assess the patients' motor function. However, these assessments need to be administered by skilled therapists to produce reliable results. This necessity of therapists' presence makes it difficult to frequently monitor and track changes in patients' functional and impairment levels, especially when patients are discharged from hospitals. Second, therapeutic exercises are highly repetitive and appear mundane to patients [96], which negatively affect patients' motivation, engagement, and adherence to rehabilitation therapies [139]. Conventionally, it is the therapists' responsibility to motivate patients to engage and adhere to rehabilitation therapies [177], which can be a significant burden to therapists. This sheds light on the importance of developing technological means to support therapists while they enhance and maintain patients' engagement to rehabilitation therapies and physically assist patients' movements. Such technological solutions are believed to contribute to reducing therapists' workload while increasing patients' recovery rate. In turn, rehabilitation therapies employing such technologies can benefit patients in the contemporary rehabilitation trend where early discharge is strongly considered even compromising patients' potential to recover in order to reduce the cost of stroke care [134, 153].

2.3 Technology-Assisted Rehabilitation and Games

To address the practical challenges in the conventional rehabilitation setting, research and clinical communities have proposed and investigated various technological solutions, such as serious games, wearable sensors, and robots. Games are investigated as a means to automate the rehabilitation process and enhance patients' engagement to therapy [94, 180]. Clinical studies suggest that the game-assisted rehabilitation can lead to a therapeutic gain in cognitive [20, 175] and motor functions [?, 167]. While games alone can be employed in rehabilitation as an independent solution, especially for cognitive rehabilitation [145], games are often used to automate the overall motor rehabilitation therapy in conjunction with wearable sensors and robots attached to patients' affected limbs. For example, the patients' joint-specific movements measured by the sensors or robots could be used as control inputs for gamified upper-limb exercises to control the avatar or the cursor in games. During this process, games are responsible for 1) automating the overall therapy session, such as presenting exercise targets, monitoring and evaluating patients' performance, as well as 2) enhancing patients' engagement to intensive exercises [71]. Despite the potential benefits of serious games in technology-assisted rehabilitation acknowledged by research and clinical communities [94], much research is still needed. Among many, it is not well understood how games can be designed to assess the patients' function/impairment accurately (e.g., cognitive function or impairment level) of stroke patients, that can be easily translated in widely accepted existing clinical assessment tools. Furthermore, it is still poorly understood how employed games affect to the interaction dynamics between therapists and patients, and its impact on a therapeutic gain in the actual rehabilitation setting. In this dissertation, we investigate these practical challenges.

CHAPTER 3

REMOTE ASSESSMENT OF COGNITIVE IMPAIRMENT LEVEL BASED ON SERIOUS MOBILE GAME PERFORMANCE: AN INITIAL PROOF OF CONCEPT

3.1 Motivation

The number of individuals with permanent cognitive disabilities is increasing in the United States because of an aging society [15]. It is important to evaluate and longitudinally track the cognitive functional/impairment level of these individuals [158], which is often done using clinically validated assessment tools, such as the Mini Mental State Examination (MMSE) [51] and the Montreal Cognitive Assessment (MoCA) [121]. During the administration of these assessments, patients are provided with different types of *stimuli* (e.g., verbal and visual) and their responses are used to evaluate their cognitive capacity. For example, in the MMSE, patients are verbally instructed by therapists to answer specific questions (e.g., orientation to time and place such as "what date is it today?") or complete a set of tasks (e.g., copying a provided drawing of a certain figure). However, these tools require the presence of trained clinical staff [162] since the presentation of instructions and stimuli must be conducted in a clinically validated, controlled manner in order to achieve the optimal assessment results [26,168]. Previous studies have shown that patients' daily condition may affect cognitive function/impairment assessment results, which can be remedied by frequent administration of the assessments (even multiple times a day) [6,155]. This constraint of conventional assessment tools requiring the presence of trained clinicians makes the frequent and longitudinal assessment difficult to be achieved in/outside the clinical setting.

Various approaches have been investigated to address such fundamental limitations of conventional assessment tools. Tele-assessment through phone calls or video conferencing has been considered to eliminate the necessity of the physical presence of trained clinical staff [103]. For instance, Brandt *et al.* devised a new questionnaire that can be administered by trained clinicians over the phone, so that follow-up assessments can be made more easily [23]. However, phone-based assessments limit the use of visuospatial stimuli and rely only on verbal stimuli, narrowing the scope of the cognitive capacity being assessed. Recent work by Absolahi *et al.* demonstrated the feasibility of administrating the MoCA via video conferencing to overcome this limitation [2]. Although these approaches could successfully eliminate the need for patients to make physical trips to clinical facilities, they still require the remote *presence* of trained clinicians and thus have minimal impact on frequent, longitudinal tracking of patients' condition.

Computer and mobile device-based approaches have been actively investigated to enable patients to self-administer cognitive assessments in remote settings [7,118,181]. Potentially, these approaches can standardize the instructions and presentation of stimuli, automatically evaluate patients' responses and answers, and compare the evaluated cognitive performance with patients' prior performance. These computerized assessments often employ simple games and present a wide variety of verbal and visuospatial stimuli. For instance, the system proposed in [26] displayed a target with a certain shape and color on the screen and asked patients to find the identical one from a given set of options. This type of stimulus is difficult to implement in conventional paper-based assessments. However, these contemporary solutions stop short at reporting newly devised assessment scores that are only specific to the developed software. Although some of these scores have been reported to moderately correlate with traditional assessments, such as the MMSE [26], Wechsler Scale of Intelligence (WISC) [7], and Wechsler Adult Intelligence Scale (WAIS) [60], they do not provide a means to translate the software-specific scores with respect to these clinically validated scores. Subsequently, clinicians need to undergo additional training to interpret the reported game-specific scores, which poses a critical translational limitation [181].

In this study, we introduce a new approach where patients can self-administer the assessment and longitudinally monitor one's cognitive impairment level in remote settings by playing a collection of serious mobile games; a preliminary version of this work on estimating the total MMSE score has been reported in [82]. With a specific emphasis on the translational impact to the current clinical setting, our technical contributions include: 1) the introduction of *Neuro-World*, a collection of six 3D serious mobile games that were designed based on different concepts of cognitive function, and 2) discussion of a machine learning-based analytic pipeline to translate game-specific performance into a clinically-accepted measure of cognitive function – the MMSE score. The proposed system's ability to accurately estimate the cognitive impairment level obtained by the MMSE score was evaluated based on data collected from a total of 12 cognitively impaired post-stroke individuals at baseline and a three-month follow-up. Furthermore, we investigated the proposed system's usability by cognitively impaired individuals and their willingness to adhere to its longitudinal use based on the System Usability Scale (SUS) – a validated tool for usability assessment.

3.2 Background

3.2.1 Mini Mental State Examination

The MMSE is arguably the most widely accepted screening tool in the clinic for objective assessment of cognitive impairment level [169]. The MMSE was developed to serially examine various dimensions of cognitive impairments in a timely manner for practical use in the clinical setting [51]. Despite the simplicity of the test, it has been validated to accurately discriminate patients' cognitive levels and track recovery trajectories [169]. The MMSE score has also been shown to correlate well with more

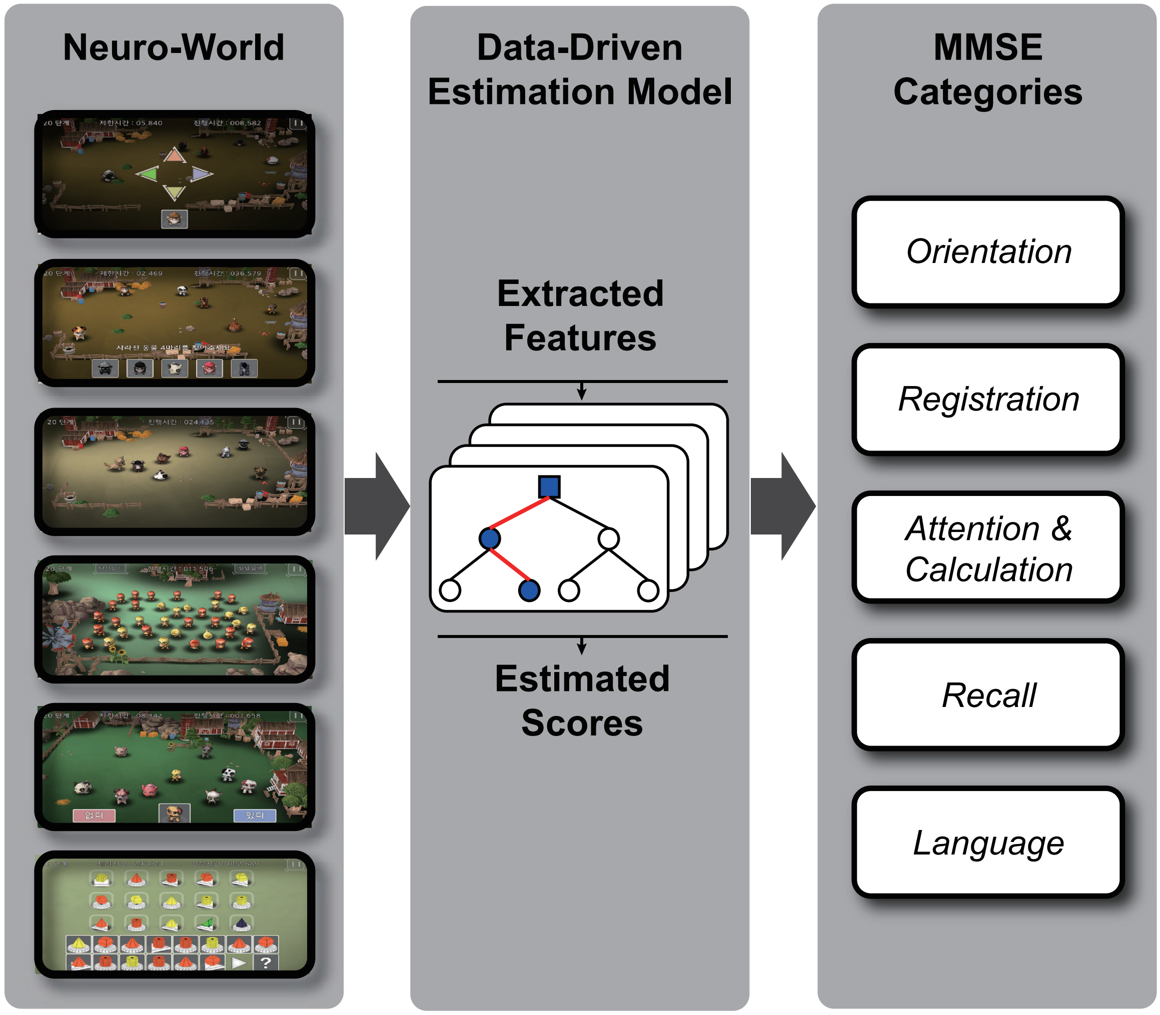


Figure 3.1: A schematic representation showing that a patient's game performance in *Neuro-World* is used to estimate the MMSE scores (in all categories) via a data-driven model constructed based on machine learning algorithms.

comprehensive, standardized instruments, such as Wechsler Adult Intelligent Scale (WAIS) [75], Modified Blessed Test (MBT) [49], and MoCA [172].

The MMSE consists of a set of questions that evaluate cognitive impairment in five different categories: 1) *orientation*, 2) *registration*, 3) *attention & calculation*, 4) *recall*, and 5) *language* [51]. *Orientation* examines if a patient can tell the current place and time. Its score ranges from 0 to 10 depending on the level of cognition. *Registration* examines if the patient can remember a set of arbitrary words presented by the therapist moderating the test. The score ranges from 0 to 3. *Attention &*

calculation examines if the patient can serially subtract 7s from 100 (this test is referred to as *serial 7*) or spell a word in a reverse order. Its score ranges from 0 to 5. *Recall* examines if the patient can retrieve a set of words that he/she remembers from memory. Specifically, it asks the patient to recall the words used in *registration*. Its score ranges from 0 to 3. *Language* examines if the patient can understand different sets of verbal or written instructions and respond to them accordingly. For instance, the patient is provided with a sheet of paper with "close your eyes" written on it and is asked to follow the instruction. Its score ranges from 0 to 9. The total MMSE score is computed by adding the scores of the five categories.

3.2.2 Grounding MMSE in a Psychological Perspective

Although the five categories of MMSE seem to measure distinct and exclusive aspects of human cognition, there exists scientific evidence showing that patients' performance in these categories are highly correlated and can be explained using a smaller number of latent cognitive processes. For instance, Fillenbaum *et al.* and Brugnolo *et al.* reported that, through factor analysis, they were able to identify two latent factors that might be able to explain more than 60% of the total variance in the MMSE scores [27, 49]. Although it is still difficult to articulate what exactly these latent factors are, there is an increasing number of research findings suggesting that cognitive function can partially be explained based on the close interdependence among different cognitive components; despite these components being traditionally believed to be modular. A review paper by Chun and Turk-Browne supports that the strong interdependence of memory and attention in processing of external stimuli (e.g. visuospatial and speech) contributes to various aspects of cognitive function [35].

Indeed, researchers have associated the cognitive functions that are characterized by the MMSE categories with memory and attention. Strub and Black explained that *orientation* to place and to time (i.e., recognizing place and time) is associ-

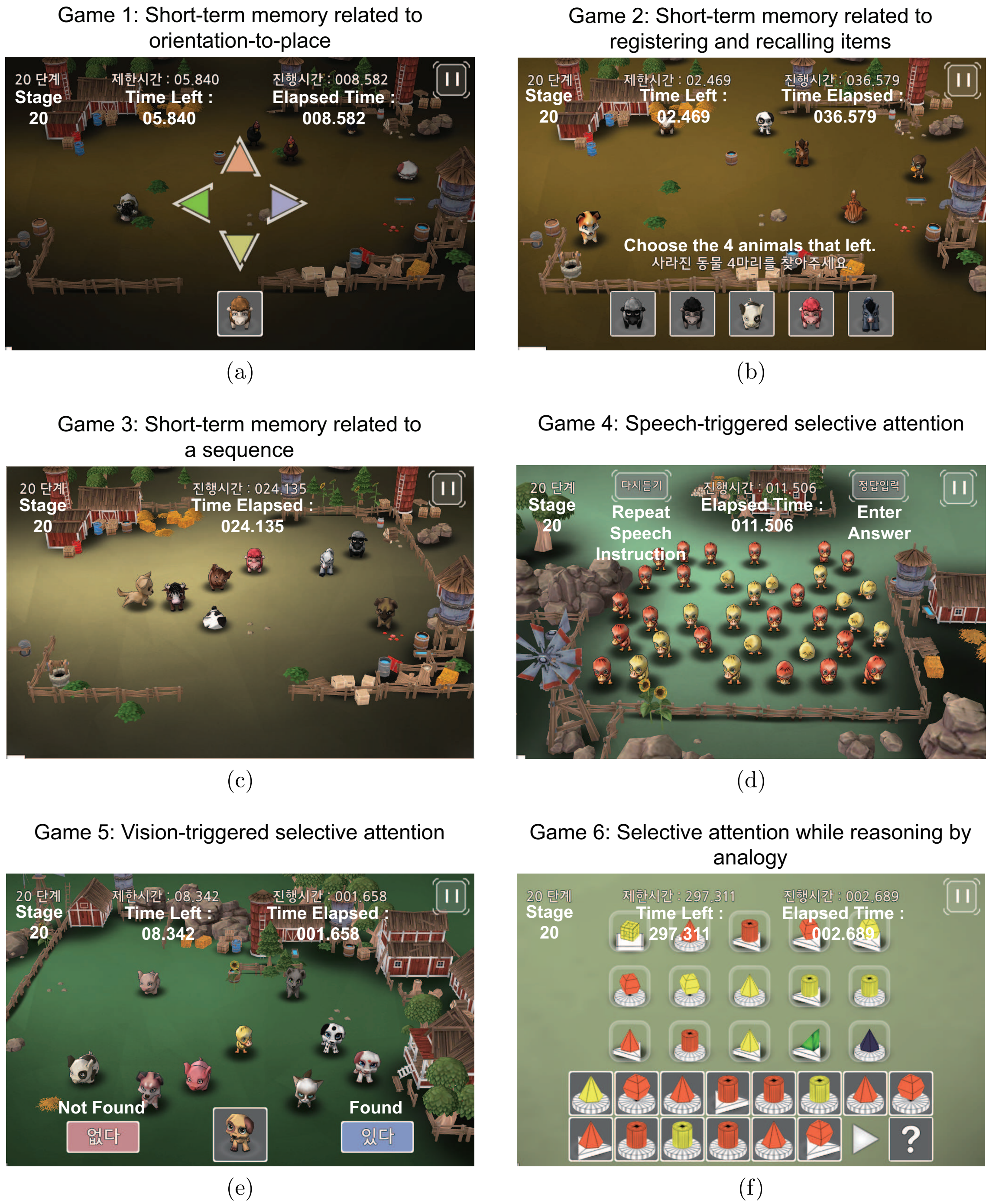


Figure 3.2: Screen shots of the six games in *Neuro-World* that were used in the study to evaluate various dimensions of cognitive impairment and estimate the categories of MMSE (courtesy of Woorisoft Inc. [185]). *Neuro-World* was administered in Korean language. English translations were manually added to the screen shots to help readers understand the written information provided in the games.

ated with recent memory since it evaluates if the patient is able to register changing factors about the place and time, and recall it when he/she is asked [161]. It has been explained that short-term memory takes an important role when it comes to *registering* and *recalling* certain items [160]. According to Miyake and Shah, working memory along with selective attention plays a significant role in executing arithmetic calculations and manipulating information in memory (such as the *serial 7* task in the *attention & calculation* test) without being distracted by other stimuli [116, 173]. It has also been suggested that *language* deeply involves working memory [10] and selective attention [45].

3.3 *Neuro-World*: A Cognitive Rehabilitation Game

Based on the potential relationship between basic cognitive processes (i.e., memory and attention) that underlie the categories of MMSE, we developed *Neuro-World* – a collection of six serious mobile games – to assess the level of cognitive impairment. The major hypotheses in this work include that 1) we can challenge the patient using basic cognitive processes of memory and attention that collectively affect the patient's responses to a set of mobile games and 2) computationally identify the relationship between the patient's game performance and MMSE scores (in all categories) by leveraging machine learning-based algorithms. Fig. 3.1 presents the conceptual connections between the *Neuro-World* games and the MMSE scores. For this preliminary study, *Neuro-World* is implemented to support the accessibility of post-stroke patients with mild cognitive impairment, and no major visual and motor impairment. Some of the implemented features of patient-accessibility include a consistent touch input interface throughout all six *Neuro-World* games and large, obvious button images that patients need to interact with, as well as substantial space around those buttons. Additionally, the default font size is large and written/spoken instructions are implemented using simple, plain language so that target patients can easily understand the

Table 3.1: Descriptions of the six games from *Neuro-World* used in this study

Game #	Task	Cognitive Concept
1	A flock of animals enters and one animal leaves the farm in one of the four directions (i.e., up, down, left, right). The patient is expected to remember and select the correct direction, to which the animal has moved. As the patient proceeds to higher stages, a larger flock of animals enters the farm and the speed that the animals enter and exit becomes faster.	Visuospatial short-term memory related to orientation-to-place
2	A flock of animals enters the farm and a subset of the flock leaves the farm. The patient is expected to remember the animals that have left the farm and select them among the presented images at the bottom of the screen. In higher stages, the number of animals that enter and exit increases and their speed gets faster to increase the difficulty level.	Visuospatial short-term memory related to registering and recalling an object
3	A flock of animals enters the farm one after another in a specific order and a subset of the flock leaves the farm. The patient is asked to remember the order that the remaining animals have entered the farm and select them in the correct order. In higher stages, the size of a flock, their moving speed, and the number of remaining animals increase.	Visuospatial short-term memory related to a sequence
4	A flock of animals with different visual characteristics are displayed on the screen. An auditory instruction (e.g. 'Find and count all the yellow ducks!') is provided to describe the visual characteristics of the animals that the patient needs to find and count. The patient is expected to enter the correct count of the described animals. In higher stages, the total number of animals increases and the descriptions of visual characteristics become more complex.	Selective attention with a speech instruction
5	A flock of animals is presented on the screen. An animal that the patient needs to find is visually presented in a separate box at the bottom of the screen. The patient is expected to find the matching animal among the presented animals and click one of the two buttons labeled 'found' and 'not found'. In higher stages, the number of animals increases and the visual characteristics of the animals become more complex.	Selective attention with a visual instruction
6	A series of targets, each of which combines multiple primitive 3D shapes and color (e.g., an orange-colored hexagonal prism on top of a cylinder), is presented in a certain pattern. The patient is expected to understand the sequential pattern in which the primitive shapes are presented. Then, the patient is asked to identify the shapes that followed the presented sequence of the shapes. In higher stages, the type of primitive shapes and the sequential pattern become more complicated.	Selective attention during visuospatial 3D geometric reasoning-by-analogy

procedure of *Neuro-World* games. Lastly, *Neuro-World* supports multiple languages, which include English and Korean, for users with different mother languages.

