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Human Computer Interaction in Stroke Rehabilitation

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Human Computer Interaction in Stroke Rehabilitation

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Information and Computer Science

by

Maryam Khademi

Dissertation Committee:
Professor Cristina Videira Lopes, Chair
Associate Professor Deva Ramanan
Associate Professor Yunan Chen

2015

DEDICATION

To my husband, Hossein.
Without his continuous support, patience, and love, the completion of this work could not have been possible.
And, to my parents. All I have and will accomplish are only achievable due to their love and encouragement.

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I would like to acknowledge my gratitude to my family, for their unconditional love and support over these past years ever since the beginning of my journey. I am especially grateful to my parents, for their encouragement, unwavering confidence, and support. My sisters, Maedeh and Mahsa, and brother-in-law, Mehrshad for never leaving my side and always being there for me.

I dedicate this work to my husband and best friend, Hossein. He always stands by me and pushes me to go beyond what I think.

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ABSTRACT OF THE DISSERTATION

Human Computer Interaction in Stroke Rehabilitation

By

Maryam Khademi

Doctor of Philosophy in Information and Computer Science

University of California, Irvine, 2015

Professor Cristina Videira Lopes, Chair

Movement impairment after stroke typically requires intensive treatments for several weeks after the initial injury. An important goal for rehabilitation engineering is to develop technology that allows individuals with stroke to practice intensive movement training without the expense of an always-present therapist. This thesis focuses on stroke rehabilitation as an HCI problem, offering an HCI-centric investigation of the design space for effective rehabilitation therapies.

We investigate an HCI-centric approach to stroke rehabilitation. First, we designed and developed a spatial augmented reality system for assessment and training of upper extremity in patients with stroke. This system leveraged a novel patient-computer interaction mode which showed patients superior performance compared to the conventional computerized stroke rehabilitation. Next we developed and evaluated a 3D free hand interaction environment for training high-level hand functions in patients. After that, we developed a tele-rehabilitation neuro-game platform designed for in-home patient's use that included several neuro-games to enhance targeted brain functions in patients. Finally, a study was designed to investigate neurobiological correlates of patients cognitive functions while using our tele-rehabilitation platform.

Based on the studies findings, we argue that the benefit of using an HCI-centric approach to stroke rehabilitation is twofold: (i) it introduces advanced computer technology that can be customized to specific patients needs; and (ii) it provides new methods to help patients with their Activities of Daily Living (ADL), both in terms of their behavioral change as well as functional capabilities. Furthermore, our game design process and principles are tailored to the challenges and opportunities of neuro-rehabilitation. This research is an in-depth analysis of how technology, and games in particular, need to be carefully considered to support effective therapies for physical rehabilitation.

Chapter 1

Introduction

1.1 Overview

Stroke remains a major cause of adult disability [26, 25], and stroke rehabilitation a challenging process. More than 795,000 people in the United States suffer from a stroke each year [97, 95]; this costs the country an estimated $38.6 billion that includes the cost of healthcare services and missed days of work. These statistics provide some insight into the importance of helping patients with stroke gain recovery.

Movement impairments after stroke typically require intensive treatments, hands-on physical, and occupational therapy for several weeks after the initial injury. Unfortunately, due to economic pressures on healthcare providers, stroke patients are receiving less therapy and going home earlier [95]. Therefore, an important goal for Rehabilitation Engineering is to develop technology that allows individuals with stroke to practice intensive movement training without the expense of an always-present therapist [92], particularly when access is a concern such as with rural location.

Computer-based methods are increasingly being seen as a mechanism to deliver stroke rehabilitation [22]. In particular, the scope of HCI applications in medicine has expanded over recent years such that today it includes physical therapy and rehabilitation.

Today, state-of-the-art technology for rehabilitation of patients with stroke includes an input device to capture patients' movement as well as a display to provide them with visual feedback. For the past decades, researchers have been working on customizing this input device to help patients with different upper extremity deficits [59, 76]. However, the current theme of research has the following shortcomings: (i) it is usually an immobile setting, i.e., it requires patients to visit clinic. Normally the setup is very expensive and therefore not feasible to be used as a tele-rehab setting at patients' home; (ii) the setting requires patients to perform unnatural hand/eye coordination due to a required extra visuospatial transformation that should be performed between the input device and the display. Thus patients are requested to master in specific skills which may or may not be practical in real-life situation; (iii) the type of games that are used for rehabilitation are neither functional nor transferable to Activities of Daily Living (ADL).