Fig. 3.2 presents the screen shots of all six games of *Neuro-World*. As suggested by the literature, patients' performances in the categories of MMSE are interdependent as they are affected by a set of basic cognitive functions. Hence, *Neuro-World* was developed using these basic cognitive concepts that are integrated within six different tasks. Table 3.1 provides detailed information regarding how tasks are presented, how the game difficulty is adjusted, and which cognitive concept guided the development of each game. Games 1–3 are related to visuospatial short-term memory with a special emphasis on orientation-to-place (i.e., four directions on the screen), individual objects (i.e., animals), and sequence (i.e., a sequence of animals that enter the screen), respectively. Games 4–6 are related to visuospatial selective attention. In game 4, the patient is provided with a verbal description (in audio) of animal targets that he/she is asked to find. In game 5, the patient is given a visual description (i.e., image) of an animal to find. Game 6 is related to visuospatial selective attention based on 3D geometric reasoning-by-analogy. While the design of each game was guided by different cognitive concepts, we acknowledge that individual games were not evaluated to identify whether they actually assessed these specific cognitive processes. However, since previous studies have demonstrated the interdependent relationship of cognitive processes, such as memory and attention, our approach of using results from all games to estimate MMSE scores does not require the individual validation of each game's cognitive target.

It has been shown that the difficulty of cognitive tasks can be modulated by a number of variables, such as the number of visual stimuli presented to the patient, duration of stimuli exposure, complexity of visuaospatial stimuli (e.g., shapes), sequential order of multiple stimuli, and their motion [30]. In a similar manner, the difficulty level of the game stages in *Neuro-World* is modulated by changing the number of animals that appear on the screen, their speed to enter and exit, the complexity of the shape combinations, and the number of animals that the patient has to count. Each game in *Neuro-World* has 20 stages where stage 1 represents the easiest level and stage 20 represents the most difficult level in terms of the required cognitive level to complete the tasks (see Table 3.1 for details). For each of the six games, the patient starts from stage 1 and continues to the highest possible stage within the time limit of five minutes; the maximum game duration is therefore 30 minutes to complete all six games. The patient can proceed to the next stage only when he/she selects the correct answer(s) of the current stage. When the predefined 5-minute is up at a certain stage of a game, *Neuro-World* terminates the game and proceeds to the next game. Since the patient is only able to proceed to more difficult stages as much as his/her cognitive function allows in a limited time (i.e., five minutes), the game-specific performance (e.g., the highest stage that the patient reached, the time spent to reach that stage, etc.) will reflect his/her cognitive capacity and impairment level. It is noteworthy that, every time the patient starts the application, *Neuro-World* generates the order of games to be played in a random fashion.

3.4 Data Collection

The research protocol was reviewed and approved by the University of Massachusetts Amherst Institutional Review Board as well as Heeyeon Rehabilitation Hospital, South Korea. Inclusion criteria for this study stipulated the recruitment of post-stroke survivors with mild cognitive impairments in their chronic phase (i.e., two years or longer since their last onset). Eligible patients from the Nursing Center at Heeyeon Rehabilitation Hospital were first evaluated for their cognitive impairment level by using the Korean version of the MMSE [84], administered by a trained therapist. Patients with mild cognitive impairment, who scored a total of 19 points or higher on the total MMSE, were included in the study to ensure that they could

Table 3.2: Demographic and clinical information about participating stroke survivors

Patient	Age	Sex	Chronicity[a] (years)	Affected Side	MFT[b]	MMSE[c] at Baseline						MMSE[c] at 3-month Follow-up						Diagnosis[d]
						O	R	A	E	L	T	O	R	A	E	L	T	
1	66	Female	13	Left	5/23	5	3	3	3	8	22	10	3	3	3	8	27	IS
2	81	Female	10.1	Right	27/22	9	3	1	0	7	20	10	3	4	3	8	28	IS
3	62	Female	9	Left	2/28	7	3	1	1	8	20	8	3	5	3	8	27	IS
4	71	Female	6.5	Left	0/28	8	3	1	2	9	23	10	3	1	3	9	26	IS & ALZ
5	80	Female	3.2	Left	25/27	10	3	1	1	8	22	10	3	5	3	8	29	IS
6	72	Female	4.5	Right	29/25	7	3	3	1	8	22	8	3	4	3	7	25	IS
7	80	Male	5.3	Left	23/24	9	2	4	1	7	23	10	3	5	3	8	26	HS
8	75	Female	6.3	Right	29/22	7	3	1	2	8	21	10	3	5	3	8	29	IS
9	77	Female	3.4	Right	28/10	10	2	1	1	8	22	10	3	1	3	9	26	IS
10	64	Female	11	Left	7/31	4	3	4	2	9	22	8	3	5	3	8	27	IS
11	85	Female	2	Right	26/21	9	2	4	1	7	23	10	3	5	3	8	29	IS
12	70	Female	6	Right	23/2	10	2	1	1	8	22	10	3	5	3	9	30	IS

[a] The number of years since the onset of the patient's last stroke until baseline.
[b] MFT scores of the left and right limbs are provided.
[c] The categories of MMSE include *Orientation* (O), *registration* (R), *attention & calculation* (A), *recall* (E), *language* (L). They were added to produce the total MMSE score (T).
[d] Ischemic Stroke (IS), HS: Hemorrhagic Stroke (HS), Alzheimer's Disease (ALZ)

understand instructions and play the game by their own efforts; 0 is the minimum and 30 is the maximum score possible on the MMSE. Patients with significant visual negligence or motor impairments (i.e., patients who scored lower than 20 on the Manual Function Test (MFT) on both limbs [117]) were excluded; 0 is the minimum (severely impaired) and 32 is the maximum (full function) possible score for the MFT.

A total of 12 post-stroke patients (73.6 ± 7.3 years old) in the chronic phase (6.7 ± 3.4 years since the last injury until baseline) participated in the study at baseline and three-month follow-up. All patients were Asian. Eleven patients (91.7%) were female and had one or more incidences of ischemic stroke. One patient had Alzheimer's in addition to stroke. One patient had a hemorragic stroke. Six patients (50%) had their left side affected. The average MFT score of the upper-limb that the patients used to play *Neuro-World* was 27 ± 3 points out of 32. No patients were exposed to *Neuro-World* prior to the study. Table 3.2 summarizes the demographic and clinical information of the participating patients.

At baseline, patients were asked to choose a place where they felt comfortable in the Nursing Center at Heeyeon Rehabilitation Hospital to play *Neuro-World*. The common places that the patients chose included their rooms, corridors, and lounges in the hospital. The Korean version of *Neuro-World* was installed on a 12.2-inch tablet computer (Galaxy Note Pro, Samsung). Researchers explained the graphical user interface of the game to patients and exposed them to the first stage for each game to help them become accustomed to the graphical and/or textual information provided on the screen. Then, patients were instructed to play all six games starting at stage 1 (easiest) and to continue until they reached their highest achievable stage within the 5-minute game time. Patients were instructed to place the tablet computer on their lap with their preferred hand next to it. This minimized the movements patients had to perform to complete each game. On average, patients spent approximately 30 minutes with *Neuro-World* – five minutes per game. After the completion of each game, *Neuro-World* stored game-specific performance values reflecting patients' cognitive function in the tablet computer; these variables will be explained in detail in Section 3.5.

During the three month period between baseline and follow-up, patients were asked to play each of the six games of *Neuro-World* for five minutes a day (i.e., a total of 30 minutes of game play a day), two days a week, in order to investigate the impact of extensive exposure to the game on the estimation of the MMSE scores (i.e., learning effects of patients to strategically complete the games rather than using their cognitive function). In case some cognitively high-functioning patients finish the highest stage (i.e., stage 20) of a game within the five-minute period, *Neuro-World* was programmed to repeat the last stage of the game until the five minutes is reached (but with randomized game configurations and thus the answers), so that patients could be exposed to the games for 30 minutes per day. Consequently, each patient completed a total of 24 sessions of *Neuro-World*, equivalent to 12 hours of game play. Our hypothesis was that changes in the game-specific values at follow-up would be directly relevant to the improvement/degradation in patients' cognitive level rather than their acclimation to the games. Patients received no other motor and cognitive rehabilitation therapies during this period. At follow-up, patients were re-evaluated for their cognitive functions based on MMSE and asked to play all six games with the same experimental procedure as the baseline evaluation. At the end of the follow-up visit, patients were asked to complete the SUS questionnaire [25] (see Section 3.5.7 for details about the SUS).

3.5 Data Analysis

In this section, we introduce our data analytic approach to construct supervised machine learning models that can translate the patients' performance in self-administered *Neuro-World* games to the cognitive impairment scores measured by the MMSE. Furthermore, we explain our attempt to understand patients' perceived usability and their willingness to adhere to the repeated use of *Neuro-World* based on the SUS.

3.5.1 Game-Specific Features

First, as explained in Section 3.3, *Neuro-World* challenges a patient's cognitive function more rigorously as he/she proceeds to higher stages by modulating game-specific variables. Thus, the highest stage that a patient is able to reach reflects the overall cognitive capacity of the patient, which is used as our game-specific performance feature (x_1).

When it comes to solving a given task, it is a commonly observed behavioral effect that the patient trades off between accuracy and time duration to complete the task (e.g., to complete a task fast but inaccurately vs. slowly but accurately) [69]. Furthermore, this trade-off is known to be conditioned on one's cognitive capacity [144]. In order to properly model the trade-off between accuracy and time duration, we need to numerically measure the number of successful and unsuccessful trials out of the total number of trials (i.e., accuracy) and the time taken to clear any given stages (i.e., time duration). Hence, we computed the total number of stages that a patient tried (x_2), successfully completed (x_3), and failed (x_4). We also measured the time taken for the patient to answer the given problems of all stages. The shortest (x_5), longest (x_6), and average time (x_7) of each game in seconds were computed. Since *Neuro-World* games involve a combination of cognitive tasks and motor activities performed both simultaneously (eye movements to solve the given cognitive task) and sequentially (moving the finger after solving the cognitive task to provide the answer on the tablet computer), values (x_5), (x_6), and (x_7) represent a combination of cognitive-motor processing and performance time. We also devised features that, we hypothesized, would be more heavily weighted to the cognitive performance of patients. More specifically, we computed the shortest (x_8), longest (x_9), and average times (x_{10}) in seconds taken for the patient to make the first touch on the screen since the game was initiated (i.e., since the visual information was provided on the tablet computer screen). Because the games require more finger movements to provide answers as the game stages increase, these latest features emphasize the cognitive aspects related to the games.

3.5.2 Feature Selection

The Correlation-based Feature Selection (CFS) algorithm [65] was applied to identify a subset of game-specific variables that were highly correlated to the MMSE score and to avoid overfitting. The algorithm selects a subset of features having high correlations to the class label (i.e., MMSE scores) and low redundancy among them, which is especially suitable for training a regression model. In this work, we attempted to construct distinct estimation models for each of the five MMSE categories and the total MMSE score (i.e., a total of six models were trained). Thus, the CSF algorithm was independently applied to the six different class labels.

3.5.3 Regression Estimation of MMSE Scores

Regression models were independently trained to estimate the six MMSE scores by using the Random Forest algorithm. Random Forest is an ensemble learning method that constructs multiple weakly correlated decision trees based on randomized features and bootstrap samples [70]. The algorithm produces the predicted label by averaging the decisions of the trees. By averaging many noisy and approximately unbiased models, the algorithm can reduce the variance of the prediction function and thus minimize the chances of overfitting [70]. All the estimation performances were evaluated using the nested leave-one-subject-out cross validation (LOSO-CV) technique. That is, we performed 12 iterations of the outer LOSO-CV for each MMSE score that leaves out one patient's data as the testing set. Within each iteration of this outer LOSO-CV, we performed another (inner) LOSO-CV, which further separated the remaining data of 11 subjects into training and validation sets, aiming to identify the optimal values of a hyperparameter for the Random Forest regression model (i.e., the number of trees). First, we defined the value range of the number of trees as from 1 to 64 based on the suggestion in [125]. The regression models with different values of the hyperparameter were examined using the inner LOSO-CV, and the model (more specifically the hyperparameter values) that yielded the highest estimation accuracy—in terms of the Root Mean Square Error (RMSE)—was selected. Finally, the selected model was evaluated using the left-out testing patient data (again, the baseline and follow-up data). The resulting estimation performances were measured using the RMSE and normalized RMSE (NRMSE). The NRMSE was computed by dividing the RMSE by the value range of the actual MMSE scores evaluated by the therapists.

3.5.4 Analysis of Feature Importance

Because the estimation performance was evaluated using the LOSO-CV technique, the feature selection algorithm was applied to different training datasets and consequently, produced a total of 12 different feature subsets. In this work, the most frequently selected features among the obtained 12 feature subsets were identified as important features. This approach has been used in the related literature [100, 127]. Due to space limitations, we analyzed the important features for estimating the total MMSE only.

3.5.5 Responsiveness of *Neuro-World* for Longitudinal Monitoring of MMSE

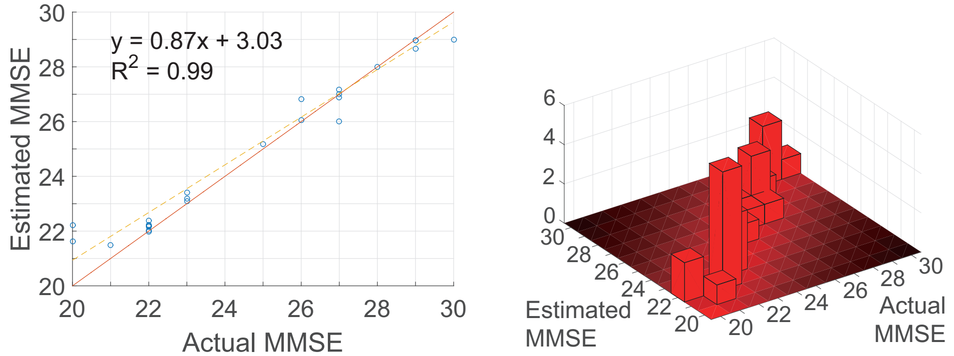
With the aim to validate the use of *Neuro-World* for longitudinal monitoring of cognitive level, we investigated whether the trained machine learning model can accurately estimate the change in the total MMSE scores between baseline and follow-up (if there exists any change). The actual and estimated changes in the total MMSE were statistically analyzed using the paired t-test.

3.5.6 Estimating MMSE Scores using a Subset of Games

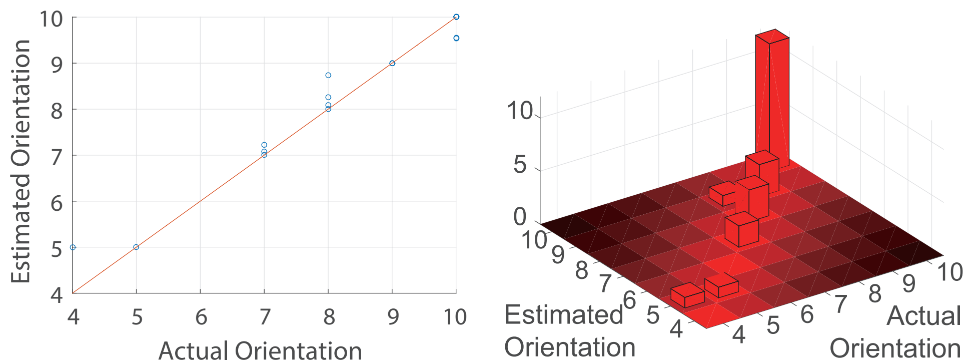
As discussed in Section 3.4, it may take up to 30 minutes for patients to complete all six games of *Neuro-World*. Considering its real-world deployment, we cannot assume that patients will complete all six games every time they are engaged with the system. Hence, we investigated the expected estimation accuracy when the game-specific performance data if only a subset of the six games were available for analysis. For simplicity, we only considered estimating the total MMSE score. The investigation was performed in a retrospective manner. Specifically, estimation models were trained for all possible combinations of different numbers of games to be played (from 1 to all 6 games). Subsequently, we produced $\binom{6}{1} + \binom{6}{2} + \cdots + \binom{6}{6} = 63$ estimation models. Each of these 63 models were evaluated using RMSE in a LOSO-CV manner. The estimation performance (in RMSE) was grouped based on the cardinality of the game subset, yielding a total of six groups. The mean and standard deviation of RMSEs within each group were computed and compared against each other using the unpaired t-test.

3.5.7 System Usability Scale

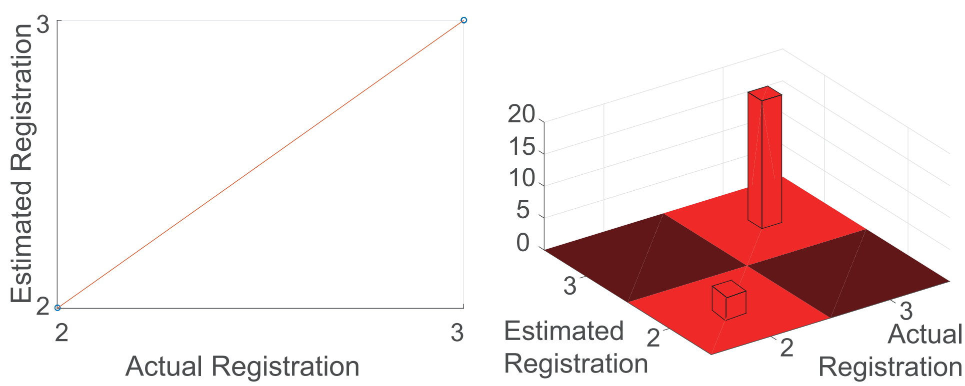
Even if the proposed approach can accurately estimate clinical scores, it wouldn't be of much clinical use unless patients find the self-administration of *Neuro-World* easy and are willing to adhere to longitudinal use. The SUS was utilized to understand the overall experience of the participating patients. The SUS consists of 10 questions, with each question scored from 1 to 5 on an ordinal scale. The odd-numbered questions ask about positive experiences and even-numbered questions ask about negative experiences using the system. Hence, scores close to 5 on odd-numbered questions and scores close to 1 on even-numbered questions indicate positive experiences with



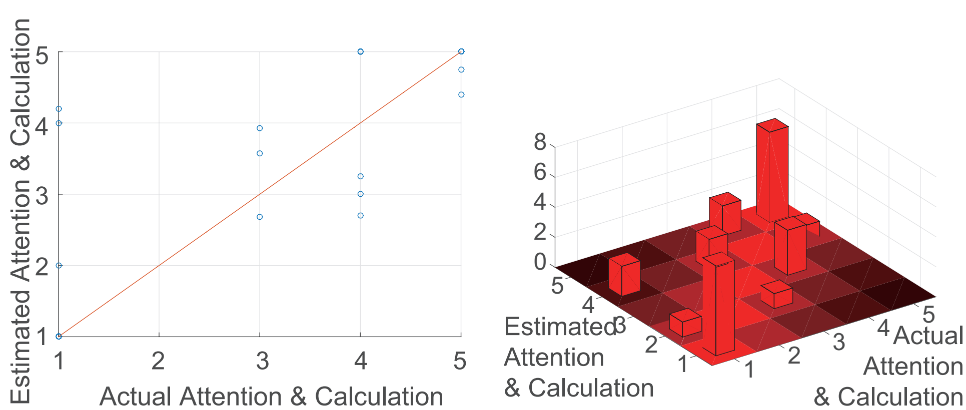
(a) Total MMSE



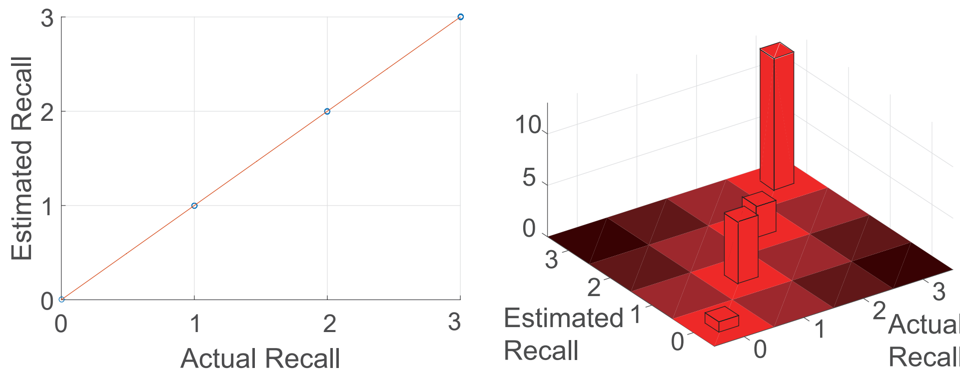
(b) Orientation



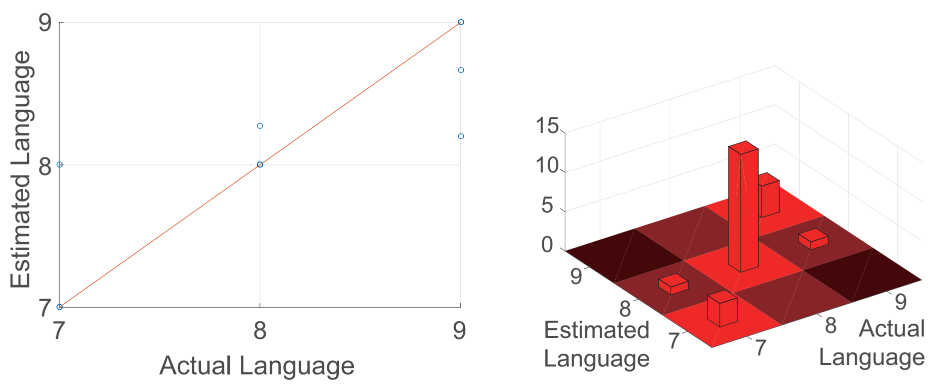
(c) Registration



(d) Attention & Calculation



(e) Recall



(f) Language

Figure 3.2: Scatter plots and 3D histograms between the estimation vs. actual scores for (a) the total MMSE, (b) *orientation*, (c) *registration*, (d) *attention & calculation*, (e) *recall*, and (f) *language*. In the histograms, each tile on the floor has the size of 1×1 points, and the height represents the number of instances at each $\langle$actual, rounded estimation$\rangle$ pair that fall within each tile. The bars on the diagonal indicate the perfect estimation ($y = x$), and the ones at the far corners indicate the maximum errors in each estimation result. The power of the correlation analysis for the actual and the estimated total MMSE scores was 1.000 based on a sample size of 12, a correlation coefficient of 0.99, and a significance level of 0.05.

Table 3.3: RMSEs and NRMSEs for all categories and the total MMSE score estimated using the features from all six games

Category	RMSE	NRMSE
Orientation	0.40	5.71%
Registration	0.00	0.00%
Attention & Calculation	1.24	24.80%
Recall	0.00	0.00%
Language	0.30	10.00%
Total MMSE	0.72	6.00%

the system. Therefore, scores for even-numbered questions are reversed, and then all the scores are summed and normalized to 100, which is the maximum possible positive usability.

3.6 Results

3.6.1 Estimating MMSE Scores

Table 3.3 presents the RMSE and NRMSE between the actual MMSE scores administered by trained clinicians and the estimated MMSE scores based on the game-specific variables of *Neuro-World*. Fig. 3.2 shows scatter plots and 3D histograms between the estimated vs. actual scores for the total MMSE (Fig. 3.3a) and all categories (Fig. 3.3b–3.2f). The estimated scores were rounded to the nearest integer to create the 3D histograms. It is important to note that all the analyses were performed in a LOSO-CV manner to provide a fair rather than an optimistic evaluation of the trained machine learning models. The presented results demonstrate that the patients' game-specific performance in *Neuro-World* can produce accurate estimations of the total and categorical MMSE scores. Furthermore, these empirical results support our initial hypothesis that the patients' performance in a subset of

Table 3.4: The five most important features that were used to estimate the total MMSE scores.

Features	Count (Perc.)
The most difficult stage reached (x_1) in Game 4	12 (100%)
The average time to solve the problem and make the first touch (x_{10}) in Game 4	12 (100%)
The average time to complete stages (x_7) in Game 5	8 (67%)
The average time to complete stages (x_7) in Game 1	6 (50%)
The most difficult stage reached (x_1) in Game 2	6 (50%)

cognitive tasks challenging various aspects of visuospatial short-term memory and selective attention can be successfully leveraged to estimate the MMSE scores.

Despite promising results in general, we observed relatively high error rates in *attention & calculation* and *language*. As discussed in Section 3.2.2, working memory and selective attention are essential in arithmetic skills that are mainly tested in *attention & calculation*. While the games in *Neuro-World* are based on concepts related to selective attention, they were not designed based on working memory concepts, which we believe has resulted in the relatively moderate estimation accuracy for the *attention & calculation* category. Similarly, we believe that the moderate estimation accuracy of the *language* category is due to the fact that *Neuro-World* games do not directly stimulate patients' language skills (i.e., using words or phrases as stimuli).

3.6.2 Analysis of Important Features

Table 3.4 presents the top five features that were most frequently selected in estimating the total MMSE throughout the iterations of LOSO-CV. The highest stage that the patient reached (x_1) and the average time taken from the stimuli presentation until the first finger touch to the screen (x_{10}) in Game 4 (i.e., speech-instructed selective attention) were selected in all iterations. The remaining three features examined the time duration to complete the task with the involvement of

Table 3.5: The frequency of the games from which the selected features were extracted in training regression models for estimating the total MMSE score throughout the iterations of LOSO-CV.

Games	Count (Perc.)
Game 1: Short-term memory related to orientation	9 (75%)
Game 2: Short-term memory related to item	6 (50%)
Game 3: Short-term memory related to sequence	5 (42%)
Game 4: Speech-triggered selective attention	12 (100%)
Game 5: Vision-triggered selective attention	8 (67%)
Game 6: Selective attention while reasoning-by-analogy	1 (8%)

motor function (x_7) in Games 5 and 1, and the highest stage the patient reached (x_1) in Game 2. Overall, only 15 features out of 60 were ever used throughout the 12 iterations of LOSO-CV. Table 3.5 summarizes the frequency of the games from which the selected features were extracted in training the regression models for estimating the total MMSE score throughout the iterations of LOSO-CV. This result shows which games contributed the most in estimating the total MMSE score reported in Table 3.3. Games 1 and 4, which primarily focus on concepts related to selective attention and short-term memory respectively, were the games that contributed the most. On the other hand, Game 6 (i.e., based on the concept of selective attention during reasoning analogy) was selected in only one iteration of LOSO-CV. These findings collectively demonstrate the significant interdependence among the features/games and an agreement with the literature that a small number of factors – hypothesized to be a combination of memory and attention in this work – might be able to explain the MMSE scores [27,49]. These also justify the use of a subset of games in estimating MMSE scores (see Section 3.6.4 for further discussions).

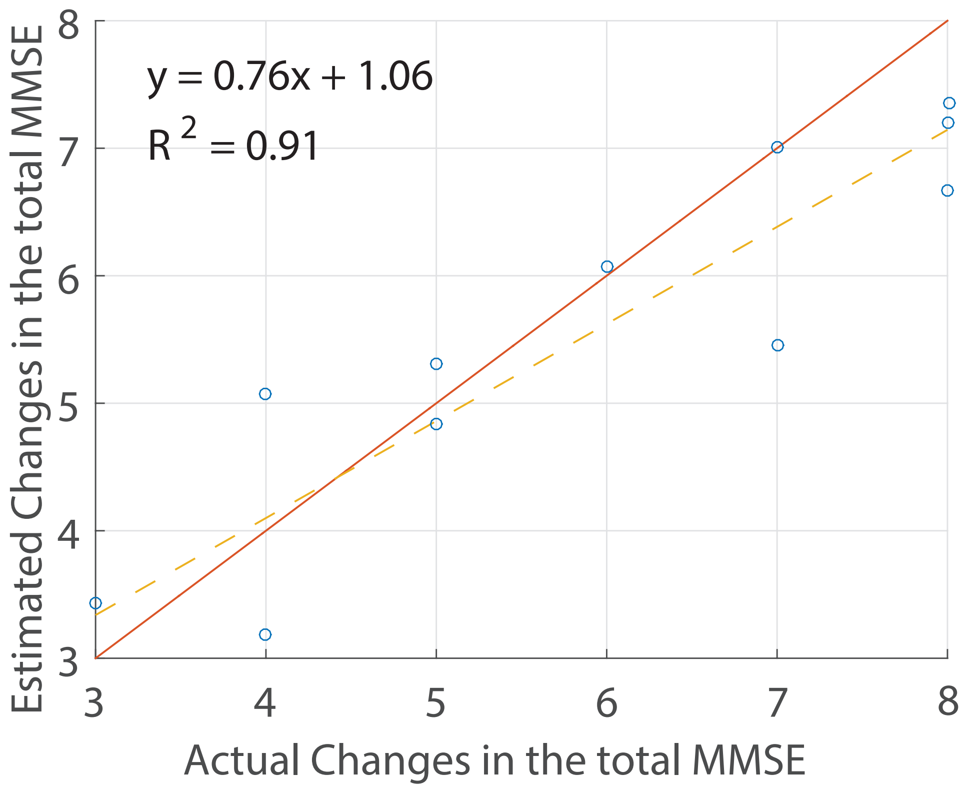


Figure 3.3: Responsiveness, which is evaluated by subtracting the total MMSE scores at baseline from the ones at three-month follow-up. These changes in the total MMSE score administered by the therapist vs. those estimated by the trained machine learning model are presented as a scatter plot. The RMSE between the actual change and the estimated change is 0.78. The difference was statistically insignificant when analyzed using the paired t-test (t-*stats* $= 1.37$, $p = 0.20$). The power of the correlation analysis for changes in the actual total MMSE and those in the estimated MMSE scores was 0.99 based on a sample size of 12, a correlation coefficient of 0.93, and a significance level of 0.05.

3.6.3 Responsiveness of *Neuro-World* for Longitudinal Monitoring of MMSE

Fig. 3.3 illustrates the responsiveness of *Neuro-World* for estimating changes in the cognitive performance during the three-month period between baseline and follow-up. The model trained using all six games was applied to estimate the total MMSE score at baseline and three-month follow-up in a LOSO-CV manner. The two scores were subtracted to compute the estimated change in the total MMSE, just as what trained therapists would do in the clinical setting to monitor and track functional trajectory.

We initially assumed that we would observe no changes in the MMSE score as patients were in their chronic phase and did not receive any motor or cognitive therapies during the period. However, to our surprise, patients demonstrated a significant improvement in the MMSE score after three months ($t\text{-}stats = -9.6$ with $p < 0.01$, paired t-test). We believe that the improvement was caused by extensively exposing patients to *Neuro-World* (i.e., playing up to 30 minutes a day, two days a week), which may end up serving as a therapeutic intervention that frequently challenged patients' cognitive capacities. However, comparison to a control group (i.e., individuals not exposed to *Neuro-World*) is necessary in order to draw a stronger conclusion for the effectiveness of *Neuro-World* as a therapeutic tool, which we believe is out of the scope of this work. Note that this would not affect our validation of the responsiveness of *Neuro-World* as patients were evaluated for their game performance and MMSE independently at baseline and follow-up.

In results, we observed the RMSE of 0.78 (NRMSE of 11.14%) with the maximum error rate of only 1.54 points between the estimated and actual changes in the total MMSE score; there was no statistically significant difference when analyzed using the paired t-test ($t\text{-}stats = 1.37$ with $p = 0.20$). This result indicates that the learning effects had minimal influence on the estimation accuracy of our machine learning models. If there were any learning effects from the extensive exposure of the game within the three-month period, we would expect to observe overestimated MMSE scores compared to the actual scores at the follow-up. This demonstrates that the proposed system can be used to accurately track the longitudinal changes in cognitive function.

3.6.4 Estimating MMSE using a Subset of Games

Fig. 3.4 illustrates the estimation performances in RMSE for the total MMSE score when different subsets of games are used to train the models. There is only

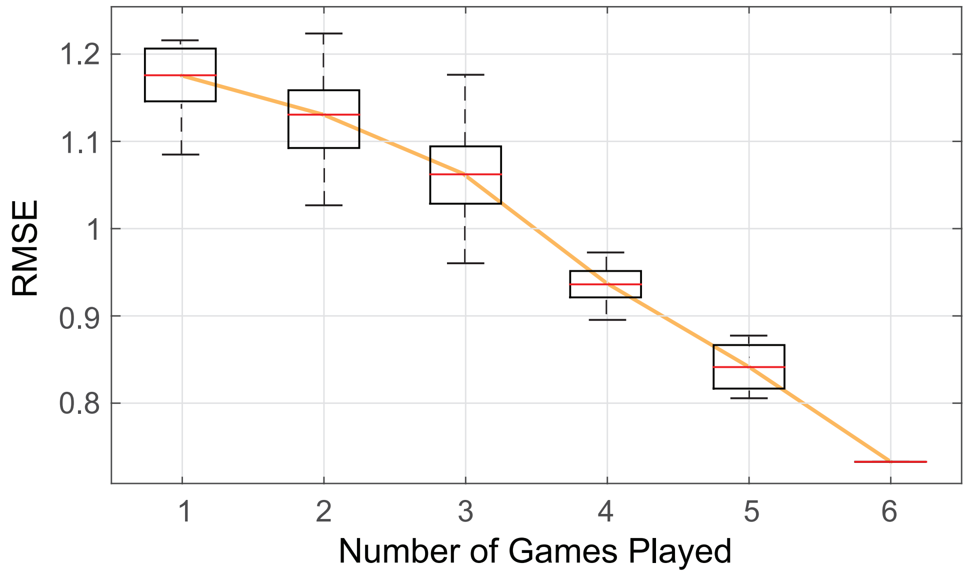


Figure 3.4: The RMSE for the estimated total MMSE scores using the features extracted from different numbers of games. The red bar within each box indicates the median of the RMSEs and the black box represents the range between 25% and 75% of the RMSEs. The black whiskers that are stretched out from the black box represent the maximum and minimum of the data while the red crosses indicate outliers.

one possible combination of six games (i.e., $\binom{6}{6} = 1$) and thus, we have a singe RMSE result while the remaining combinations of less than six games have multiple RMSE results. We computed the mean and standard deviation of RMSEs for each cardinality: 1.17 ± 0.07, 1.13 ± 0.05, 1.07 ± 0.05, 0.94 ± 0.03, 0.86 ± 0.03 for one to five games, respectively. The referent RMSE when using all six games was 0.72. The box plots in Fig. 3.4 show that the median RMSE decreased monotonically as we used larger numbers of games in training. Unpaired t-tests between these pairs revealed that using more games yielded better performance in a statistically significant manner. Although these results suggest the use of a larger number of games to achieve greater estimation performance, it is noteworthy that the average RMSE of the single game models was only 1.17 whereas the value range of the actual MMSE was from 20 to 30 (NRMSE of which was only 10.63%). This result supports the notion that it would

Table 3.6: The statistics of patients' responses to the SUS. The responses for each question are presented in raw scores that range from 1 to 5, where 1 indicates 'strong disagreement' and 5 indicates 'strong agreement'. The total SUS ranges from 0 to 100 where a higher score indicates a better experience by the respondent. Scores between 70 and 80 can be considered to provide good usability [13].

	Questions	Score ($\mu \pm \sigma$)
1	I think that I would like to use this system frequently.	4.17 ± 0.80
2	I found the system unnecessarily complex.	2.42 ± 1.04
3	I thought the system was easy to use.	3.92 ± 1.04
4	I think that I would need the support of a technical person to be able to use this system.	2.92 ± 0.76
5	I found the various functions in this system were well integrated.	4.33 ± 0.47
6	I thought there was too much inconsistency in this system.	2.17 ± 1.40
7	I would imagine that most people would learn to use this system very quickly.	4.25 ± 0.60
8	I found the system very cumbersome to use.	1.58 ± 0.64
9	I felt very confident using the system.	4.08 ± 0.64
10	I needed to learn a lot of things before I could get going with this system.	2.08 ± 0.64
	Total SUS	73.96 ± 8.62

be still possible to provide reasonably accurate estimation of the total MMSE score even when results from only a small subset of games are available for analysis.

3.6.5 System Usability Scale

Table 3.6 summarizes the patients' perceived usability of *Neuro-World* assessed by the SUS. The total SUS score obtained from the patients (73.96 ± 8.62 out of 100) supports that the overall experience was positive; scores between 70 and 80 can be considered to provide 'good' usability [13]. Particularly, patients responded that they would frequently use the system (4.17 ± 0.80 out of 5), which suggests that longitudinally monitoring patients' cognitive impairment levels via frequent administration would be feasible. On average, patients' responses were neutral to the perceived difficulty of the *Neuro-World* interface (2.42 ± 1.04), which was corroborated by their neutral responses to the need for support from a technician (2.92 ± 0.76). Patients reported that they do not need significant efforts to learn until they become comfortable administering *Neuro-World* (2.08 ± 0.64), which is also confirmed by their responses that majority of people would learn how to administer *Neuro-World* very quickly (4.25 ± 0.60). Hence, it can be understood that the current interface of *Neuro-World* is easy for patients to learn and use (4.08 ± 0.64).

3.7 Discussion

In this work, we introduced a novel means to accurately estimate a clinically validated cognitive assessment score (i.e., the MMSE) that can be self-administered by a patient without the supervision of trained clinicians. Towards that end, we developed *Neuro-World*, which comprises six games based on concepts related to visuospatial short-term memory and selective attention. Furthermore, we introduced a supervised machine learning approach where the extracted game-specific performance features were used to estimate the target MMSE scores. The presented prelimiary results obtained from 12 post-stroke individuals with mild cognitive impairments showed that *Neuro-World* can be used to accurately estimate the total MMSE scores, as well as scores in the MMSE categories, when evaluated using the LOSO-CV technique. Especially, among the estimation models presented in this study, the one that estimated the total MMSE score (Fig. 3.3a) provided the best accuracy (NRMSE = 6.00%). The system also showed great responsiveness in detecting changes over the period of three months in one's cognitive function (with RMSE of 0.78), supporting that the system's potential to longitudinally track the progress of functional level. Lastly, based on the SUS, participating patients reported good usability and willingness to frequently use the system. The total score of our SUS of *Neuro-World* was 73.96 ± 8.62, indicating good usability.

The results provided in Fig. 3.4 support that we can obtain an acceptable estimation accuracy for the total MMSE score using only a subset of games, although a larger number of games would yield more accurate estimation results. Moreover, results in Table 3.5 summarize the importance of the six games for estimating the total MMSE score. Hence, when the proposed system is deployed in real-world settings the order of the games should be arranged according to their importance (i.e., Game 4, Game 1, Game 5, Game 2, Game 3, and Game 6) to maximize its clinical effectiveness. Furthermore, when the system is utilized to longitudinally track changes in one's cognitive level, the system can incorporate an adaptive adjustment of the difficulty level (i.e., stages) rather than asking the patient to always begin the game from the easiest level. For example, the system can start at the last stage of the patient's previous play and proceed to higher or lower stages depending on game performance. We assume that this strategy would reduce the amount of time required for the patient to be engaged in the system to obtain an accurate estimation of his/her cognitive level, ultimately improving the longitudinal adherence rate.

We envision that the proposed approach can be used in residential settings where the trajectory of an outpatient's or even a potential candidate patient's cognitive ability in the real-world can be monitored via the patient's frequent and longitudinal self-administration of *Neuro-World*. The collection of the estimated MMSE scores can be reported back to the patient's clinicians where the long-term monitoring and caring can be conducted in a more resource-efficient manner. The clinician will also be able to refer to the trajectory of the estimated MMSE scores from *Neuro-World* in order to evaluate the effectiveness of the prescribed intervention and develop individually-tailored therapeutic programs. Indeed, it has been reported that individualized home-based cognitive rehabilitation programs can improve the patient's cognitive performance [138], which sheds lights on our ultimate vision of integrating *Neuro-World* into a systematic home-based monitoring and rehabilitation platform. Our system can also be used in an inpatient setting as an automated preliminary screening test. Accurate evaluation of cognitive impairment level conventionally requires the administration of a set of clinically validated assessment tools as well as informal interviews [66, 112]. If a patient can self-administer *Neuro-World* and the corresponding MMSE score can be automatically reported to clinicians during the waiting time in the clinic, we believe that this would help clinicians spend their time more optimally and reduce the amount of the patient's time spent in the clinic. In turn, this will improve the overall quality of clinical services and optimize clinical resources.

CHAPTER 4

REHABILITATION GAMES IN REAL-WORLD CLINICAL SETTINGS: PRACTICES, CHALLENGES, AND OPPORTUNITIES

4.1 Introduction

Upper-limb impairments due to stroke cause weakness, diminished dexterity, and limited ability to perform reaching and grasping movements [170], thereby affecting stroke survivors' performance of essential Activities of Daily Living (ADLs) and leading to significantly lower health-related quality of life [48,67]. There exists robust scientific evidence supporting that repetitive, high-dosage rehabilitation exercises performed in a therapeutically appropriate, quality manner could improve motor abilities of patients[1] [87, 151, 152, 165] as a result of motor learning processes (i.e., neuroplasticity) [19, 29]. However, it is challenging for patients to stay engaged in seemingly mundane, repetitive exercise movements and, at the same time, maintain their attention on the quality of their movement execution (e.g., speed, accuracy, smoothness, and postures), both of which are essential in maximizing therapeutic outcomes [93]. In turn, low motivation in stroke patients and their poor engagement in therapy serve as a major barrier that hinders their potential functional recovery [139].