1.2 Summary of Work and Contributions

In this dissertation, we focused on human computer interaction in stroke rehabilitation. Together with a team in the Medical School, we designed several computerized setups that try to address the main concerns regarding the above-mentioned problems with state-of-the-art computerized rehab therapies. Figure 1.1 shows how the studies are connected with respect to these problems. The main activities of this dissertation can be summarized as follows:

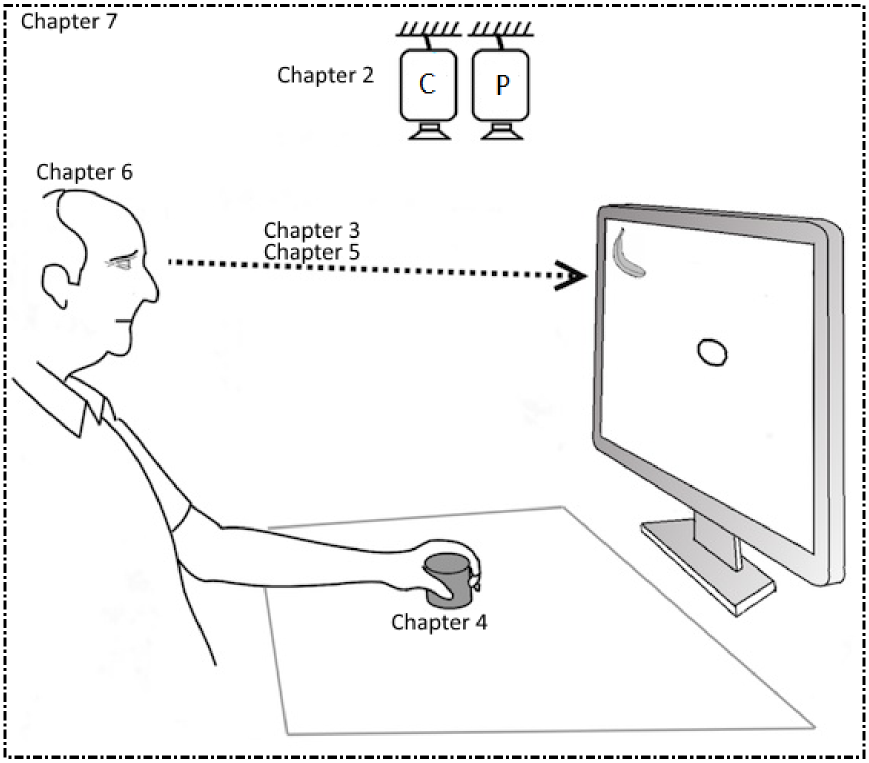


Figure 1.1: Overview of studies: how chapters are connected with respect to current rehabilitation problems

1. Designing and developing a spatial augmented reality system for assessment and training of upper extremity in patients with stroke. The result of two normal subjects proved functionality of the system.

2. Developing Augmented Reality (AR) and Virtual Reality (VR) setups to compare performance of healthy individuals in the "Pick-and-Place" task, which is part of many activities of daily living (ADL's) and one of the major affected functions stroke patients mainly expect to recover. Superior performance of our 14 healthy subjects in AR setup motivated us to follow up with running our study on patients with stroke.

3. Developing and evaluating 3D free hand interaction for training high-level hand functions in patients. The performance of 14 patients with stroke correlated strongly with their clinical assessment, showing validity of using 3D free hand interaction as a good measure of patients' performance in their rehabilitation program.

4. Proposing a new patient-computer interaction mode and comparing it with the conventional computerized stroke rehabilitation. The result of 18 patients with stroke confirmed superiority of our proposed interaction mode to conventional methods.

5. Developing a tele-rehabilitation game platform designed for in-home patient's use. The setup was evaluated by both healthy and patient subjects.

6. Designing a study to investigate neurobiological correlates of HCI based on tele-rehabilitation neuro-game training. This included designing and developing neuro-games to enhance targeted brain functions. Our results confirmed improvement of patients in terms of behavioral changes during one-week training program.

Throughout this dissertation, we made two important contributions. First, we addressed whether HCI can support the design of more effective rehabilitation therapies. Based on our findings, the benefit of using an HCI-centric approach to stroke rehabilitation is twofold: (i) it can introduce advanced computer technology that can be customized to specific patients needs; and (ii) it can provide new methods to help patients with their Activities of Daily Living (ADL), both in terms of their behavioral change as well as functional capabilities.

Second, we repurposed familiar games for entertainment to be intended for serious purposes such as improving cognitive control of patients with stroke. We believe the insights gained during our design process can inform many others designing games for specific user groups, especially those with decreased function due to neurological disease.

1.3 Dissertation Organization

The rest of the dissertation is organized as follows. Chapter 2 features a Spatial Augmented Reality system for rehabilitation of hand and arm movement. The table-top home-based system tracks a subject's hand and creates a virtual audio-visual interface for performing rehabilitation-related tasks that involve wrist, elbow, and shoulder movements. It measures range, speed, and smoothness of movements locally and can send the real-time photos and data to the clinic for further assessment. To evaluate the system, it was tested on two normal subjects and proved functional.