A number of studies have investigated the use of serious games to improve therapeutic gain through enhanced patients' motivation and engagement level in rehabilitation therapy. Clinical research communities have attempted to validate the

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[1] *Stroke survivor* is the conventionally accepted term in the clinical literature to represent those individuals who survived from a stroke in any recovery stage (e.g., acute, sub-acute, chronic). However, because therapists generically referred stroke survivors that they were treating as *patients* in the collected data, we used both terms interchangeably in this work.

therapeutic effectiveness of commercial off-the-shelf (COTS) games (e.g., Nintendo Wii or Sony PlayStation) in upper-limb rehabilitation [150, 167]. Although more rigorous clinical evidence is necessary to conclude the effectiveness of COTS games in rehabilitation therapy [150, 167], some clinical studies suggest that serious games may improve the rate of recovery in patients' motor function [111, 157]. However, on the other hand, a review paper by Lohse *et al.* suggested that the motivation level enhanced by the use of games vary among patients, which may leads to different therapeutic outcomes [106], but no in-depth discussions were provided. In another study by Brütsch *et al.*, authors quantitatively showed that therapists' active involvement in the game-assisted therapy (e.g., providing additional feedback for patients' performance) may significantly improve the clinical outcomes [28]. Similarly, in conventional rehabilitation, it has been widely accepted that patients' engagement and adherence level may vary [39, 88, 124], and that therapists play significant roles in maintaining patients' engagement and ensuring the quality of performed exercise movements [177,182]. While there has been some speculation about the roles of therapists in moderating game-assisted therapy sessions and suggestions around different engagement levels in patients, there have been no studies that investigated these matters in depth.

As of now, the majority of studies in human-computer interaction communities stopped short at investigating the usability of rehabilitation games [4,5,12] only after deploying the system to patients and clinicians for a relatively short period of time (e.g., a few days). There exists a handful of observational studies that particularly focused on game-assisted stroke rehabilitation therapy in real-world clinical settings after long-term deployment of the games [135]. This causes an inevitable gap between reality and our understanding of stroke patients' heterogeneous engagement patterns, therapists' roles, interaction dynamics between patients and therapists, and practical challenges they encounter. More importantly, such a gap hinders us from analyzing the actual therapeutic impacts of game-assisted stroke rehabilitation. To systematically comprehend the dynamics among patients, therapists, and games—thereby the resulting therapeutic effectiveness—it is critical to investigate game-assisted rehabilitation therapy in real-world settings where such interventions are routinely employed on a daily basis [12, 14].

Our research goal in this study is to achieve a deeper understanding of the interaction dynamics between patients, therapists, and games, and the associated challenges in enabling game-assisted rehabilitation therapy. Towards that end, we established a partnership with a rehabilitation hospital in South Korea, where serious games were used as part of its routine stroke rehabilitation program. We first video-recorded 11 one-on-one therapy sessions between therapists and patients, spanning a total of 5.5 hours of observation, that employed a commercially available serious game system specifically designed for stroke upper-limb rehabilitation (see Section 4.3.4 for details). Patients involved in this study had been receiving 30-minute-long game-assisted therapy sessions five times a week for at least one month. Furthermore, we conducted semi-structured interviews with 15 therapists who had at least three months of daily experience moderating game-assisted therapy. The video-recorded therapy sessions and audio-recorded interviews were then analyzed using Thematic Analysis [24]. Our key findings in this study include identifying 1) four different types of interesting engagement patterns in patients and the resulting interaction dynamics with therapists and the game system, 2) therapists' comprehensive and orchestrating roles in maintaining patients' engagement and therapeutic values, and 3) practical challenges experienced by therapists in game-assisted therapy. More specifically, some notable findings include the conflicts between therapists and patients who are overly engaged in the entertainment aspect of game-assisted rehabilitation therapy, active involvement of therapists as a leading user of the game system, the importance of the game system's customizability for therapists to support patient-centered interventions, and the importance of training for therapists to effectively moderate game-assisted therapy. Building on these findings, we offer promising design implications for rehabilitation games such that therapists can better support patient-centered, individually-tailored, game-assisted therapy programs and maximize therapeutic outcomes.

4.2 Related Work

4.2.1 The Use of Games in Stroke Rehabilitation and Its Challenges

Research and clinical communities have considered games as an effective means to enhance patients' motivation, engagement, and adherence to seemingly repetitive and banal task-oriented therapy (e.g., repetitions of reaching and/or grasping movements) [89, 140]. As a result, a large volume of studies have focused on investigating the clinical effectiveness of COTS games in upper-limb rehabilitation for stroke patients (e.g., flexion and extension of the affected shoulder, elbow, and wrists, and ab/adduction of the affected shoulder). Some studies suggest that game-assisted therapy using COTS games can yield motor recovery in stroke patients. For instance, Yavuzer *et al.* reported that stroke survivors who received 18 half-hour sessions of game-assisted therapy using the PlayStation II EyeToy achieved statistically significant improvement in the performance of ADLs [187]. Choi *et al.* found a significant improvement in stroke patients' upper-limb motor function after practicing 20 half-hour sessions of game-assisted therapy using the Nintendo Wii [33]. According to Lee, patients improved their muscle strength and ability to perform ADLs after 18 hour-long sessions of game-assisted therapy, each of which consisted of a 30-minute XBox Kinect game play session and a 30-minute conventional therapy session [98]. In addition, a few studies suggested that game-assisted rehabilitation therapy or game-assisted therapy in conjunction with conventional rehabilitation therapy may lead to a greater recovery rate when compared to conventional therapy alone. For instance, Manlapaz *et al.* reported that, after 12 half-hour therapy sessions, patients who received Nintendo Wii-based therapy achieved greater improvement in their motor function and spasticity (i.e., resistance to muscle stretching, a common motor symptom in stroke patients) compared to those who received conventional physical therapy [111]. Finally, Sin *et al.* showed that patients who practiced a combination of XBox Kinect-based therapy and conventional occupational therapy achieved a greater improvement in motor function and range of motion when compared to those who only received conventional occupational therapy [157].

While the primary research goals of the above-mentioned prior work were on validating the clinical effectiveness of serious games in rehabilitation, a few studies have briefly discussed the usability issues that stroke patients experienced with the game systems (all of which were COTS systems). Rand *et al.* suggested that COTS games could be cognitively and physically too difficult for some patients to self-administer because the games and their interfaces are developed for the purpose of entertainment in the non-disabled, healthy population [141]. Alankus *et al.* found that patients with significant fine-motor impairments were not able to continuously hold the Nintento Wii controllers and needed to affix the controllers to their hands using a strap. Similarly, Lange *et al.* stated that eight out of 20 stroke survivor participants were not able to complete the initial calibration process that Xbox Kinect used to customize its skeletal tracking model to participants' different body configurations, and the remaining 12 patients managed to complete the process only with therapists' assistance [95]. Due partially to this, Lohse *et al.* suggested that game-induced patients' motivation and engagement may vary depending on patients' impairment level, and the involvement of therapists might be necessary in game-assisted therapy [106]. Subsequently, the user interfaces of COTS games might hinder the effortless game play of stroke patients, which in turn could hurt their motivation in game-assisted therapy. Since motivation is considered one of the most important factors that could affect the clinical outcomes of rehabilitation therapy [108], variations in the game-induced motivation pattern may affect the outcomes in real-world clinical settings. Although these studies have hinted the potential heterogeneity in the engagement patterns of stroke patients depending on their cognitive and impairment condition, there exists no studies to date—to the best of our knowledge—that systematically and conjointly investigated the interaction dynamics among patients, therapists, and games, which calls for more in-depth research endeavor.

4.2.2 Lack of Understanding of Therapists's Roles in Game-Based Stroke Rehabilitation

Indeed, clinical studies suggest that patients' cognitive and motor impairments can affect their performance of exercise movements in conventional therapy. Cognitive impairments affect patients' abilities to process external stimuli, pay attention, and self-monitor their own movements [39, 88, 124]. Motor impairments hinder the execution of therapeutically appropriate movements and, consequently, patients often develop task-specific *compensatory behaviors* using their less affected body parts (e.g., lifting their shoulder to raise their hand or leaning their trunk forward to reach out to grab an object) [102]. These behaviors are clinically important because they may lead to a phenomenon referred to as *learned non-use* (i.e., patients learn to cease using their affected limb) [92, 164], which significantly hampers brain plasticity, the key to maximizing functional recovery throughout the rehabilitation process [99, 102]. In conventional rehabilitation settings, it is therapists' responsibility to design therapeutic activities and adjust their difficulty levels to best accommodate patients' different impairment conditions [63, 119, 146], and to provide verbal and physical feedback to maintain patients' engagement as well as the quality of patients' exercise movements [177, 182].

Although some previous studies have hinted the necessity of therapists' involvement in game-assisted therapy [95, 106], there have been no prior studies that specifically investigated therapists' active roles in serious game-based rehabilitation therapy. This is partially due to a belief that serious games can—to some extent—automate a part of therapists' roles. For instance, a study by Balaam *et al.* on the development of a personalized gaming system for patients with different impairment types and severities briefly reported that therapists' involvement was necessary to assemble different gaming components to accommodate patients' specific needs and enable personalized therapy [12]. Alankus *et al.* attempted to develop rehabilitation games that could enhance patients' compliance to the regimen. The authors mentioned that therapists were substantially involved in designing therapy sessions by selecting the type of games to play and the associated difficulty level in order to accommodate heterogeneous impairment conditions and the recovery pace of different patients [5]. Similarly, Joo *et al.* hinted that occupational therapists were needed to determine games that were suitable for individual patients and to personalize the game equipment (e.g., affixing Nintendo Wii remote controllers to patients' hand using straps) [79]. Deutsch *et al.* briefly suggested that feedback produced during Nintendo Wii games may not be sufficient to ensure the quality of patients' movements and recommended therapists' involvement and supervision during game play [41]. The above-mentioned studies independently suggest that therapists' involvement is much needed in game-assisted therapy to ensure therapeutic benefits. However, these studies mainly focused on either validating the therapeutic effectiveness of COTS games or improving the usability of games for stroke patients, rather than systematically analyzing therapists' roles and practical challenges they face during game-assisted therapy and studying how serious games could be better designed to support their roles.

4.2.3 The Use of Game-Based Stroke Rehabilitation in Real-World Settings

Studying the dynamics of rehabilitation game play in real-world clinical settings is particularly important [18], as it can reveal complex and unexpected phenomena that cannot be otherwise observed in controlled, experimental settings [12, 14]. Despite research communities' strong emphasis and recommendation for investigating healthcare technologies "in the wild", there exist only a few studies that have studied the use of rehabilitation games after adopting the regimen as part of the routine clinical practice for a long-term period. One notable example on stroke rehabilitation is an observational study by Pickrell *et al.* that was conducted in a hospital setting over a four-month period [135]. Aiming to understand effective feedback strategies to enhance patients' motivation, Pickrell and colleagues investigated game-assisted therapy sessions for exercising standing-balance using a custom-designed game [21] as well as a set of Nintendo Wii games. While the major objective of the work in [135] was to offer design guidelines for appropriate feedback to maximize patients' motivation level, the authors also hinted that not every stroke patient enjoyed game-assisted therapy and some patients considered that game-generated feedback was not helpful. In addition, the authors observed that therapists provided various assistance to support patients' game play. However, patients' engagement patterns, therapists' roles, and challenges were out of their research scope and not discussed in depth.

There exist some observational studies that investigated game-assisted therapy in real-world settings, although targeting different user/patient populations [8, 32, 56]. Gerling *et al.* explored the practical challenges and opportunities of using games in long-term care facilities to motivate the elderly population for physical exercises [56]. The study focused on understanding the elderly's experience of games and on discussing game design guidelines to integrate games into self-administered leisure activities. Annema *et al.* analyzed the overall procedure of game-based therapy for children with cerebral palsy and patients with multiple sclerosis to understand ways to enhance the usability of games for therapists [8]. The authors reported that therapists found it difficult to deliver therapy effectively and secure enough net exercise time when utilizing COTS games (e.g., Nintendo Wii) partially due to the complex configuration/calibration mechanism, unskippable cinematic animations, and lack of reports on patients' performance. Cheng *et al.* sought to understand the context of using COTS games (e.g., Nintendo Wii) in a rehabilitation hospital setting with a goal to enhance the engagement of patients with brain injuries to therapeutic regimens [32]. The authors concurred with the findings by Annema *et al.* on the limited net practice time and briefly mentioned therapists' roles in game-assisted therapy. However, these prior studies do not provide in-depth discussion about different engagement patterns of patients and the underlying traits that could have affected patients' apparent engagement patterns. Furthermore, it was not discussed how such patterns can affect therapists' roles and their strategies, and challenge them in assuming their roles. Stroke can affect patients' cognitive and motor function in varying degrees. Such variation introduces greater complexity to patient characteristics, therapeutic goals, and interaction dynamics among patients, therapists, and games, which cannot be understood by the findings of the above-mentioned prior studies. This creates a gap in our understanding and knowledge, which highlights the need for investigating both stroke patients, therapists, and their interactions during routine game-assisted therapy in real-world clinical settings.

4.3 Study Design

This study aims to achieve a better understanding of current practices and challenges that arise while therapists interact with patients and games in the actual clinical setting where rehabilitation games are used as part of the *routine* rehabilitation program. Furthermore, it is our goal to offer design and research suggestion to better support patient-centered, personalized game-assisted rehabilitation therapy. This section describes our study design in detail to achieve these goals.

4.3.1 Study Site

We conducted our study at Heeyeon Rehabilitation Hospital (HRH) in South Korea. We strategically chose our study site due to its access to a large number of stroke survivors with various functional and cognitive conditions, the hospital's active adoption to state-of-the-art rehabilitation technologies (including game-assisted therapy systems), and therapists' daily exposure to such technologies. The hospital ran both a rehabilitation center and a nursing home facility. In August–September 2018, when the observational studies and interviews were conducted, approximately 700 patients were residing in the entire hospital, about 500 of whom were post-stroke patients with a variety of impairment types and severities. The hospital employed over 120 full-time therapists at the time of this study, about 60 of whom were occupational therapists. The hospital operated rehabilitation technology solutions in its routine rehabilitation program. Game-assisted rehabilitation tools that were routinely utilized at HRH included the Rapael Smart Board (Neofect, South Korea/USA) for gross upper-limb movement rehabilitation, and the Smart Pegboard and Rapael Smart Glove (Neofect, South Korea/USA) for fine-hand movement rehabilitation. Besides the serious game technologies, therapists also regularly conducted computerized cognitive therapy using RehaCom (HasoMed, Germany) for the cognitive rehabilitation and robot-assisted therapies for upper and lower limbs using Armeo, Erigo, Lokomat, and Andago robots (Hocoma, Switzerland). As part of their work requirement, therapists had regular meetings and peer training, where they reviewed academic papers and shared their experiences in intervention skills with each other. Hence, albeit the possibility of inter-variability in the therapy style among therapists, it was reasonable to assume that they shared common intervention strategies to some extent.

4.3.2 Participants

In order to understand general interaction dynamics between therapists, patients, and the game system during game-assisted therapy, we recruited pairs of an occupational therapist and a patient who had been engaged in game-assisted upper-limb therapy. The inclusion criteria stipulated that occupational therapists needed to have conducted at least three months of game-assisted therapy using the target rehabilitation game system (i.e., Rapael Smart Board; see Section 4.3.4 for details) and patients needed to be undergoing and had received the game-assisted therapy everyday (i.e., seven-times a week) for at least one month at the point of recruitment. All study participants were recruited by word of mouth and/or study fliers that described the anticipated study procedure (see Section 4.3.3) and the inclusion criteria. When the potential subjects volunteered to participate in the study, research staff explained the risks/benefits associated with the study and obtained informed consents for video-recording their therapy sessions. A total of 11 pairs of occupational therapists (7 females, 25 ± 2 years old, 2 ± 1 years of practices, 9 ± 3 months of moderating game-assisted therapy; mean $\pm$ standard deviation) and stroke patients (6 females, 69 ± 12 years old, 1.3 ± 0.7 years since their latest stroke) were recruited. The patient participants had a wide range of motor function (i.e., spanning from severely impaired to highly functioning patients in terms of 49 ± 21 points in Wolf Motor Function Test [184]) and mild cognitive impairment (i.e., 23 ± 4 points in Korean Mini Mental State Examination [84]). Second, in order to further understand occupational therapists' thoughts and lived experiences from the interactions observed in the video-recorded sessions, we recruited 15 occupational therapists (10 females, 25 ± 2 years old, 3 ± 2 years of practices, 9 ± 3 months of moderating game-assisted therapy) for an one-on-one, audio-recorded semi-structured interview. The same inclusion criteria were applied to these therapists. Eleven of these 15 therapists also participated in the aforementioned video-recorded sessions. The average duration of

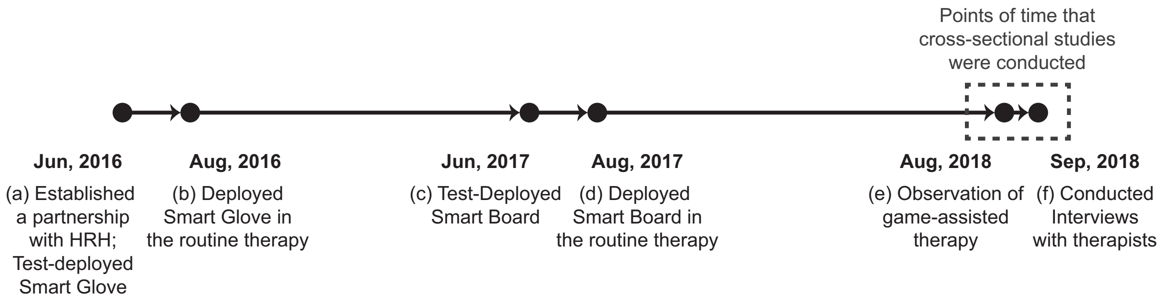


Figure 4.1: The timeline of step-by-step processes taken to conduct the proposed study over two years. (a) The authors and HRH established a partnership. HRH test-deployed one unit of Smart Glove for fine-hand motor function therapy in June 2016. During the test-deployment, HRH contacted the research team at the University of Massachusetts Amherst (UMass) and asked for technical consultation on the use of games in rehabilitation therapy. The first author visited HRH on a daily basis for two months, built rapport with therapists, and discussed their experiences with Smart Glove. (b) HRH deployed one unit of Smart Glove in routine rehabilitation therapy. (c) HRH test-deployed one unit of Smart Board for gross arm rehabilitation therapy in June 2017. During the test-deployment, the research team at UMass again served as consultants, which led to the first author's another daily visits to the hospital for two months. During the visits, the first author further developed rapport with therapists, and discussed their experiences with Smart Board. (d) HRH deployed one unit of Smart Board in the routine rehabilitation therapy. Throughout the HRH's deployment of rehabilitation games, the researcher team observed unanticipated interaction dynamics between therapists and patients, discrepancies between the expected and actual patients' engagement patterns, and therapists' roles in game-assisted therapy, which led to the conception of this research study. (e) The first author video-recorded game-assisted therapy sessions using Smart Board in HRH in June 2018. (f) The first author conducted interviews with occupational therapists at HRH in September 2018.

the interviewed therapists' experience in game-assisted therapy was also nine months. Therapists stated that they administered approximately 1–2 game-assisted therapy sessions per day, which amounts to 270–540 sessions in the nine-month period. Therapists also estimated that they would treat approximately 10–20 different patients using game-assisted therapy in the nine-month period.

4.3.3 Procedure

The overall study procedure is illustrated and summarized in Fig. 4.1. The experimental procedure was approved by the Institutional Review Boards (IRB) of the University of Massachusetts Amherst (IRB# 2018-4850) and HRH. The recruitment of participants was conducted in two sequential stages. For each pair of a therapist and a patient who agreed to participate in the study, one randomly-chosen therapy session was video recorded in August 2018 (Fig. 4.1). We decided to video-record the therapy sessions, rather than observing in person, to minimize disrupting or influencing the usual interaction dynamics. The video camera was installed on the ceiling with a top-down view above the Rapael Smart Board to minimize the obtrusiveness of the equipment. This provided an unoccluded view of the patient's movements and physical interventions provided by the therapist. An external microphone was connected to the video camera and placed on the side of the Smart Board tablet computer so that the conversation between therapists and patients could be clearly recorded. The video-recorded therapy sessions were conducted in a room of size approximately 4×4 m^2 with a glass wall that people could see through. There was one unit of Smart Board in the room, which could serve 14 30-minute-long therapy sessions per day.