In Chapter 3, we study the task of pick-and-place, which is part of many activities of daily living (ADLs) and one of the major affected functions stroke patients mainly expect to recover. We developed an exercise consisting of moving an object between various points, following a flash light that indicates the next target. The results show superior performance of healthy subjects in spatial AR versus non-immersive VR setting. This could be due to the extraneous hand-eye coordination, which exists in VR whereas it is eliminated in spatial AR.

In Chapter 4, we leverage the technology of free-hand interaction to rehabilitate patients with stroke. We modified the game of Fruit Ninja to use Leap Motion controller's hand tracking data for stroke patients with arm and hand weakness to practice their finger individuation. In a pilot study, we recruited 14 patients with chronic stroke to play the game using natural interaction. Their Fruit Ninja (FN) scores show high correlation with the standard clinical assessment scores such as Fugl-Meyer (FMA) and Box-and-Blocks Test (BBT) scores. This finding suggests that our free-hand Fruit Ninja's score is a good indicator of the patient's hand function and therefore will be informative if used in their rehabilitation.

Chapter 5 examines two forms of interaction namely Indirect Interaction (IDI) and Direct Interaction (DI), incorporating the popular Fruit Ninja game into each. An IDI approach to gaming substitutes a virtual environment in place of the real world [13], directing the subject's attention towards the virtual world (here, the computer monitor) rather than to the real world (here, the paretic hand as it moves towards across the table) [61]. A DI approach to gaming overlays computer-generated virtual objects into the real world. Such real-world activities may be more intuitive than many IDI-based approaches, which might promote massed practice. A DI approach may also allow patients to practice real-life functional tasks safely, for example, a patient might work on being independent in the kitchen by working with computer-generated objects and thus with zero risk of spilling, burning, or electric shock. On the other hand, an IDI-based approach might nonetheless have advantages, for example, to promote recovery of visuospatial skills, or by using modulation of cognitive demands to promote motor recovery. The optimal choice of human-computer interface varies across individuals, over time, and according to specific goals. The current study provides insights into how different human-computer interfaces affect motor performance and thus might influence motor recovery and motor skill acquisition after stroke.

In Chapter 6, we talk about computer games, as they have the potential to make physical and neural rehabilitation more engaging than traditional rehabilitation procedures, therefore leading to potentially more efficient therapies. Over the past several years, we have been designing and assessing such games with stroke patients. We developed our games using a projector-based platform and conducted pilot studies to evaluate these therapies. This study focuses on the many issues of game design for this particular population: stroke patients. Designing games for this group is considerably different than designing games for general entertainment. Specifically, the design of these games has concrete objectives such as improvement of motor and cognitive control that are not important for healthy gamers. As such, game design needs to be informed by a deep knowledge of specific areas of the brain that play a crucial role in cognitive control, and the physical movements in the game need to stimulate those areas. We contribute a new perspective to game design by considering the brain's neuro-anatomical function, given specific objectives.

Chapter 7 lists lessons that we learned throughout this research. It gives an in-depth analysis of how technology, and games in particular, need to be carefully considered to support effective therapies for physical rehabilitation. Finally in Chapter 8, we conclude the dissertation by summarizing the results of this research and proposing future work.

Chapter 2

A Spatial Augmented Reality Rehab System

This chapter describes collaborative work previously published at [51]. My role in that project was design and development of the AR system, data collection and analysis, and writing the paper.

2.1 Introduction

This work features a Spatial Augmented Reality system for rehabilitation of hand and arm movement. The table-top home-based system tracks a subject's hand and creates a virtual audio-visual interface for performing rehabilitation-related tasks that involve wrist, elbow, and shoulder movements. It measures range, speed, and smoothness of movements locally and can send the real-time photos and data to the clinic for further assessment. To evaluate the system, it was tested on two normal subjects and proved functional.

We have developed a low-cost, Spatial Augmented Reality system that allows individuals with stroke to practice hand and arm movement exercises at home or at clinic with minimal interventions of a therapist. Different from Virtual Reality (VR) in which the real world is fully replaced with a virtual environment, Augmented Reality (AR) does not replace the real world but augments a user's view of the real world with virtual objects. Applying AR technology in RE is a new paradigm for the research in Assistive Technology (AT) [110]. AR-based RE devices provide the patient with better control over augmented environment in such a way that he feels more realism and interact in a more intuitive way.

We designed intuitive and natural interactions that can help a patient practice the foundation of manual activities that are central to activities of daily living, such as reaching, wrist-tilting, pointing, and grasping. Involving the patient in such simulations of daily activities is expected to have the additional advantage of fostering a more positive psychological approach to the rehabilitation experience. Moreover, the proposed system can be adapted to a portable low-cost home-based device that includes communications for remote interaction with a therapist and medical team. Thus the patient can work independently, without a constant need for therapist interaction.

2.2 Background

Rehabilitation engineering applications are specially designed to recover certain impaired functions of individuals with disabilities. Since our focus in this chapter is motor function, in the following, we discuss the state-of-the-art research that has been carried out in AR-RE domain.

Luo et al. [92, 110] measured the force and assist finger extension using mechanical devices. They presented a training environment for rehabilitation of hand opening in stroke survivors. This environment integrated Augmented Reality with assistive devices for the process of repetitive training of grasp-and-release tasks. One potential criticism of the system is that therapist intervention was necessary, as the patient needs to wear equipment that would be hard to don without assistance. Correa et al. [85, 84] developed GenVirtual, an AR game musical, that provided a natural, fingertip/toe tip-based interaction. The intention of this chapter was to help patients with motor coordination. On the other hand, GenVirtual had little effect for individual with low mobility. Alamri et al. [24] proposed a framework that takes advantages of the AR-based rehabilitation processes with a 2-D web camera and fiducial markers. The system supported the training of daily activity, though, due to use of fiducial markers, the setup can be complex in the absence of a therapist.

Compared to the above platforms, our system requires the patient to wear minimal equipment: two small color markers on their fingers. The second difference is that our platform is a Spatial Augmented Reality system, using an inexpensive projector to augment virtual objects. This projector lets user have a large range of motion on therapy table to do variety of movements. Third contribution of the system is that our designed exercise program includes fundamental hand movements which cover a wider range of stroke patients with different impairments.

2.3 Method

AR rehabilitation is an interesting and useful adjunct to traditional therapy by leveraging benefits of both real and virtual world training such as providing immersive experience for users, objective quantification of the training process, and motivating way of using massed practice. By developing an AR rehab system, the coordination system of user's real world unifies with the virtual world. This let patients feel as if the assistive virtual objects, that are displayed to help them carry out their exercises, are actually present and belonged to real world rather than being apart in a separate screen.

2.3.1 Experiment Setup

our setup includes a conventional computer, a low cost webcam, and a projector. The subject sits in front of a table that serves as a platform for virtual objects to be projected on it. The subject's hand movements are followed by a camera, while he is looking on the table and interacting with the virtual objects superimposed on it (Figure 2.1). Our system has the potential to be used locally, in a clinical environment, as well as remotely, in the patient's home where it would remain accessible by a therapist through a tele-rehabilitation system. The system's setup is easy to learn for the patients, making the system comfortable to use even without therapist's presence.

We developed several vision algorithms to locate and track the hand of the subject using color marker and motion information. The system can quantify the motion captured by camera using computer vision methods.

Along with the implementation of the system, we designed several tasks based on daily life activities. These involve primitive postures of the hand including reaching, tilting, pointing, and grasping, which require control on various hand parameters such as: range, speed, smoothness of movement, and size of grip (Table 2.1). This way, we measure some important performance factors that can be used to assess a patient's progress across weeks of therapy. We also calculate the completion time of each task for the subjects.

Giving dynamic feedbacks on performance of the user throughout the tasks such as playing

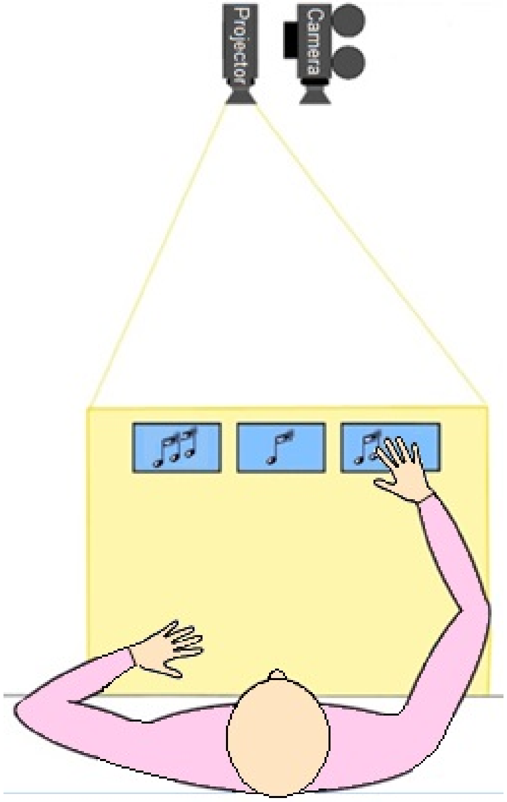


Figure 2.1: Experimental setup of spatial AR rehab system

sounds and augmenting virtual objects in response to the user, the system increases the quality of subject's interaction with it.

2.3.2 Rehab Exercises

In the following, we will discuss the AR rehab exercises that we designed as part of our system. Note that our suggested primary tasks have the potential to be used in variety of interactive and engaging games that can keep patients engaged and motivated despite the fact that they are performing continuous repetitive movements.