In order to gain a better understanding of current practices and challenges, we conducted one-on-one semi-structured interviews with therapists in September 2018 (Fig. 4.1). Interviews lasted for 30 minutes on average, either in an empty office or in an uncrowded hallway within HRH based on the therapists' preference. Questions were designed based on the analysis of the entire video-recorded game-assisted therapy sessions, focusing on identifying representative interactions between therapists and patients. Therapists were asked to share their thoughts based on their overall experience with game-assisted therapy in general, not limited to the specific interactions that we observed in the videos. Furthermore, although our observations were made on the therapy sessions that employed Rapael Smart Board, the therapists were allowed to talk about their broader experience with other rehabilitation games during the interview. We asked therapists about patients' responses towards games and therapists' strategies for effective therapy when encountering patients' different response patterns (e.g., *In the video-recordings, we observed different attitudes in patients during game-assisted therapy. Can you tell me more about patients' response patterns to rehabilitation games and your interventions for effective therapy?*) and how it affected therapists' intervention (e.g., *How and who select games or difficulty levels to personalize games for patients? Why?*). Then, we asked about the representative roles of therapists (e.g., *In the video-recordings, therapists provided substantial amount of feedback or/and assistance to patients during game-assisted therapy? Can you describe your intervention strategies more?*). We also asked therapists about the challenges they faced (e.g., *Can you tell me about the challenges you experienced? What do you think are the primary reasons for the challenges?*).

4.3.4 Apparatus: RAPAEL Smart Board & Games

Out of the three rehabilitation game platforms that were routinely used at HRH (i.e., Rapael Smart Board, Rapael Smart Glove and Smart Pegboard), this study focused on the Rapael Smart Board system [159]. The system is specifically designed to rehabilitate gross-arm movements in stroke survivors, which made it easier to visually analyze the interactions when compared to the other two platforms that focus on fine-hand movements. Furthermore, Rapael Smart Board has previously shown to be effective in improving the functional level and range of motion in stroke survivors [128].

System Configuration. Smart Board is composed of 1) an 18-inch touchscreen tablet computer and 2) a tabletop board with two degrees of freedom cylindrical handle (i.e., a controller for patients), as shown in Fig. 4.2a. The size of the board is $16.1 \times 11.2 \times 4.8\ cm^3$. The system is provided with a forearm support and a Velcro

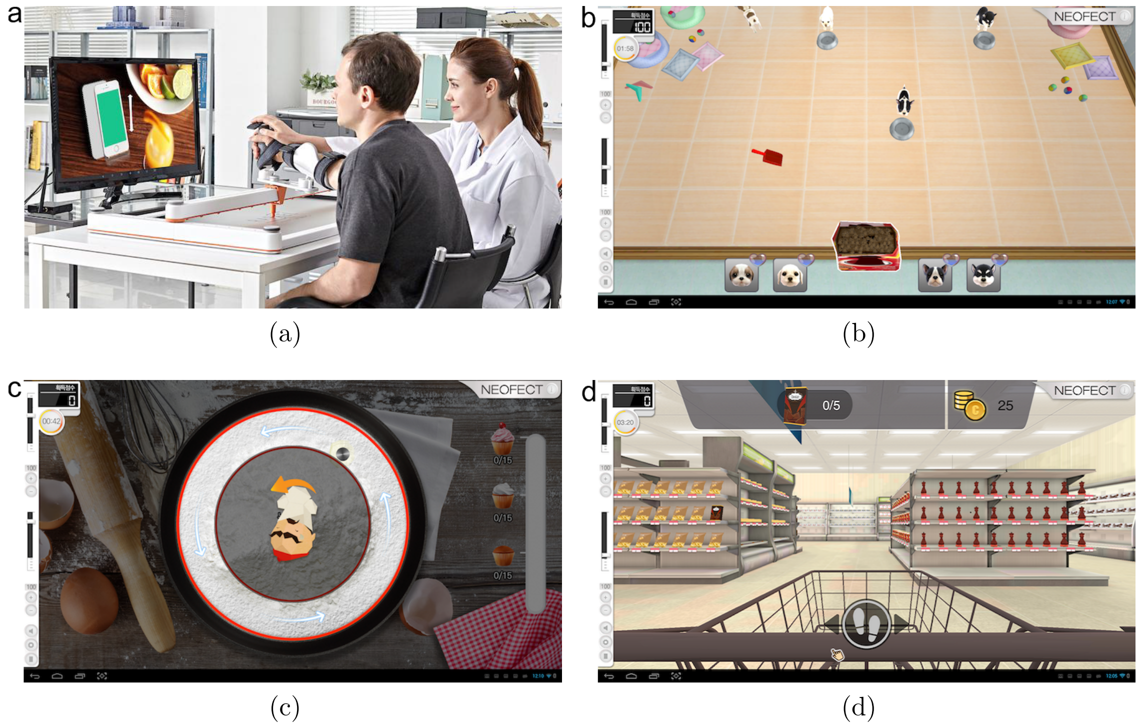


Figure 4.2: The RAPAEL Smart Board and the screen shots of three example games that practice different types of upper-limb movements (courtesy of Neofect Inc. [123]). (a) A demonstration of game-assisted therapy using Smart Board. (b) The pet-feeding game, in which patients need to make point-to-point two-dimensional reaching movements to move food to feed dogs and cats. (c) The dough-mixing game, in which patients need to repeat circular hand movements following a visual trajectory (i.e., to remain inside the rim of a bowl) to make bread dough. (d) The grocery-shopping game, in which patients need to move around a grocery store by reaching to arrow keys that are displayed on the bottom of the screen and collect the asked grocery items again using point-to-point reaching movements.

strap that can be used to assist stroke survivors with severe motor impairments (see Fig. 4.4a). The forearm support helps patients to move their arm more easily against gravity. For patients with severe impairment in fine-hand movements, their hand and fingers could be strapped to the handle using the Velcro strap.

Calibration of Game Play for Patients with Different Motor Impairment Level. Game-assisted therapy sessions start by assessing patients' upper-limb range of motion in a two-dimensional horizontal space (i.e., the Smart Board). During the assessment, patients need to voluntarily reach their hand (i.e., the handle) as far as possible to identify the boundary of their range of motion, based on which the positions of reaching targets in the actual game play are determined.

Supported Games and Movement Monitoring. The game play of Smart Board is controlled by patients' hand position (i.e., the Cartesian coordinates of the handle). At the time of the study, Rapael Smart Board supported 17 different games. Five of these 17 games were designed to exercise the upper-limb range of motion, nine were focusing on the shoulder-elbow joint coordination, and the remaining three were focusing on both the range of motion and joint coordination. Notable games that were frequently used in the observed therapy sessions include 1) the pet-feeding game (Fig. 4.2b), in which patients need to make point-to-point two-dimensional reaching movements to move food to feed dogs and cats, 2) the dough-mixing game (Fig. 4.2c), in which patients need to repeat circular hand movements following a visual trajectory (i.e., to remain inside the rim of a bowl) to make bread dough, and 3) the grocery-shopping game (Fig. 4.2d), in which patients need to move around a grocery store by reaching to arrow keys that are displayed on the bottom of the screen and collect the asked grocery items again using point-to-point reaching movements. For all games, point-to-point reaching movements are considered successful if the distance between the patients' hand position and target position becomes smaller than a system-defined threshold. Trajectory-following movements are considered successful if patients' hand follow the suggested guideline while staying within the set boundary.

Difficulty Adjustment. Most games available on Rapael Smart Board support three different difficulty levels (i.e., difficult, normal, and easy) to personalize the therapy. For most games, the system modifies the difficulty level by adjusting 1) the number of targets presented on the touchscreen monitor and/or 2) the time limit for patients to complete the required exercise movements. Shoot 'em up style games, on the other hand, had a larger number of difficulty levels (e.g., by adjusting the number and movement patterns of approaching missiles to avoid), which were automatically adjusted on-the-fly based on the patient's game performance using a proprietary algorithm.

Performance Reports. Smart Board employs two different approaches to assess and report patients' performance of game play (equivalently, rehabilitation motor tasks). Whenever patients successfully reach to a target for reaching motor tasks or stay within the provided visual guidelines for trajectory-following motor tasks, the game system adds points and displays the accumulated score on the touchscreen monitor. When a patient completes a game, the total score is again displayed on the monitor. Furthermore, therapists have access to patients' performance of previously completed game plays via three different visualizations: 1) the regions that patients reached during the game play (i.e., two-dimensional range of motion), 2) the trace of two-dimensional hand trajectories during point-to-point reaching movements, and 3) the trace of hand trajectories during trajectory-following tasks. All the aforementioned measures and visualizations were computed under an assumption that the affected shoulder of patients is properly aligned to the origin of the games' coordinate system.

4.3.5 Data Collection and Analysis

In total, we gathered 11 video-recordings of therapy sessions that amount to 5.5 hours and 15 audio-recordings of interviews with therapists that amounts to 7.5 hours of audio. The entire video- and audio-recordings were transcribed and translated from Korean to English by a research staff member. The transcripts of the video-recordings included the contextual information (e.g., the room layout, the positions of therapists and patients, whether patients used wheelchair or arm supports), non-verbal (pauses, sighs, laughter, gestures, physical interactions among therapists and patients) and verbal information (e.g., monologue by therapists, dialogue between therapists and patients). All authors participated in an iterative process of data analysis, from which we extracted main themes by analyzing the transcripts using Thematic Analysis [24]. Then, the abstract themes that could explain the observed phenomena were identified, upon which implications of our research were discussed.

4.4 Findings

Table 4.1 summarizes the findings in three themes that we identified: 1) four different engagement patterns of patients in therapy and rehabilitation games, 2) the leading roles of therapists throughout game-assisted therapy, and 3) challenges faced by therapists while facilitating patient-centered game-assisted therapy. Both the video-recorded and interview data were used to derive the above-mentioned themes. However, the therapists' interviews were more heavily used in the analysis, because the interview data provided more in-depth and comprehensive understanding of various patient engagement patterns, the context of therapists' roles and their interactions with patients, and the challenges and needs that therapists experienced (all of which were constructed based on our preliminary understanding from the video-recorded data). We discuss each theme in detail in the following subsections.

4.4.1 Engagement Patterns of Patients in Game-Assisted Therapy

We observed stroke patients' attitudes and engagement patterns in game-assisted rehabilitation therapy. Based on our results, we classified stroke patients into four different groups, which include 1) *overcharged gamers*, 2) *attentive cooperators*, 3) *inattentive apathetics*, and 4) *old-fashioned enthusiasts* (Fig. 4.3). We further discuss the engagement patterns and characteristics of each group, as well as how those patterns affect the therapist-patient interactions and the potential benefits of game-assisted therapy.

Table 4.1: Summary of the identified themes, subthemes, and their description

Theme	Subtheme	Description
Engagement Patterns of Patients in Game-Assisted Therapy (Section 4.1)	• Overcharged Gamers • Attentive Cooperators • Inattentive Apathetics • Old-Fashioned Enthusiasts	Patients show four different engagement patterns while participating in game-assisted rehabilitation therapy.
Critical Roles of Therapists as the Orchestrator (Section 4.2)	• Designing the Therapy • Instructing the Game Play • Correcting Inappropriate Movements • Cheerleading the Therapy	Therapists show four different roles to maintain patients' engagement level and ensure therapeutic gain during game-assisted therapy.
Therapists' Challenges and Needs (Section 4.3)	• Challenges to Prepare the Game Systems • Challenges in Run-Time • Challenges from Lack of Understanding of Therapists' New Roles in Game-Assisted Therapy	Therapists experience three types of practical challenges while administrating game-assisted rehabilitation therapy.

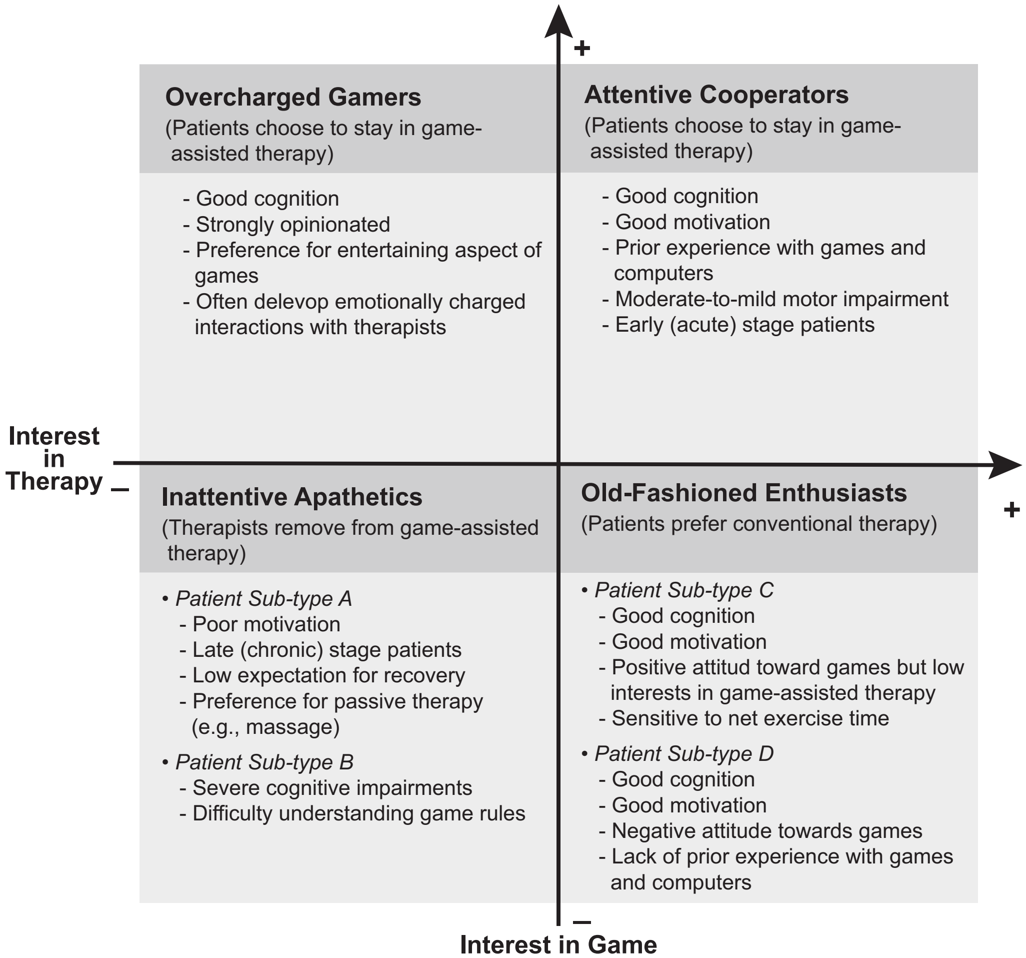


Figure 4.3: Representative patient characteristics based on patients' engagement patterns in game-assisted therapy. The horizontal axis represents if patients have interest in therapy while the vertical axis represents if patients have interest in rehabilitation games. The interview data reflecting the therapists' overall experience in game-assisted therapy were mainly used to identify these patient characteristics.

Overcharged Gamers. From the interviews with therapists, we could identify a group of patients who were engaged with games mainly for entertainment rather than therapy. The interviewed therapists believed that, in general, patients' engagement level could be enhanced during game-assisted therapy when patients have a sense of ownership in selecting games. However, according to therapists, more ownership does not always lead to therapeutically meaningful exercises. Therapists said 1–2 out of 10 patients express strong opinions about what and how they wanted to play games.

> *Some patients have strong opinions on the time duration and the set of games they want to do. When they don't find the game interesting, they just don't do [the movements] any more after trying a couple of times. [...] They have their own way of playing games. [...] They also have a sequence of games they have to play. [...] It's really difficult [to moderate game-assisted therapy sessions] with strong-willed patients.* – T3

The games that these patients prefer often involve exercise movements that are physically easy for them to perform and have minimal therapeutic impacts on the stroke-affected motor function. Therapists would first try to persuade these patients to play (or equivalently exercise) therapeutically more appropriate games (movements).

> *I try to reduce the time duration of playing those games [that are not beneficial to patients] and convince patients to play therapeutically more beneficial games for them. I say "What about another one? Would it be okay to play this one?"* – T3

In response, such strongly opinionated patients would even let go of the game handle and refuse to engage, explicitly expressing annoyance and saying *"I'm not going to do it,"* as one therapist mentioned (T14). According to therapists, such conflicts on selecting appropriate games lead to emotionally charged interactions between therapists and patients. This becomes amplified especially when patients keep insisting on playing games they like and pursuing entertainment.

> *I end up raising my voice and go like "You should do this game! Why won't you try this? Other games are no good for you! You have to practice this movement [supported by the game]! If you are not going to do this, there is no reason to use this Smart Board at all!" Then patients go mad like 'Boom!'* – T7

When patients play the games they want, they would simply *play* and *enjoy* rather than to *exercise* arm movements induced by the game. According to therapists, patients would recruit extremely abnormal compensatory behavior[2] when they lose attention on their movement quality. For instance, T4 stated, *"They even use both*

[2] Readers are referred to the definition of *compensatory behaviors* in Section 4.2.2.

[affected and unaffected] hands [to move the game controller]." Another therapist shared a similar experience:

> *When patients focus on playing games too much, they totally forget about their postures.* – T7

The same therapist first demonstrated proper movements in an upright sitting posture, followed by exaggerated compensatory movements with her trunk and said, *"In this posture, you need to move your arm like this. However, they are like 'bang bang bang,' almost breaking the controller."* Other therapists further supported that patients who are overly engaged in games recruit significant compensatory behavior. When therapists try to correct patients' movements, some patients explicitly resist, as one therapist explained:

> *I wanted to correct his posture, but then he said "I don't want to pay attention on any of those. I just want to do it the way I want."* – T12

Since such a demeanor could result in physical struggle and resistance, therapists would wait until the patient finishes the game, as one therapist stated:

> *When I lay my hand over his shoulder and try to suppress compensation, he shrugs off my hand and does not let me touch him. [...] What do I do for that patient? I cannot really do anything until he finishes the game.* – T7

Consequently, when patients have strong opinions on selecting games and overly engage in the entertaining aspect of the games, therapists could struggle to properly administer game-assisted therapy in a way that benefits the patients. In turn, patients may not practice therapeutically appropriate exercise movements nor achieve functional gain. More importantly, serious game-assisted rehabilitation therapy in stroke survivors may induce the development of therapeutically undesirable compensatory behavior for some overly engaged patients if they are not closely supervised by therapists, which could even be detrimental to their functional recovery.

Attentive Cooperators. Another patient group that we identified includes those who would cooperatively follow the lead of therapists and accept their suggestions during game-assisted therapy. Patients in this group are willing to try the games that therapists suggested even though they may not like the recommended games.

> *Patients would tolerate [the games] even if they don't like [them]. [...] They don't say "no."* – T4

For these cooperative patients, therapists occasionally ask for patients' preferences and opinions in choosing a game in an attempt to provide more ownership of the therapy to patients, hence enhancing their engagement level. However, only 2–4 out of 10 of these patients would actually express their preferences to therapists, and the remaining 6–8 patients would ask therapists to choose the most therapeutically appropriate games for them (T2), demonstrating a strong emotional bond and trust with their therapists (also referred to as *rapport*). Therapists supported that they often establish a strong rapport with *attentive cooperators* and emphasized its importance in game-assisted therapy as much as in conventional therapy.

> *They do what you ask to do when you establish a good rapport. However, if not, they are not going to do what you ask. [...] There was a patient. When he practiced with me, he tried to reach* 5 *cm more [than he could comfortably do]. However, when he practiced with other therapists, whom he didn't have a good rapport with, he would try just a little and give up.* – T8

In one video-recorded therapy session (V3), cooperative interactions based on a good rapport were witnessed throughout the game-assisted therapy session. Both the patient and the therapist enjoyed game play suggested by cheerful laughter and friendly conversation, while the patient listened and tried to reflect the therapists' verbal and physical feedback during game play.

We asked therapists for potential factors that could have contributed to these patients' high engagement level and cooperative attitude. Therapists stated that *attentive cooperators* usually include those patients who are in their early stage of recovery and thus are particularly motivated to improve and return to their normal life.

> *When patients just had a stroke, they are like "I have to get better quickly and go back home."* – T10

From our interviews, therapists also stated that cognitive and motor impairment levels are other important characteristics of patients in this group. Therapists said that *attentive cooperators* often have moderate cognitive impairments. For instance, as will be discussed later, patients with severely impaired cognitive function will not be able to engage (see *inattentive apathetics*, *Sub-type B*), whereas some patients with good cognition perceive rehabilitation games as childish (see *old-fashioned enthusiasts*, *Sub-Type D*). Therapists stated that *attentive cooperators* often have moderate motor impairment level. Patients with severe motor impairment often feel that the performance of active exercise movements (i.e., voluntary arm movements without physical assistance from therapists) is especially difficult and consequently, lose interests in game-assisted therapy quickly (T4). On the other hand, patients with specifically good motor function could easily complete the games and become bored with the game-assisted therapy (T4). Therapists also explained that *attentive cooperators* often have prior experience with computers and games (T11).

We asked therapists if rehabilitation games would provide added values if patients were already motivated and cooperative. T9 responded *"Yeah, they have greater motivation in game-assisted therapy than in conventional therapy."* Overall, therapists believed that games would further improve these patients' adherence to the rehabilitation program as a whole.