Task 1, Reaching: in this task (Figure 2.2a), three melody boxes are projected on the subject's desk, in different orders. The subject is expected to reach out for the projected

Table 2.1: Upper-limb motion, their corresponding designed tasks and performance parameters

Part	*Posture*	*task*	*Parameter*
Hand	Grasping	Task 4	Velocity Smoothness Time of completion
Wrist	Pronation/Supination	Task 2	Angular Velocity Smoothness Rotation Time of completion
Wrist	Flexion/Extension	Task 3	Angular velocity Smoothness Rotation Time of completion
Wrist	Adduction/Abduction	Task 3	Angular velocity Smoothness Rotation Time of completion
Arm	Reaching	Task 1	Velocity Hand position Smoothness Time of completion

box. As soon as the hand enters the area of active box, a drum note is played. This is the basis of an engaging game to help subject reach out for different targets in a certain period of time, using active-box hints that correspond to different notes of a melody. At the end of the game, the subject can see his score on the screen which has been calculated based on how fast and correct he could reach out the active box and eventually make a pleasant music. In this game, we are using occlusion-based interaction (subject's hand entering the area) as well as dynamic feedback (sound).

Task 2, Pronation/supination (tilting) of wrist: in this task (Figure 2.2b), the subject is asked to hold a cup and tilt it as if he is pouring its content on the table. As the task starts, the subject should empty the cup's content in 5 or more tilt-and-hold-still postures. To give him more natural feel of pouring water on the table, as the subject tilts the glass, virtual

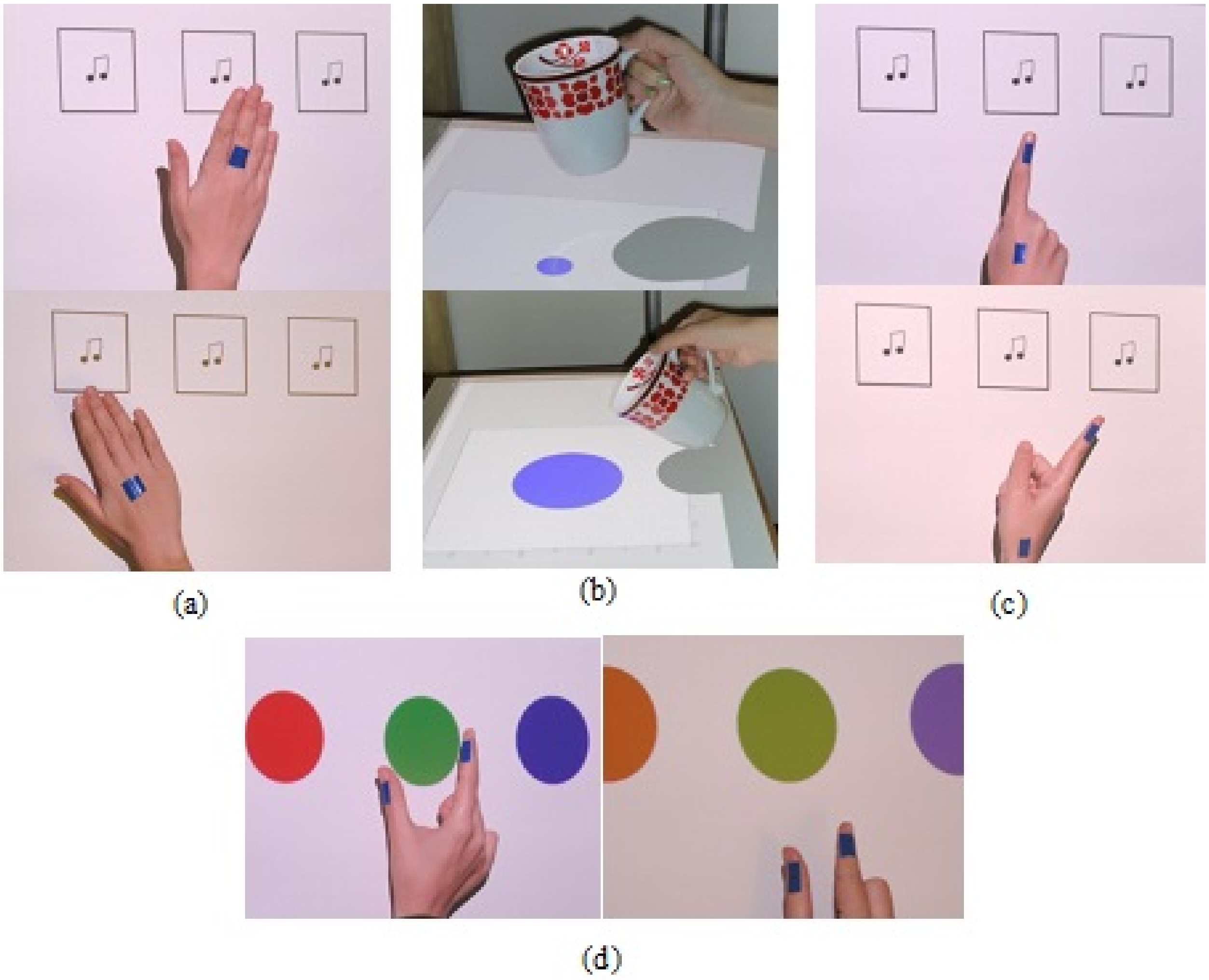


Figure 2.2: (a) Task 1: Reaching melody boxes to play drum sounds; (b) Task 2: Holding and tilting a mug to gradually pour virtual water; (c) Task 3: Pointing to melody boxes to play drum sounds; and (d) Task 4: Grasping random size-position circles

water (blue circle) is displayed beneath the cup, which simulates the amount of water that has been already poured out. The more the subject repeats tilting the cup the larger the blue circle becomes. We monitor the changes in area of blue circle to get a sense of how well the subject is able to do the task smoothly and in control. By employing the daily life tasks as mentioned above, we believe patients get more confidence in their real life activities as they already practiced doing them in therapies' sessions. In this task, we leverage dynamic feedback (growing blue circle) to let subject know whether he is controlling the task at a normal, healthy pace.

Task 3, Pointing: for this task (Figure 2.2c), we ask the subject to wear two small color markers: one on his wrist and the other on his index finger. Then we ask him to point to different melody boxes that are projected on the table and make various sounds out of them. The pointing action is repeated in two postures: one involves adduction/abduction (Figure 2.2c top) and the other one involves flexion/extension of wrist (Figure 2.2c bottom). Here, again, playing sound as dynamic feedback help the subject know that he has successfully targeted each box throughout the task.

Task 4, Grasping: in this task (Figure 2.2d), we target those patients who have a problem opening their hand for grasping. We ask the subject to wear the same color markers as previous task but this time one on the thumb and the other on their index finger of the impaired hand. The subject then has to grasp a random size circle that appears on a random position on the desk. Due to the circle's different sizes and positions, the subject had to adjust finger position to generate the correct size grasp in order to get the circle. A sound (dynamic feedback) is played to let the subject know when he has succeeded and shall proceed to the next grasp.

2.4 Results, Discussion and Conclusion

The purpose of this pilot study was to prove the system is functional, anticipating potential problems and gaining experience using the technology in a laboratory setting. Figure 2.3a illustrates the position of the subject's hand while each was reaching out the melody box. As can be seen, the subject's hand traverses back and forth between a common point (start of movement) and the three melody boxes that were projected on the table. Figure 2.3b shows tilting angle of the mug while the subjects were gradually pouring water on the table. Figure 2.3c illustrates wrist and index finger positions of the subjects to examine whether they were able to perform the pointing task. Figure 2.3d demonstrates thumb and index finger positions while the subjects were trying to match their grip's size to the size of the projected circle.