Inattentive Apathetics. The next patient group we identified include those who do not engage in conventional nor game-assisted rehabilitation therapy. For these patients, games do not provide any added merits or motivation for them to actively participate in the rehabilitation processes. Based on the interviews with therapists, we further identified two sub-types of patients within this group. The first sub-type includes patients who have poor motivation for rehabilitation in general (i.e., *Patient*

Sub-type A in Fig. 4.3) and the second sub-type includes those who have severely affected cognitive function (i.e., *Patient Sub-type B* in Fig. 4.3).

Therapists explained that the first sub-type of patients often had prolonged motor deficits since their stroke (e.g., more than several years). As a result, these patients have low expectations for potential recovery and show poor motivation to engage in therapy. T11 stated, *"If it has been a while since their stroke and if they are in their chronic stage, [...] they are like 'What can be improved?'."* Therapists believe that the use of rehabilitation games do not provide any notable improvement in the motivation level or adherence to the therapeutic regimen for patients who initially have poor motivation in conventional therapy. T14 stated the following while demonstrating a leaning posture:

> *I initially thought that games would motivate those who were not motivated. However, when patients didn't really have any motivation, they would just lean back and stay like this [during game-assisted therapy].* – T14

Indeed, in one video-recorded therapy session, the patient was minimally engaged throughout the game-assisted therapy session even when the therapist verbally encouraged the patient and directed her attention to rehabilitation games and game-induced movements (V10). The therapist expressed her frustration and sighed multiple times as her patient stayed disengaged despite her continuous efforts:

> *What can I do for you? [...] Please, please. [...] You are not really focusing at all.* – V10

Another therapist shared similar experiences during the one-on-one interview:

> *Some patients simply want to receive a therapeutic massage. They just say "Give me a massage. I don't want anything other than a massage." [...] Even though we take them to game-assisted therapy sessions, they won't make any voluntary movements. We end up giving them massages in front of Smart Board.* – T15

Indeed, in one video-recorded therapy session, the patient received a therapeutic massage throughout most of the therapy session and was involved only in passive reaching movements where the therapist physically assisted the patient's upper-limb movements (V4). Rehabilitation games were not used at all in the session.

According to therapists, patients with severely affected cognitive function (i.e., *Patient Sub-type B*) would have a hard time understanding how to play games and perform the instructed movements:

> *To be honest, only a small group of patients are eligible for such game-based therapies. You need to have at least some cognitive function to understand how to do those games. [...] Because of poor cognition, there are many games that patients cannot really do at all.* – T1

Patients would refuse to participate in game-assisted therapy when they cannot comprehend the game play instructions. T3 said *"Patients with poor cognition don't seem to have an interest in games. When they have a hard time [understanding], they look irritated and say 'Let's just go back to my room.' "* Even when some patients participate in game-assisted therapy sessions, the games would not provide any added values or merits to the therapeutic activities, according to T13's comment: *"They just keep looking at my [demonstrating] hands and not the screen. [...] They try to imitate my hand [movement] because they don't know how to do [expected exercise movements]. She only does what I tell her to do."*

In sum, for *inattentive apathetics*, games do not effectively improve motivation or engagement to rehabilitation. Therapists explained that they usually discontinue game-assisted therapy for these patients and instead provide them with passive therapy, such as therapeutic massages or physically-assisted exercises.

Old-Fashioned Enthusiasts. The last group of patients includes those who prefer conventional, non-game-assisted therapy over game-assisted therapy. According to therapists, 1–2 out of 10 patients fall into this group. Therapists suggest that these patients are aware of the importance of active engagement in therapeutic regimen and already passionately participating in conventional rehabilitation therapies. From the interviews with therapists, we were able to further identify two different sub-types of patients in this group (i.e., *Patient Sub-types C* and *D* in Fig. 4.3). The first sub-type of patients (i.e., *Patient Sub-type C*) believes that they could work hard and make motor improvement without the assistance of games since the practiced exercise movements are essentially the same. In addition, according to therapists, these patients are attentive to maximally utilizing the limited therapy time with therapists and do not want to reduce the net practice time by adopting games.

> *Some patients say that games are not really necessary because they can do [the same exercise movements in conventional therapy sessions] just with therapists. They say they can practice those movements and believe "It's just a matter of using games or not." [...] They do not want to waste even a single minute of their [30-minute] therapy session.* – T10

In our study site, the rehabilitation game-equipped room was located on the sixth floor. If patients were on different floors therapists had to bring them to the sixth floor, and the travel time was counted as part of the 30-minute therapy time. Many patients also had impairment in their gait and had to use an elevator, which could take up to several minutes. This resulted in reducing the net exercise time and influenced patients in this group to prefer conventional therapy over game-assisted therapy. T10 stated, *"It's not like they are negative to rehabilitation games. They like games, but it's quite inconvenient for them to come all the way up [to the sixth floor]."*

Therapists describe the second sub-type of *old-fashioned enthusiasts* (i.e., *Patient Sub-type D* in Fig. 4.3) as those perceiving rehabilitation games as inappropriate for their dignity (e.g., considering games as more appropriate for youngsters).

> *Some patients with good cognition say "This is a toy for kids. What are you going to do with this to me?" [...] They mention "I want therapy. Not this [game]. I want to receive real therapy."* – T7

Another therapist shared a similar experience.

> *I wanted him to practice the movements [that are supported by some games], but he didn't like them because games looked childish to him. He said "Do I really have to do this?"* – T8

When therapists were asked for the potential reasons that may have caused such negative perceptions and attitudes of patients towards game-assisted therapy, therapists thought that the lack of patients' prior experience with computer and video games could be one of the factors. T4 stated, *"You know, these patients have never played video games before."* We asked therapists if previous exposure of patients to traditional, non-computerized games (e.g., card or board games) would lead to a positive attitude towards rehabilitation games. Therapists explained that patients may not want to engage in rehabilitation games even if they enjoy conventional games.

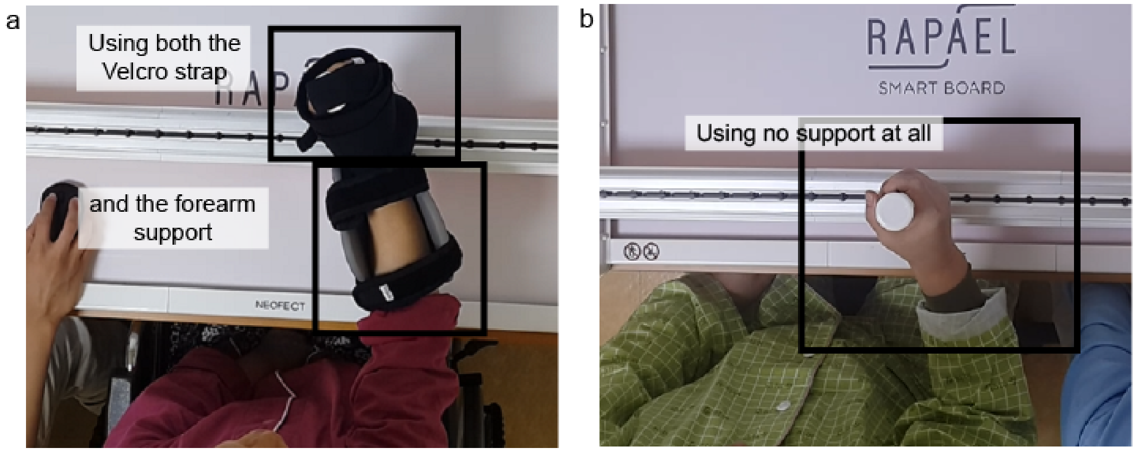
> *Those who play real card games, like pokers, think rehabilitation games are childish. Because of fine motor impairment, they really have a hard time holding cards. Nevertheless, they still try hard to play those card games but not rehabilitation games.* – T9

Another major factor that influences these patients' negative perceptions towards serious games could be the style of graphics (cartoon-like) used in the games. T8 said, *"We think these patients could benefit from practicing with Smart Board, but they think gaming graphics are too childish."*

4.4.2 Critical Roles of Therapists as the Orchestrator

Our analysis revealed that therapists play comprehensive and orchestrating roles during therapy sessions to maximize clinical outcomes for their patients. We identified four major roles of therapists in game-assisted clinical rehabilitation, which include 1) *designing the therapy*, 2) *instructing the game play*, 3) *correcting inappropriate movements*, and 4) *cheerleading the therapy.*

Designing the Therapy. We found that therapists strategically prepare game-assisted rehabilitation sessions to provide personalized, patient-centered therapy by selecting which games to play (or equivalently, which exercises to perform), the difficulty levels, and arranging assistive tools (i.e., a forearm support and Velcro strap) to support patients' different impairment level. Furthermore, therapists actively adjust



(a) (b)

Figure 4.4: (a) The patient had difficulty making a firm grip around the controller and practicing arm movements against gravity. The therapist applied both the forearm support and the Velcro strap to physically assist the patient's exercise movements. (b) The patent can make a firm grip and move against gravity on his own. The therapist does not apply the forearm support nor the Velcro strap.

their designs during the therapy sessions based on patients' responses to the regimens. The interviews with therapists revealed that they try to balance patients' engagement levels and therapeutic benefits by selecting a combination of entertaining games that patients prefer and games that therapists deem therapeutically meaningful (i.e., negotiating with patients).

> *I let them play what they want for three minutes and ask them to play what they need to play for six minutes in return. I repeat this within the therapy session to keep their engagement and yet make the overall session more therapeutically meaningful.* – T9

Therapists also carefully select the difficulty level for the games to maximize the therapeutic outcomes.

> *I control the difficulty level most of the time. [...] When patients seem to do well, I would stop the game and restart at a higher difficulty level.* – T3

Therapists were asked for the reasons that they would not offer patients complete freedom to choose games. Therapists answered that their selection of games would be essential to ensure clinical relevance and benefits of game-assisted therapy.

> *If I completely leave [selecting games] to patients, wouldn't it lead to poor recovery? If patients practice games that challenge the cognitive aspects more while they need to improve their range of motion, it wouldn't be much helpful. Most patients cannot make such decisions on their own.* – T1

Therapists further explained that patients, including the *attentive cooperators*, show preference for the games that they have played before or the associated exercise movements are easy to perform rather than exploring for therapeutically challenging games.

> *Patients rarely choose difficult games. They usually choose the games that induce the movements they can do easily.* – T11

Therapists selectively choose to use assistive tools (i.e., a Velcro strap and a forearm support) to accommodate patients' motor impairment levels, so that patients can better focus on the specific motor function that therapists aim to practice. When patients have difficulty grasping and holding on to the controller (i.e., poor fine-hand function), therapists use a Velcro strap to affix the patients' hand to the controller so that patients can focus on regaining gross-arm function. T4 described, *"When patients don't have a strong grip, we wrap a Velcro strap around their hand and the controller. We selectively use the strap to adjust the level of support for patients."* When patients' gross-arm motor functions are severely deteriorated, therapists use the forearm support attached to the handle in order to attenuate the amount of gravity so that patients can perform gross-arm movements more easily. In the video-recorded sessions, 3 out of 11 patients used a forearm support and 10 out of 11 patients used a Velcro strap throughout the game-therapy sessions. Fig. 4.4a shows a patient who used both the forearm support and the Velcro strap, and Fig. 4.4b shows a patient

(a) (b)

Figure 4.5: (a) The patient failed to recognize the reaching target position instructed by the graphical visual stimuli. The therapist directs her attention to the target with a pointing gesture. (b) The patient lost attention before finalizing a reaching task to the target. The therapist puts her hand over the patient's hand to complete the task together while verbally directing the patient's attention to the target.

who could voluntarily grasp and practice movements against gravity without the assistive tools. These findings collectively shed light on the importance of therapists' strategic decisions in personalizing game-assisted therapy for individual patients. As patients' motor functions improve over time, therapists would adjust the use of assistive tools accordingly. T7 stated that, *"I would use a forearm support in the beginning and then remove it over time."*

Instructing the Game Play. Our analysis revealed that therapists employ various approaches to provide additional instructions regarding game-related rules to their patients—especially for those with cognitive impairments—despite games providing visual instructions on the screen via text and animated images. Therapists communicated their instructions using three different methods: verbal, gestural, and hands-on physical assistance.

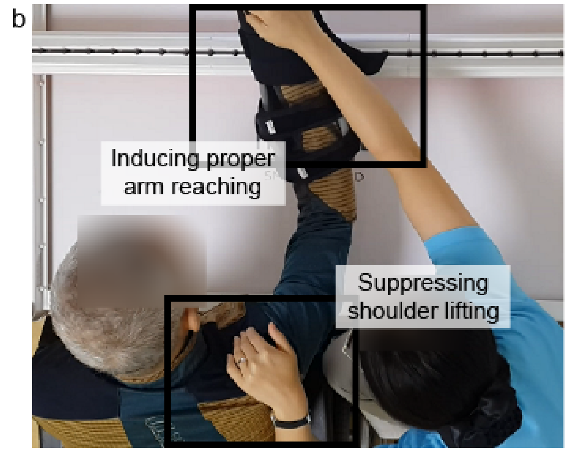
During the calibration procedure to measure the range of motion (see Section 4.3.4), therapists often verbally instructed patients to induce the maximum voluntary range of motion. For instance, in one video-recorded session (V2), the therapist made an analogy between the expected hand movement and painting: *"Let's paint the screen. Move [your hand] back and forth."* In combination with verbal explanations, therapists physically demonstrated the expected movements for the range of motion assessment. For instance, in V1, the therapist swung her arm from left to right in the air while saying, *"Let's make a big circle from your left to your right. [...] Let's try one more time. [...] Yes, you're making a beautiful circle."* When patients did not comprehend the instruction from the verbal or gestural explanations, therapists also provided physical assistance by placing their hand over the patient's hand and moved together until the patient understood the instruction (V2).

A similar pattern of instructions was observed while patients were engaged in actual game play. Especially when games simultaneously provided multiple visual stimuli on the screen, patients demonstrated difficulty directing and maintaining their focus on the appropriate visual stimuli (e.g., targets to reach). As a consequence, therapists had to repeatedly direct the patient's attention to the appropriate visual stimuli or explain their meaning throughout the therapy sessions. For instance, in a shoot 'em up style game, patients had to avoid missiles and stay alive to advance to higher stages and gain higher scores. In one video-recorded session (V3), the patient chased missiles rather than avoiding them. The therapist repeatedly explained the game rules and expected movements to the patient:

> *[Missiles are] Incoming. Incoming! No! Dodge! [...] Get out [of those missiles]. Don't dive into missiles. [...] When you touch them, you will die.* – V3

The therapist made pointing gestures to direct their patients' attention to the correct targets on the screen (Figure 4.5a). In another video-recorded therapy session, the patient had difficulty locating the reaching targets on the screen and the therapist had to continuously point at the targets throughout the session (V8). Sometimes, patients did not reach all the way to the targets and stopped their movements in the

(a)



(b)

Figure 4.6: (a) The patient slouched while performing arm movements. The therapist taps the patient's shoulders and reminds of a proper sitting posture. (b) The patient lifted his shoulder to compensate reaching movement rather than fully extending his elbow. The therapist suppresses the shoulder compensation and pulls the hand forward to induce a proper arm reaching movement.

middle. In such cases, therapists physically assisted their patients to complete the movements. For instance, in V5, the therapist placed her hand over the patient's hand and moved to the target together while verbally explaining *"Here. All the way here. Go and follow the arrow."* (see Fig. 4.5b). As described herein, due to patients' limited cognitive capacity, therapists' additional instructions are necessary to help patients understand, follow, and play games.

Correcting Inappropriate Movements. Another important role of therapists during game-assisted therapy is to correct patients' improper postures and suppress abnormal compensatory behaviors in order to induce therapeutically more meaningful exercise movements. T2 quoted,

> *Honestly speaking, I believe posture is the most important thing that patients need to pay attention to. [...] I always start correcting patients' posture. [...] That may negatively affect the engagement of patients [in playing games]. But, even if you execute a movement just once, I think it is important to do it in a right way.* – T2

Indeed, in the video-recorded therapy sessions, it was frequently observed that therapists provided their patients with detailed verbal explanations to yield therapeutically desirable movements.

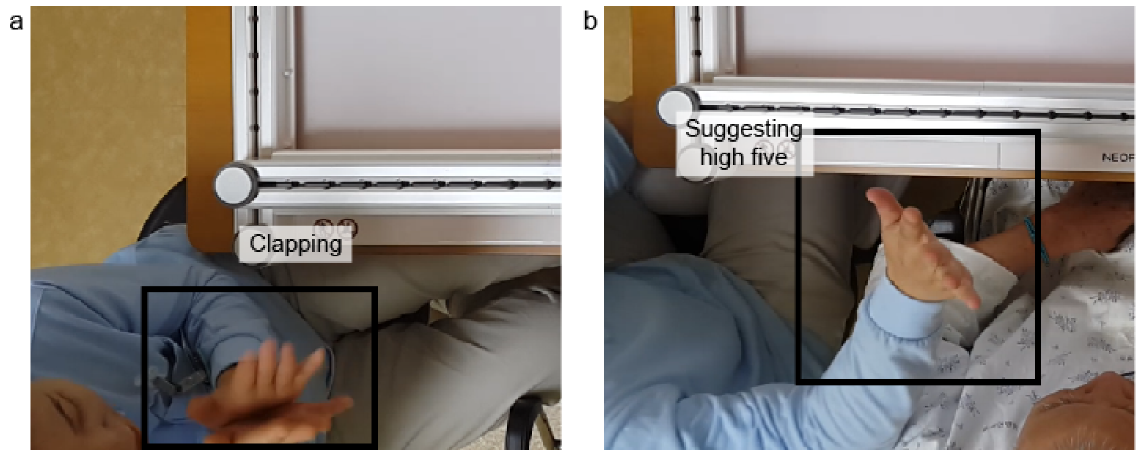
> *Don't lean back. Keep your trunk away from the chair-back. [...] Reach [your hand forward]. [...] Don't do it with your trunk. [...] Now, bring [your hand] back. Your trunk should stand still. [...] You need to move your hand back.* – V6

In addition to verbal explanations, therapists may provide physical feedback to patients as needed. For instance, in one video-recorded therapy session (V11), the therapist gently tapped on the patient's back and said *"sit up and open up your shoulders"* to induce an upright sitting posture when the patient started to slouch (Fig. 4.6a). For patients who employed significant compensation, therapists went beyond the gentle tapping and physically suppressed patients' compensations. In another video-recorded session (V8), the therapist pushed against the abnormally lifted shoulder with the left hand, and grasped and pulled the patient's hand to the reaching target with the right hand in order to enforce a therapeutically desirable reaching movement (Fig. 4.6b).

When we asked therapists for the reasons that they emphasize therapeutically appropriate postures and movements, therapists answered that such movements are essential in yielding the true motor recovery and minimizing undesired pain or injury, especially when the engagement factors of the games stimulate and influence patients to maintain their entertainment values (e.g., to be able to continue their game play or obtain higher game points) by generating clinically undesirable movements (e.g., compensatory behaviors).

> *Patients feel forced to make movements quickly in game-assisted therapy and tend to recruit muscle groups in atypical manners. It can cause additional pain.* – T13

The same therapist further explained that such pain may serve as a major factor to disengage patients from game-assisted therapy sessions.



(a) (b)

Figure 4.7: (a) The patient cleared a game stage and the game played visual and audio fanfare. The therapist claps to further motivate the patient. (b) The patient cleared a game stage. The therapist suggests a high five to the patient.

> *They say "It hurts again. I don't want to do it." [...] Patients wouldn't know what they are doing wrong unless we tell them.* – T13

These findings support the imperative role of therapists in supervising and intervening to promote patients' appropriate postures and movements, thereby maximizing the therapeutic outcomes.

Cheerleading the Therapy. Another important role of therapists in game-assisted therapy includes their efforts to applaud patients when they perform therapeutically-appropriate movements, comply with therapists' feedback, and/or successfully complete a game with good performance. In one of the video-recorded therapy sessions (V1), when the patient demonstrated smooth joint elbow-shoulder coordination during a reaching movement, the therapist complimented by saying, *"That was a nice stretch of your elbow. Wow, you didn't hit anything. Nice!"* In another video-recorded therapy session (V6), the therapist complimented the patient when he successfully complied with the feedback: *"Try to move your hand forward and backward. Come all the way back. [...] Don't use your trunk. [...] Yes! That's right!"* When the patient successfully cleared a game stage, the therapist cheered and clapped (Fig. 4.7a) in addition to the game-provided audio-recorded fanfare and animated graphics (V2). In one video-recorded session (V6), the therapist suggested a high five after the patient successfully completed a game (Fig. 4.7b).

When we followed up with therapists for the reasons that they provide additional encouragement, therapists first explained that, given a pool of games, patients end up repeatedly playing only a small subset of games that are relevant to their specific impairment condition. T13 said, *"There is no patient who plays all 17 games. There's only a limited number of games that each patient needs to practice and finds interesting. [...] Patients are often left with only three-to-four games to play."* Therapists argued that patients often lose interests in game-assisted therapy after some time and therapists have to provide extra cheerleading to motivate patients and improve their adherence to the therapeutic regimen.

> *When you play games everyday, you get so used to them. It's not just patients, I think anyone would be bored. [...] When I compliment and cheer for patients, they seem less bored and doze off less during the therapy.* – T8

4.4.3 Therapists' Challenges and Needs

As we discussed in the previous subsection, therapists play key roles in enabling effective game-assisted therapy. In this section, we identify three major challenges that therapists experience as a *leading user* of the rehabilitation game system while administering patient-centered therapy. The challenges revolved around 1) *challenges to prepare the game system*, 2) *challenges in run-time*, and 3) *challenges from lack of understanding of therapists' new roles in game-assisted therapy.*

Challenges to Prepare the Game System. Prior to every game-assisted therapy session, therapists had to align patients to the coordinate origin (i.e., the centerline) of the Smart Board in order to personalize the system based on the patients' anthropometic characteristics (e.g., sitting-height). The alignment is particularly important because the Smart Board games provide graphical feedback of patients' hand positions (e.g., the location of the jet fighter in a shoot 'em up style game) based on the assumption that patients are properly aligned to the Smart Board. First, therapists position patients to the centerline of the system to face the monitor. In the observed video-recorded sessions, most patients used wheelchairs and were not physically able to self-align to the system, so therapists operated the wheelchairs to perform the alignment. Then, therapists adjusted the height of the table, on which the Smart Board was placed, to patients' sitting-heights. Since there were no visual references that therapists could use to find the correct alignment, it was possible that patients were not perfectly aligned to the game system. Potential misalignment could introduce 1) a discrepancy between patients' actual movements and the game system's measured movements within each therapy session and 2) inconsistency in the measure of patient performance across multiple therapy sessions. T13 stated,

> *The sensor measurement is significantly affected by where patients sit and face. [...] When the position of the chair [that patients sit] moves, patients' same movements are measured differently.* – T13

Subsequently, incorrectly measured hand movements can cause significant difficulties for therapists to moderate therapeutically important exercise movements. T15 commented,

> *When patients are not facing the front direction correctly, their movements and the game cursors do not match. [...] Stroke patients often don't have normal cognitive function and don't comprehend their movements well. [...] They simply believe that the perceived cursor movements and their own hand movements match.* – T15

Furthermore, therapists emphasized the importance of consistent alignment across multiple therapy sessions, particularly when different therapists had to see the same patient (T12). For instance, when the designated therapist for a patient has a day off, a peer therapist has to substitute the game-assisted therapy session (T12). The inter-therapist variability in the alignment could lead to different measurements of motor performance. Due to the above-mentioned possibilities for misalignment, the summary of a patient's motor performance generated by the Smart Board system may not reflect the patient's actual motor performance, as well as its longitudinal tracking over time. T14 commented that *"Movement measurement depends on how patients sit. [...] Although patients' performance is consistently getting better, the performance shown in game-generated reports may fluctuate over time."* Such inconsistency may lead to therapists' and patients' distrust of game-generated reports on patients' performance, as T13 stated:

> *To be honest, I end up not checking the [game-generated] reports. [...] I don't really trust [the reports].* – T13

In our interviews, therapists argued that observable and tangible references need to be provided by the game system to properly align patients. One therapist proposed an idea of integrating the Smart Board with a table and a chair, positions of which could be explicitly controlled by therapists.

> *A table and a chair could have been integrated with Smart Board, and their positions could be controlled like up, down, forward, and backward. [...] They could be integrated as a complete package.* – T13

The findings reported in this section demonstrate that even a simple rehabilitation game system with only two degrees of freedom (i.e., a handle moving in a two-dimensional space) needs careful preparation and arrangement in order to yield appropriate therapeutic outcomes and accurate measurements of motor performance. It is particularly important that the game system provides a convenient way for therapists to adjust the system to the patient's physical and anthropometric conditions, or otherwise becomes a great burden for therapists to enable personalized, game-assisted therapy.

Challenges in Run-Time Therapists often face difficulty while delivering personalized game-assisted therapies for individual patients when therapeutic goals set by the therapists are not well supported by 1) the system-provided variables determining the difficulty level of game-induced movements and 2) the criteria evaluating patients' performance of exercise movements. Furthermore, game system's limited user interface for therapists—the *leading user* of the rehabilitation game system—to interact with and control the game system during run-time could hamper the effective moderation of therapy sessions.

In order to adjust the difficulty level of game-induced exercise movements in Rapael Smart Board, therapists were given a single variable: selecting one of the three stages of increasing difficulty levels that was preprogrammed into the games. When this variable did not adequately support the therapeutic goals set by therapists, therapists were not able to deliver the therapy that they deemed appropriate for individual patients. Patients often need to practice different aspects of movements, such as the ability to precisely control hand movements, greater range of motion, or faster and smoother movements (T2, T6, T7, T12). However, the preprogrammed difficulty level of the Smart Board games were designed to mainly challenge patients' movement speeds by either 1) adding more targets to reach within a given time or 2) decreasing the time duration within which patients need to complete the motor task. T2 provided an example with the jigsaw puzzle game, in which patients assembled tessellating pieces to produce a complete picture. *"When you select a more difficult stage in the jigsaw puzzle game, less amount of time duration is given to patients until they could completely assemble the puzzle."* The therapist further stated that the discrepancy between personalized therapeutic goals and the preprogrammed goals in games could lead to therapeutically undesirable consequences.

> *If [the game] focuses too much on patients' movement speeds, then [patients] end up employing significant compensatory movements and making less precise movements.* – T2

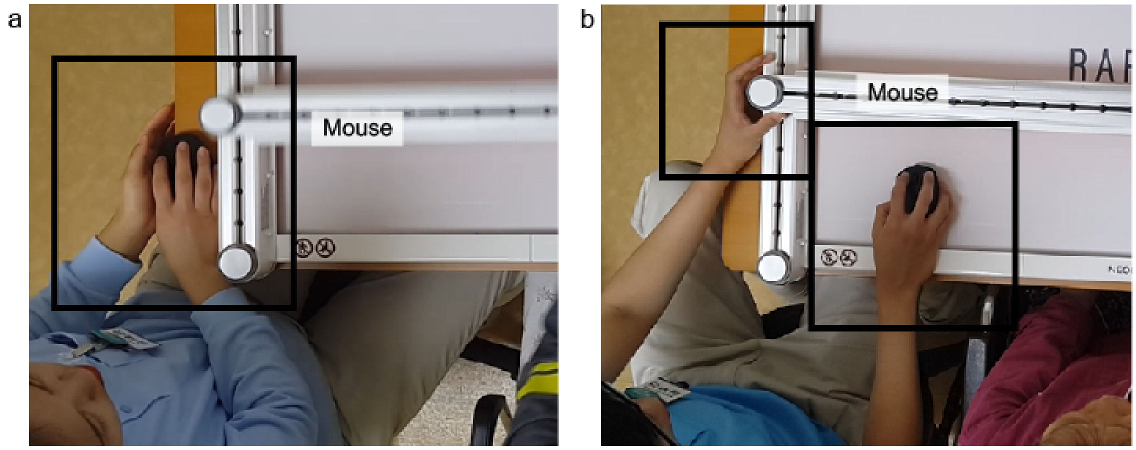
T6 shared a similar experience. The therapist wanted a patient to practice for a larger range of motion, but the preprogrammed game configurations could not support the exercise. The therapist gave an example with the constellation-drawing game in which a set of stars (i.e., reaching targets) are displayed and patients have to sequentially connect the stars to complete a drawing of a constellation. This game changed the number of stars to adjust the difficulty level rather than placing them further away to practice a greater range of motion, which may be more relevant to some patients depending on their motor condition. The therapist explained that he ended up re-calibrating the system to increase the measured range of motion beyond that of the patient's active range of motion (see Section 4.3.4 for details regarding the calibration process). Such a 'hack' enabled the games to place the reaching targets further away from the patient and induced a greater range of motion.

The interviews with therapists also revealed that the Smart Board's criteria to determine patients' successful movements did not always conform to the criteria of therapists. For example, in point-to-point reaching exercise movements, games considered a reaching movement successful as long as a patient's hand (i.e., the handle) reached the target. In contrast, therapists considered a reaching movement successful only when its quality (e.g., smoothness, speed, or presence of compensatory behaviors) was satisfactory. For instance, one therapist described,

> *When I saw [a patient's movements], the patient didn't really do movements correctly. [...] Even when the patient used compensatory movements, games said the movements were successful and I talked to myself like "Ah, that's not it."* – T12

Consequently, therapists ended up correcting patients' exercise movements based on their own evaluation of motor performance (see *Correcting Inappropriate Movements* in Section 4.4.2 for details), rather than simply relying on what was provided by the games.

In our observation, therapists demonstrated difficulty interacting with the game system to control variables to enable personalized therapy, mainly due to the system's limited interaction interface. As we previously discussed, therapists often sit next to



(a) (b)

Figure 4.8: (a) A therapist is placing a third-party wireless mouse on the edge of the desk to interact with the system. She is supporting the mouse with her left hand to prevent it from falling. (b) A therapist placed the mouse on the Smart Board while the patient completely stopped movement. He is holding the game handle to secure a sufficient space to move his mouse.

or behind the patient (e.g., Fig. 4.6) to orchestrate the therapy session. However, the touchscreen of the game system was located across the Smart Board controller, which was out of the therapists' reach. Therapists ended up utilizing a third-party wireless mouse to interact with the game system in an uncomfortable manner (see Fig. 4.8). Therapists often placed the mouse on the edge of the table, on which the Smart Board was placed, the Smart Board itself, or on their lap so as not to interrupt patients' exercise. During the interview, they expressed their frustration about the limited interfaces of the rehabilitation game, which did not consider therapists as a leading user (T2, T3).

The findings reported herein suggest that therapists may be able to moderate therapy sessions more effectively if the game system provides 1) flexibility in adjusting and customizing game-induced exercise movements to individual patients' motor deficits, 2) more accurate and clinically relevant evaluation of patient's motor performance, and 3) a comfortable means to interact with the game system.

Challenges from Lack of Understanding of Therapists' New Roles in Game-Assisted Therapy. Our findings in the previous sections showed that therapists go beyond merely helping patients to play rehabilitation games but to administer the entire game-assisted therapy sessions. In our interviews, therapists strongly expressed the need for proper education or training to learn how to effectively utilize rehabilitation games as a therapeutic tool. For instance, a first-year therapist, T14, stated:

> *My first exposure to rehabilitation games was during my internship. When I joined [Heeyeon Rehabilitation Hospital], I did not know what to do [in game-assisted therapy]. [...] There were no textbooks. No professors taught me how to do therapy using rehabilitation games when I was in my college.* – T14

The same therapist said that they identified their roles in game-assisted therapy based on the lived experience of senior therapists or their own trial-and-errors.

> *I had to ask other senior therapists. [...] I struggled a lot. [...] I think I should just try more.* – T14

Another therapist also concurred and explicitly emphasized the necessity of formal training on game-assisted therapy.

> *When you get to use [the rehabilitation games] right away [without any training], you won't know if you have to actively provide physical assistance to address patients' compensation. [...] If there is some training on game-assisted therapy, then therapists can be aware of their roles more clearly. Such training will lead to more efficient use [of the rehabilitation games].* – T8

We asked therapists for any undesirable consequences that could occur due to the lack of understanding or proper training. Therapists explained that the inappropriate use of rehabilitation games can cause negative side effects, such as pain or injury.

> *The use of games can cause pain or injury when rehabilitation games are inappropriately used. So, it's important for therapists to understand the specifics of game products and appropriate ways to apply them. [...] This makes it difficult especially for those who are new to game-assisted therapy.* – T13

Another therapist shared her own experience such that inappropriate use of assistive tools (e.g., wrapping a Velcro strap) by incompetent therapists could lead to the reduced net therapy time and patients' distrust in therapists, both of which could significantly affect the outcomes of game-assisted therapy.

> *A patient talked to me the other day. She said that she felt quite bad when incompetent therapists administered her game-assisted therapy. [...] She asked me if I could take over or teach her therapist [how to deliver therapy in game-assisted therapy]. [...] When her hand gets out of the strap, then she's losing [the net therapy] time again.* – T7

These findings collectively suggest that clear identification of therapists' roles and appropriate, comprehensive training on the game platform is necessary to accelerate therapists' learning curve and enhance the quality of game-assisted therapy sessions.

4.5 Discussion

Our study revealed that, in actual clinical settings, patients show different engagement patterns during game-assisted therapy based on a number of factors, such as their motivation level, cognitive and physical impairment, and prior experience to games and technologies. We also observed and categorized therapists' comprehensive roles encompassing the administration of the entire game-assisted therapy sessions, in which therapists constantly interacted with patients as well as the game system. In this section, we further discuss our findings and compare them to prior work, mostly around optimizing patients' engagement and their therapeutic gains in game-assisted therapy. Then, we discuss the limitations of our work.

4.5.1 Customized Approaches for Patients with Different Engagement Patterns

Our study results identified four patient groups that show different engagement patterns to game-assisted therapy.

Deliberate Reduction of Entertainment Features for *Overcharged Gamers*. The first patient group—*overcharged gamers*—strongly pursue the entertainment value of rehabilitation games rather than focusing on the therapeutic value, which is the actual goal of game-assisted therapy. During game play, these patients insist on playing the game that they strongly prefer, which usually involve therapeutically less meaningful movements, and/or recruit severe compensatory behaviors. In the literature, Lange *et al.* similarly argued that patients may focus less on their impairments as a result of playing games during therapy [95]. The effect of such shifted focus may lead patients to recruit significant, therapeutically-undesirable compensatory behaviors, as we observed in our study. However, most studies on serious games for rehabilitation have focused on investigating how to enhance patients' engagement to games [107]. For example, researchers have applied the Flow Theory in designing rehabilitation games such that patients can better focus on (or improve attention to) game play [22, 110]. The Flow Theory asserts that, in order for a player to experience the fun (in our context, engagement), the difficulty level of games should be appropriately adjusted to balance between the player's ability and the amount of challenge that the player encounters during the game play [38]. For another example, previous studies on serious games in healthy elderly individuals reported that participants could be more engaged in exercises when they are provided with challenging games and attain the feeling of achievement [40, 56]. However, our study suggests that such an approach might not be applicable in the same way to *overcharged gamers* who are already excessively immersed in game play and consequently depreciate the therapeutic values. We believe that this is associated with the unique functional characteristics in stroke survivors that 1) the impairments are prominent only in some parts of the body (e.g., stroke-affected limb) and 2) it often requires great efforts (or even with pain) to generate game-required movements using the affected limb that they are aiming to rehabilitate. Consequently, when *overcharged gamers* are challenged during game play to generate a movement with the stroke-affected limb, they choose rather an easy solution to address the challenges—i.e., compensating the movements using other less-affected body parts such as swinging the trunk to reach to a target—so that they can maintain their entertainment values. Therefore, it may be necessary to introduce serious games to stroke survivors with care based on their propensity for games and/or design games that can deliberately reduce the entertainment features to enhance their attention to the therapeutically important factors.

Strong Rapport and Supervision for *Attentive Cooperators.* The second patient group represents *attentive cooperators* who actively engage in therapeutic exercises and follow the lead of therapists in game-assisted therapy. These patients are often in their early stage of recovery, as discussed in Section 4.4.1. Some of the observed traits of these patients concur with what has been reported in previous studies. For instance, Yu *et al.* reported that, in conventional therapy, patients would better adhere to rehabilitation in their early recovery phase when they are eager to recover and return home [189]. Furthermore, our results also showed that *attentive cooperators* establish strong rapport (i.e., a strong emotional bond and trust) with their therapists, and potentially diminished rapport may lead to patients' poor adherence to therapists' instruction and game-assisted therapy. In conventional non-game-assisted rehabilitation process, the rapport between therapists and patients have been recognized as an important factor that significantly affects patients' compliance to therapy [154]. Our findings support that serious games are another form of therapeutic activities and hence, the strong rapport between the patient and therapist is as important as in conventional therapy.

It is noteworthy that therapists strongly believe that they should have the ownership to moderate game-assisted therapy (e.g., selecting what games to play or adjusting difficulty level) for most patients regardless of their engagement patterns to maximize therapeutic benefits. Therapists occasionally asked some *attentive cooper-*

ators to choose a game but never the difficulty level. Unlike our findings, previous studies on serious games in healthy elderly individuals reported that participants enjoyed selecting the games to play from a variety of choices [55, 56], and such improved ownership over games eventually enhanced their adherence level [133, 148]. We believe this discrepancy is again related to the unique functional characteristics in stroke patients that they—including *attentive cooperators*—show a strong preference in playing games that they are familiar with or functionally easy to play, which is therapeutically undesirable.

Prehabilitation Before Game-Assisted Upper-limb Rehabilitation for *Inattentive Apathetics.* The third patient group (i.e., *inattentive apathetics*) includes those who did not engage in game-assisted therapy due to either their low motivation for rehabilitation in general (i.e., *Patient Sub-type A*) or their poor cognitive function (i.e., *Patient Sub-type B*). Previous studies suggest that patients with chronic impairments often have little confidence in their potential recovery of the lost motor function and consequently, show poor adherence to the prescribed rehabilitation regimens [34]. Furthermore, patients' low motivation and lack of belief in potential recovery may be related to the symptoms of depression as it has been reported that patients with severe depressive symptoms or a history of diagnosed depression would poorly adhere to therapies and achieve a lower recovery rate [59]. Hence, we believe it is convincing to *prehabilitate* patients' cognitive impairments and depressive symptoms before introducing to game-assisted therapy to further enhance their motivation and engagement level. Specifically, patients' poor cognition can challenge them to engage in therapy properly and pay attention to executing therapeutically meaningful exercise movements [39, 88, 124]. Hence, we believe these patients need to go through cognitive prehabilitation before they are introduced to game-assisted motor rehabilitation.

Educating on Added Value of Game-Assisted Therapy for *Old-Fashioned Enthusiasts.* The last patient group includes *old-fashioned enthusiasts* who prefer conventional therapy over game-assisted therapy. It is important to note that these patients are motivated for and engaged well with non-game-assisted, conventional therapy and thus, game-assisted therapy may not be necessary. Perhaps, games can be introduced to patients only when their motivation and engagement level become deteriorated after extensive exposure to conventional therapy. Furthermore, more individualized approaches could be taken to appeal to these patients based on their preference or preconception of therapy and games. One type of patients in this group (i.e., *Patient Sub-type D*) perceive games as childish and not serious (or therapeutic) enough. The characteristics of these patients have been previously witnessed in a few studies. For instance, Pickrell *et al.* reported that some stroke patients in their observational study believed that games were only suitable for children [135]. Lewis and Rosie, in their review paper, suggested that stroke patients viewed games as supplementary to conventional therapy and believed that game-assisted therapy would provide limited therapeutic benefits [104]. We believe it is possible that these patients may preserve their negative attitudes toward rehabilitation games even when their motivation level for conventional therapy is decreased unlike *Patient Sub-type C*. Perhaps, *Patient Sub-type D*'s negative attitudes toward game-assisted therapy could be understood and approached from the viewpoint of the Trans-Theoretical Model (TTM), which has been applied to conceptualize patients' health-related behaviors and its change [137]. The TTM explains that those who are uninformed or under-informed about the expected benefits of a new behavior may not intend to adopt the new behavior (i.e., a precontemplation stage). Hence, one possible way to help people change their health-related behaviors includes improving their awareness of the consequences of a current and a new behavior [137]. In our case, we may explicitly inform and educate stroke patients about the purpose and potential benefits of rehabilitation games so that they can make a transition to the contemplation and later stages, prior to introducing them to games. Yet another potential approach to introduce game-assisted therapy to this type of patients is to design the games that appear less cartoonish (or childish) and incorporate the aspects of conventional therapeutic apparatus, which we will discuss in more detail in Section 4.6.1.

Identifying Patient Types Prior to Prescribing Game-Assisted Therapy. Identifying the above-mentioned engagement patterns prior to prescribing game-assisted therapy could be used to optimize clinical resources. Unfortunately, there are no studies that have investigated traits and predictors of stroke patients' (or more broadly, patients undergoing rehabilitation) engagement patterns in game-assisted therapy. On the other hand, there has been a large volume of research to understand the potential predictors of patients' attitude and participation level in conventional, non-game-assisted rehabilitation therapy. For example, patients' perceived importance and understanding of the necessity of rehabilitation for functional recovery [47, 90, 109], impairments in cognition and audio/visual sensation [91, 101], and depression and/or emotional status [136, 156] have been identified as factors that could significantly affect patients' motivation, engagement, and adherence to therapeutic regimens. Independently, predictors for the engagement level in games—often associated with excessive engagement and addiction issues—have been actively studied. Factors such as gender, age, and psychological conditions (e.g., attention, mood, and anxiety) and psychopathological conditions (e.g., attention-deficit/hyperactivity disorder and depression) have shown as potential predictors for pursuing excessive engagement in games [61, 77, 183]. We believe that the above-mentioned predictors, along with what we have observed in our study (e.g., chronicity, motor impairment level, and prior exposure to games), could be similarly applied to identify stroke patients' perception and inclination to therapy and entertainment values, and thus their engagement patterns in game-assisted therapy.