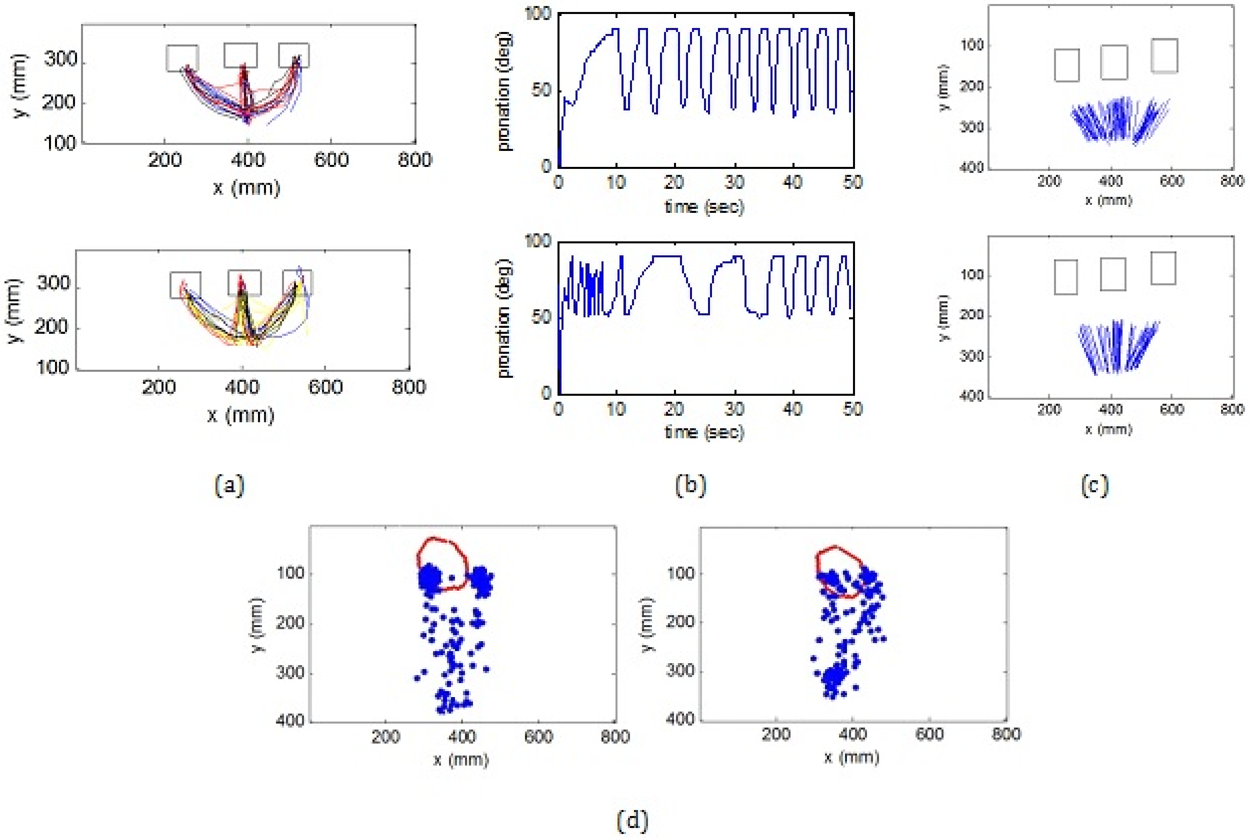


Figure 2.3: User study results with the first subject (upper plots) and the second subject (lower plots) performing tasks 1-4: (a) Reaching; (b) Tilting; (c) Pointing; and (d) Grasping

Augmented Reality technology has the potential to impact traditional rehabilitation techniques. This approach has the potential to address a number of needs in stroke rehabilitation. Chief among these is the use of a high ecology environment that is maximally relevant to functional goals. Performing tasks in an Augmented Reality environment might generalize to real life settings to a greater extent than with other computer-based approaches. As an extension of this, object affordance can be directly adjusted by the therapist, with real objects incorporated into tasks as desired. This system can control for extraneous distractions that sometimes exist in real life therapy environments, and furthermore the therapist can choose how many extraneous objects to include in each trial. The system insures safety and comfort, for example, no water is spilled on the subject or wires when the tilting task is performed by a patient with post-stroke hemiparesis.

A key advantage of the current approach is the tasks practiced in therapy can be modified by a therapist based on a patient's specific needs. For example, the size, texture, or friction characteristics of an object can be varied in relation to motor or sensory deficits. The language requirement for task performance can be adjusted from zero to high; in this way, patients with aphasia are eligible to use the system, in contrast with some rehabilitation approaches. An object's location, orientation, or attentional valence can be easily adjusted, a feature of particular value to patient's with neglect after non-dominant hemisphere stroke. The cognitive demands of a task can be adjusted in numerous ways using this approach, a feature useful for the treatment of patients with cognitive impairments, a common finding after stroke. Attentional valence can also be adjusted, for example, the same grip might be to hold an ice cube in a cafe or a gold nugget in a mine. This is particularly relevant to maximizing patient motivation, a perennial concern across the weeks of stroke rehabilitation, and also has implications for vocational rehabilitation.

The current report describes development of a Spatial Augmented Reality system for rehabilitating upper extremity function after stroke. A novel performance-driven exercise program was outlined, in which a patient practices primary hand gestures mostly used in daily activates. These gestures include reach, tilt, point, and grasp, examining parameters such as range, speed, and smoothness of hand, arm, and wrist movements. The AR rehabilitation system was evaluated with two healthy subjects as a proof of concept.

Further studies are planned to elucidate the clinical efficacy of our AR therapy for stroke patients. As future work, we also plan to add haptic feedback [4] to our system. This is especially important for those patients who need to recover their muscle strength. With haptic feedback [54, 57], we can even improve the effectiveness of the rehabilitation systems and make interaction process more realistic. To reach this target, instead of using bulky equipment, we generally use personal and daily-life objects such as cup, book, pen, etc [56, 66]. These have the added advantage of high task ecology with respect to activities of daily living. In addition, future work will include more engaging games to increase the variety of therapy solutions and adaptability to patient abilities, so that a therapist or patient can match the amount of challenge necessary to keep the rehabilitation advancing. In these games, we take advantage of skin detection methods and Microsoft Kinect [53] for more accurate and natural 3-dimensional positioning.

We will use the current AR platform in next chapter to study performance of healthy individuals in the “Pick and Place” task.

Chapter 3

Comparing “Pick and Place” Task in spAR vs niVR

This chapter describes collaborative work previously published at [65]. My role in that project was design and development of the “Pick and Place” Task in the AR system, data collection, statistical data analysis, and writing the paper.

3.1 Introduction

Introducing computer games to the rehabilitation market led to development of numerous Virtual Reality (VR) training applications. Although VR has provided tremendous benefit to the patients and caregivers, it has inherent limitations, some of which might be solved by replacing it with Augmented Reality (AR). The task of pick-and-place, which is part of many activities of daily living (ADLs), is one of the major affected functions stroke patients mainly expect to recover. We developed an exercise consisting of moving an object between various points, following a flash light that indicates the next target. The results show superior performance of subjects in spatial AR versus non-immersive VR setting. This could be due to the extraneous hand-eye coordination which exists in VR whereas it is eliminated in spatial AR.