If predictors for one's engagement patterns to game-assisted therapy could be identified, we can optimize clinical resources towards the patient group that will mostly likely cooperate with their therapists and benefit from the therapy. For instance, stroke patients may be screened based on their cognitive and motor function (e.g., using the Mini Mental State Examination [52] and Wolf Motor Function Test [184], respectively) and depression level (using the Hospital Anxiety and Depression Scale [190]), which are often periodically administered in rehabilitation hospitals. Then, based on the identified predictors, patients could be interviewed to further understand their potential attitude towards game-assisted rehabilitation therapy. The selected patients may be provided with a trial session to observe patients' reactions, based on which patients could be included in or excluded from the game-assisted therapy program. Therefore, the identification of predictors and in-depth evaluation of screening mechanisms for patients' future engagement patterns remains as important future work.

4.5.2 Therapists' Roles, Practical Challenges, and Needs for Training

Therapists' Roles in Game-Assisted and Conventional Therapies. Although our study is the first to systematically analyze lived experiences of therapists to understand their roles and practical challenges they face during routine game-assisted therapy in actual clinical settings, there have been a number of previous studies that suggested the necessity of therapists' supervision during game-assisted therapy. Prior studies briefly mentioned therapists' roles to prevent any potential exacerbation of pain or injury and to ensure the exercise quality in children with cerebral palsy and patients with multiple sclerosis [8], brain injury survivors (e.g., traumatic injuries) [32], and stroke survivors [135]. Deutsch *et al.* reported that the evaluation of patients' exercise movement quality provided by COTS games (i.e., Nintendo Wii) was not adequate and recommended therapists to provide feedback [41]. Furthermore, Brütsch *et al.* showed that therapeutic outcomes were significantly better when therapists closely supervised robot- and game-assisted gait therapy sessions [28]. Our findings corroborate these acknowledged needs of therapists. In our study, we took a step forward to analyze therapists' comprehensive, orchestrating roles as well as their strategies to moderate game-assisted therapy sessions. We found that therapists' roles in game-assisted therapy do not appear to be much different from their roles in conventional therapy. In conventional rehabilitation settings, therapists need to identify attainable goals of improvement for patients, administer therapies to help patients achieve the goals, assess patients' progress, and iterate the aforementioned processes until discharge [96]. In this process, therapists' are responsible for designing therapeutic activities and adjusting their difficulty levels that best accommodate individual patients' impairment characteristics [63,119,146], and for maintaining patients' engagement and ensuring the quality of patients' exercise movements [177, 182]. It is noteworthy that therapists believed that the use of rehabilitation games contributed to reducing the workload of therapists by automating the process of presenting exercise movements, and observing and evaluating movements' performance to some extent (T5). Also, therapists stated that, by employing rehabilitation games, it was easier to induce voluntary movements from patients (T8), build rapport by talking about game play (T9), and physically less-burdensome because they could use assistive tools to help patients exercise against gravity (T4, T11). However, an in-depth comparative analysis of therapists' roles when games are used vs. not used in therapy, and the understanding of how games assist different roles of therapists remain as future work.

Practical Challenges that Therapists Face. Despite the acknowledged needs of therapists in game-assisted therapy for stroke survivors, there is only a limited understanding of practical challenges that therapists experience. Our findings demonstrate the importance of and therapists' challenges to properly aligning patient to the game system for accurate monitoring of movements. The importance of patient-to-game alignment has been similarly acknowledged in a study by Geurts *et al.* [58], which studied the application of camera-based or wearable sensor-based COTS games in patients with spasticity. Our study also reported therapists' challenges in adjusting the difficulty level of games to design personalized rehabilitation programs that can specifically focus on different impairment characteristics (e.g., smoothness, compensation, precision, and range of motion), mainly because the games provided a limited means to configure the difficulty level. Augstein *et al.* also briefly reported that therapists were not satisfied with the preprogrammed difficulty levels of games and desired to have more flexible control over the game parameters [9]. These suggest a need for highly configurable game systems that can provide flexibility for therapists' to enable personalized therapy programs. On the other hand, the increased complexity of game operation would demand extensive training for therapists to become competent in moderating game-assisted therapy sessions.

Needs for Training on Game-Assisted Therapy. Our study provides empirical evidence that therapists heavily rely on their own lived experience in moderating game-assisted therapy and demand for proper education or training. In conventional therapy, it has been well recognized that therapists' competency in multi-faceted skills—which include but not limited to therapeutic knowledge, and physical and social intervention skills—is an important factor to enable quality therapy [68]. It has also been emphasized that such competency affects the establishment of strong rapport with patients and can be achieved via continued offline and online education and training [46, 114, 179]. For another example in robot-assisted therapy that involves much more complex assistive tools, manufacturers (e.g., Hocoma, one of the most active manufacturer in the rehabilitation robot industry) often provide a series of extensive in-person training sessions [72], as well as online training materials [73], to help therapists deliver personalized therapy using their robotic solutions. In sum, our findings support that it may be necessary to design game systems that can provide flexible configurations to enable personalized therapy and to provide carefully designed training sessions for therapists to learn how to operate game platforms effectively.

4.6 Design Implications

Our study revealed that patients exhibit different engagement patterns depending on the level of motor and cognitive impairment, as well as their interests in game and rehabilitation therapy. Each patient has unique motivating and demotivating factors, such as a propensity for entertainment values and preconception towards video games. Therapists strive to accommodate these patients in the forefront by playing multiple roles. Building on these findings, we offer a series of design implications, focusing on 1) a modularized game system where appearance, physical/cognitive challenge, and the focus of therapeutic exercise are flexibly configurable, so that patients can play a personalized rehabilitation game offering higher engagement level while maintaining therapeutic benefits at the same time, 2) automatic sensing capability to monitor the quality of exercise movements and incorporate the measured information to game play, so that patients can maintain the therapeutic values throughout therapy sessions, and 3) an effective real-time game customization interface for therapists to minimize their burden in system and contents set-up, so that therapists can fully engage with their patients.

4.6.1 A Modularized Game Architecture Supporting Flexible Configuration

Unlike the traditional video game design that pursues the maximum level of engagement of players to the content, rehabilitation games aim to provide the users with a balanced experience between engagement and therapeutic relevance (e.g., quality of movement). Also, the design of rehabilitation games should consider different levels of players' cognitive abilities and preferences for game styles. To address these challenges, we suggest a modularized and easily re-configurable game architecture, consisting of the following four components: 1) physical movements for rehabilitation, 2) game mechanics and difficulty level, 3) social game play, and 4) visual appearance.

In this architecture, the mapping between physical movements and their manifestation in the games can be easily altered or remapped depending on the context of rehabilitation. The game system used in this study (i.e., Rapael Smart Board) only allowed pre-determined exercise movements to play a specific game. For example, in the shoot 'em up style game or pet-feeding game (Fig. 4.2b), patients must perform reaching movements to control the jet fighter or the pet foods to play the game, respectively. In the dough-mixing game (Fig. 4.2c), patients had to perform joint coordination movements (i.e., making circular movements) to play the game. A game system allowing therapists to mix and match between the required physical movements and game contents (e.g., making circular movements to control the jet fighters) will provide patients with more personalized gaming experience while achieving the rehabilitation goals, especially for ones with strong preferences for a certain set of games (e.g., *overcharged gamers*). In designing this flexible architecture, developers may take an advantage of previous studies that have investigated the mapping and balancing techniques between heterogeneous input modalities (i.e., exercise movements) [57, 129, 130, 188]. Furthermore, for *overcharged gamers*, games can be configured to deliberately reduce the patients' enjoyment of playing games (i.e., entertainment values) to enhance their attention to the quality of their exercise movements (i.e., therapeutic values). This relates to the concept of Dynamic Difficulty Adjustments (DDAs) in video game design [76, 105], where the technique has been mainly used to keep the game player in the maximum band of enjoyment (i.e., the flow channel) [76]. On the other hand, we suggest leveraging techniques to push the patient out of the flow channel to maintain the entertainment values of rehabilitation games to the level that patients can pay attention to their movement quality and hence achieve therapeutic benefits.

Social play (e.g., multi-player mode) can be selectively employed for patients who have particularly low motivation to participate in therapy (e.g., *Patient Sub-type A* of *inattentive apathetics*). For example, patients' peer patients, significant others, or family members such as grandchildren can play the game together to motivate the patients to participate in game-assisted therapy, inspired by previous studies in designing competitive multi-player games [56] and inter-generational game play [1, 85, 86]. However, our findings suggest that caution needs to be executed when involving multiple participants in rehabilitation games. For instance, other players' participation in game play may distract patients from their roles (e.g., similarly to *overcharged gamers*) and deteriorate the quality of game-assisted therapy. Preferably, we suggest rehabilitation games be designed to support cooperative play (rather than competitive play), such as previous examples of inter-generational games where players can play in different roles [85, 86].

We envision that reconfigurable visual appearance can help enhance participation of some patients who were not initially interested in game-assisted therapy. Our findings demonstrate that patients can react differently to the same cartoon-like graphics (e.g., *inattentive apathetics*, *Patient Sub-type B* vs. *old-fashioned enthusiasts*, *Patient Sub-type D* in Fig. 4.3). *Patient Sub-type B* of *inattentive apathetics*, who often have a severe cognitive impairment, have difficulty processing realistic graphics and consequently become disengaged. On the other hand, *Patient Sub-type D* in *old-fashioned enthusiasts* perceive rehabilitation games childish and not therapeutic enough. The reconfigurable visual settings can accommodate these patients of different propensity and cognitive level. Graphical representation can be adjusted to look uncomplicated (e.g., just a simple 2D rectangular object rather than a jet fighter) to help *Patient*

Sub-type B of *inattentive apathetics* better comprehend and engage in therapy. On the contrary, the appearance can be adjusted to look like real-world therapeutic apparatus, which can provide *old-fashioned enthusiasts* an impression that rehabilitation games are not for entertainment but for serious therapeutic purposes. Furthermore, we suggest providing a more fine-grained way to adjust game difficulty level (rather than only three difficulty levels in Rapael Smart Board) to accommodate cognitively impaired patients.

4.6.2 Serious Games that can Monitor Quality of Exercise Movements

Our findings showed one of the most important roles of therapists—or perhaps the most important role according to T2—is to supervise and ensure the quality of exercise movements that patients perform during therapy sessions. If game systems can automatically assess the quality of exercise movements and provide feedback during game play, it can continuously remind patients about the importance of appropriate movement execution and reduce some of therapists' overwhelming roles to orchestrate the entire therapy sessions. Assessment of movement quality can be generally achieved using camera sensors [11, 43, 174] or wearable inertial sensors [81, 83, 132, 143, 176]. Wearable sensor-based approach leverages multiple inertial sensors (varying from 1 to 5 sensors) to measure the movements and orientations of different body parts that are often used in compensatory behaviors (e.g., trunk). Although the wearable sensor-based approach have shown to accurately monitor the presence of compensatory behaviors, it increases the obtrusiveness of the technology as patients need to carefully position multiple sensors on their body, which can further increase the preparation burden for therapists. On the other hand, the camera-based approach, which often utilizes RGB and depth sensors like Microsoft Kinect [115], can monitor patients' movements in a minimally obtrusive manner. However, camera-based solutions require patients to be carefully oriented towards the sensor to secure the direct line-of-sight [142]. It is noteworthy that the game system itself requires therapists to carefully align patients to the game system for the accurate translation of patients' physical movements to the movements in game play (see *Challenges to Prepare the Game System* in Section 4.4.3 for details). Hence, incorporating a camera sensor to provide therapists a means to accurate align patients to the game system during the calibration process and to continuously monitor patients' movements quality during therapy seems to be an appealing solution.

The measured information regarding the quality of exercise movements can be delivered to patients and therapists in different ways. For example, visual or auditory feedback can be used to remind patients regarding the quality of the performed movements [174]. The game system can also provide mechanical feedback (e.g., interrupting the movement of the handle when patients show undesirable behavior) [166] or software feedback (e.g., increasing game points only when movements are performed with appropriate quality or punishing when undesirable behaviors are observed) [4]. It is noteworthy that providing feedback regarding the movement quality or integrating the quality information as part of the game play will increase the therapeutic values of game-assisted therapy but, at the same time, will act as a factor that somewhat disengages patients from their entertainment values (as T2 explicitly stated in Section 4.4.2). It remains as an important research problem to find the optimal balance between the therapeutic and engagement values (e.g., application of DDAs as we discussed in Section 4.6.1) in order to maximize the engagement level while maintaining the therapeutic effectiveness.

4.6.3 A Dedicated User Interface for Therapists Enabling Efficient Control

To enable therapists to orchestrate the aforementioned game components and thereby keeping the balance between the therapeutic and engagement values during run-time, we suggest a real-time user interface that allows therapists to configure game settings (e.g., entertainment factors) in a subtle and unnoticeable manner to induce patients to perform therapeutically appropriate movements. It may include a hand-held or foot-pedal remote to minimize the patients' sense of being controlled by the therapists. Our study findings demonstrate that strongly opinionated patients become disengaged from game-assisted therapy when the patients' preference and therapists' suggestion conflict with one another. It puts therapists into a dilemma. That is, if they explicitly enforce therapeutically desirable execution of exercise movements to strongly opinionated patients, it is likely to decrease their motivation to participate in game-assisted therapy (see *Overcharged Gamers* in Section 4.4.1). This finding is consistent with a previous study reported that explicit and transparent balancing diminishes self-esteem and perceived relatedness, whereas hidden and implicit balancing improves self-esteem without significantly affecting the outcomes of games [57]. Our suggested user interface can be used in the following way. When a patient tends to develop compensatory behaviors during game play, the therapist could configure the game to decrease the range of motion in the game or the speed of the game pace using a small remote controller—which is hardly noticeable from the patient's sight—so that the patient can perform movements without severe compensatory behavior. We also emphasize that the overall usability of the game system for therapists should not be overlooked. As our study illustrates, therapists control games entirely on behalf of patients (see *Designing the Therapy* in Section 4.4.2) using a mouse on the edge of a table, on the game controller itself, or on their lap (see *Challenges to Prepare the Game System* in Section 4.4.3). On the other hand, in order to physically interact with patients (see *Correcting Inappropriate Movements* in Section 4.4.2), therapists often sit next to or behind their patients. In other words, therapists need to continuously re-position themselves to control the game platform and interact with patients during therapy sessions. Hence, a dedicated, portable user interface is needed for therapists to efficiently interact with games and moderate game-assisted therapy.

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH PLANS

To make a significant impact on the quality of real-world rehabilitation practices, this dissertation reported our research findings in the perspective of holistic, end-to-end research into game-assisted rehabilitation for stroke survivors. We introduced the development and evaluation of a data-driven approach that can accurately estimate patients' cognitive function in clinically-validated standardized assessment scores (i.e., MMSE) based on patients' self-administered game play (Chapter 3). Grounded in the neuropsychological findings that fundamental cognitive processes can explain various aspects of human cognition, we 1) developed *Neuro-World* that stimulate patients' short-term memory and selective attention in six different game tasks and 2) devised a supervised machine learning approach that translated quantified patients' performance in *Neuro-World* into the target MMSE scores. Our quantitative evaluation with 12 chronic-stage stroke survivors demonstrated that the accurate estimation of patients' cognitive function accurately is indeed possible, which indirectly confirms the neuropsychological findings that drove the development of *Neuro-World*. While the deployment of the proposed approach to patients in the uncontrolled, real-world setting and the investigation of its impact to patients' engagement and therapeutic benefits is currently underway, we leveraged *RAPAEL Smart Board* to demonstrate our efforts to understand the real-world interaction dynamics of therapists and patients during their routine upper-limb motor rehabilitation therapy sessions (Chapter 4). From the analysis of 11 video-recorded game-assisted therapy sessions and 15 audio-recorded interviews with therapists, we revealed unexpected stroke patients' engagement patterns in game-assisted therapy sessions, substantial therapists' roles in maintaining patients' engagement level and therapeutic quality during therapeutic exercises, practical challenges, and needs that therapists experienced while assuming their roles. These findings enhanced the research community's understanding of the therapeutic impact of rehabilitation games on the interaction dynamics between therapists and patients in game-assisted therapy. Furthermore, we discussed the potential ways to integrate game-assisted therapies in the overall rehabilitation service and the potential design implications of games that can better support the needs of both therapists and patients. These research results demonstrated our vision of a holistic, end-to-end research approach, in which the development of rehabilitation technologies are firmly grounded in scientific evidence and validated for their potential efficacy. Furthermore, through the investigation into the real-world scenario in the long-term routine deployment of developed technologies, we revealed the gap between the anticipated and the real impacts and discussed how it could be bridged through further development and research.

5.1 Future Work for Game-Based Cognitive Function Assessment

There are several directions that our approach to game-based cognitive function assessment can be improved. First, although we used LOSO-CV technique to produce a fair evaluation rather than an optimistic one [53], the current study involved the relatively small number of subjects. Also, most of the participating patients were female, and their cognitive impairments were developed by an ischemic stroke. Consequently, more rigorous validation of the proposed system and analytic framework to a larger, gender- and comorbidity-controlled population and other diagnoses remains as future work to achieve greater generalizability.

Second, although we demonstrated that we could estimate patients' cognitive function relatively accurately even with a smaller subset of the *Neuro-World* games, we only investigated the efficacy using a systematically identified permutation of games. However, since the three games focus more on short-term memory and the rest focus more on selective attention, there may exist a combination of games that can outperform other combinations in accurately estimating patients' cognitive function. This problem can be formulated in the perspective of sensor selection problem and leverage various machine learning algorithms [64, 80], which can be interesting future research.

Third, this study only involved individuals with mild cognitive impairments in order to ensure that the patients can self-administer *Neuro-World*. We expect that patients with moderate-to-severe cognitive impairment will have difficulty administering the games themselves, which remains as a limitation of the proposed system, because the proposed approach assumes that patients can play the games by themselves. For future studies, we may consider a new set of features that capture more primitive user interactions even before proper game playing, such as whether patients can select the appropriate icon to start *Neuro-World* at all or the time to select it, in order to apply the system to individuals with severe cognitive impairment.

Fourth, the current implementation of *Neuro-World* has not been thoroughly evaluated for accessibility (easiness-to-use) in patients with cognitive impairments. To partially address this limitation, our preliminary study was conducted using a tablet computer with a relatively large screen size (12.2 inches). This implies that when *Neuro-World* is deployed on a smaller screen (e.g., a smartphone), the visual information may provide additional challenges to individuals with cognitive impairments. This may, in turn, affect patients' game performance of *Neuro-World* and subsequently, the estimation accuracy of our data analytic model. The investigation of the proposed system's generalizability and patient-accessibility remains as future work.

Lastly, the developed system and the discussed future extension assume the evaluation in the controlled setting. Essentially, we hope to deploy *Neuro-World* to stroke survivors in their free-living environment and investigate to understand if the proposed approach can accurately estimate patients' cognitive function in the uncontrolled setting. Furthermore, the impact of using *Neuro-World* on patients' long-term engagement and adherence to cognitive rehabilitation in patients' residential settings.

5.2 Future Work in Investigating the Use of Rehabilitation Games in Real-World Settings

The findings from the investigation into the use of rehabilitation games during routine game-assisted therapies provided us with insights into future development directions. First, this study involved a relatively a small number of study participants at a single site in South Korea, and thus there may exist county- or hospital-specific cultural effects on therapists' strategies in game-assisted therapy. Furthermore, the rehabilitation games used in our study involved gross upper-limb movements, and thus the reported results herein should be taken with care when reflecting on different rehabilitation programs such as fine-hand, gait, or cognitive rehabilitation. Also, the current study mainly focused on the lived experiences of therapists. The thoughts and experiences by patients, especially those who exhibit negative attitudes to rehabilitation games and game-assisted therapies, were not analyzed in the patients' perspective. Consequently, similar studies that consider the above-mentioned limitations can be conducted to achieve a more generalized understanding of the games' impact on the interaction dynamics between patients and therapists in overall game-assisted rehabilitation settings.

Second, the design implications that we discussed in this dissertation can be reflected in the development of more therapeutically effective and engaging rehabilitation games. For instance, a modularized game architecture that supports the flexible specification of 1) physical movements for game inputs, 2) difficulty levels for balancing patients' engagement between the entertaining and therapeutic aspects of games, and 3) visual appearance to balance patients' cognitive burden to process visual information and their perception of games. Furthermore, in order to enable therapists to control such modularized games efficiently, dedicated user interfaces can be developed. The developed interfaces can be evaluated for their usability and efficacy while therapists orchestrate different modulated components in game-assisted therapy. Furthermore, sensor- or camera-based approaches to monitor the quality of patients' exercise movements can be developed and evaluated for its effectiveness in inducing more therapeutically desirable movements from patients.

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