3.2 Background

Medicine is one of the important application areas for virtual reality, leveraging it for games and scientific visualization [122]. The scope of VR applications in medicine has expanded over the recent years such that today it includes physical therapy (PT) and rehabilitation. VR has been found very effective for both mental and physical therapy. One of the primary origins of disability in the developed countries is stroke [3]. It is a rapidly developing loss of brain function(s) resulting from lack of blood flow caused by either a blockage, or a hemorrhage [106]. Stroke often affects upper-extremity motor functions [33]. These impairments hold back stroke patients in performing ADLs severely. In an early stage after stroke, patients receive upper-extremity physiotherapy. This includes goal-oriented reaching and pick and place tasks which incorporate real object manipulation [119, 114, 53]. Methods of motor function assessment such as Purdue Pegboard Test, Fugl-Meyer, or ARAT are based on the subjects' performance in the above-mentioned tasks [41, 18, 115].

3.2.1 Virtual Reality Therapy

Unlike conventional and robotics-assisted technologies, Virtual Reality is a cost-effective alternative that let users interact with a simulated world using special hardware and software [50]. Besides, including VR into stroke rehabilitation caused a great increase in patient's motivation to more enthusiastically follow the rehab sessions [16, 59].

3.2.2 Augmented Reality Therapy

In contrast to VR, Augmented Reality superimposes a computer-generated image on a user's view of the real world. It not only preserves some benefits of leveraging VR such as fully controlled setting and measurable feedbacks, but also needs less computation time to model the 3D environment [104]. In AR, patients experience a more engaging and natural interaction rather than VR. Virtual objects can be manipulated in an intuitive and natural way to maximize learning ADLs [51]. The haptic feeling [66] of the real objects could bring on a more natural interaction. In addition, patients do not need to don external devices attached to their hand or body.

There is consensus amongst therapists that as the interaction of patients with the physical environment is reduced, their ADLs recovery starts to deteriorate [98]. Thus an essential factor to successful recovery is to increase the patient's level of interaction with their environment.

AR environments are flexible enough to provide customization in terms of complexity, required feedbacks, etc., of the exercises based on patients particular needs [50]. This is especially important, considering that physical conditions of the patients change regularly, and thus adjusted systems should be easily provided.

In addition, augmented reality games have been reported highly engaging for patients undergoing therapy. As [12] investigated, about 65% of patients are likely to give up their physical therapy rehabilitation session. Further, Tinson [116] provided evidence that stroke patients within a clinical unit spent only 30 to 60 minutes per day for actual therapy while 40% of their time, they are not engaged with any activity. In stroke rehabilitation, it is a key factor to have the patient involved with the training exercises frequently; otherwise the desired level of recovery will not be achieved.

3.2.3 Difference in Cognitive Perception of AR and VR

To have effective interaction with real-world objects, the brain builds a spatial representation of them [35]. For target-oriented movements (e.g. pointing and reaching), the target's relative position to the hand should be converted to the body-centered coordinate. There is a transformation chain of reference frames that yields a common body-centered representation [108, 37]. The location of an observed target is coded in retinal coordinates. By considering the relative spatial information of the eye and head positions, we can transform the retinal coordinates to head-centered coordinates. This representation is required to be further transformed into body-centered coordinates by considering the head position relative to the body. When position of the observed target and hand are translated to the common body-centered reference frame, spatial difference between them is calculated which leads to forward plan of an action.

To interact with a non-immersive VR setting (which is widely used in stroke rehabilitation), the subject needs to perform at least one extra transformation to translate the virtual world's coordinate to the body-centered coordinate while it is not required in spatial AR. The extra transformation could be challenging to stroke patients while it may not even be necessary to recover their ADL's.

The study's main contribution is thus studying the effect of the extra transformation on performance of the subjects in AR versus VR settings. By comparing the score of the subject while performing pick and place task in both AR and VR environments, we verify whether it varies at all.

The remaining of the work is organized as follows: Section II describes the method including the procedure, setup, and subjects. The data analysis is presented in Section III. Finally, conclusion and future work are discussed in Section IV.

3.3 Method

3.3.1 Subjects

We conducted a within subject experiment including 14 healthy subjects. There were 7 males and 7 females, aged 22 to 45 years old. All subjects performed the task with their dominant hand and they were instructed about the tasks before the experiment. They were told to hit the targets as fast as possible where hitting occurs as soon as the cylindrical object touches any edge of the target squares. They also had a trial test to get familiarized with the task and learn the task. Each subject was asked to play both AR and VR tasks.

3.3.2 Procedure

We developed a pick-and-place task in which a subject pick a cylindrical object and place it inside a virtual square that appears on a random location. The subject needs to reach for the square as if he/she is hitting a target with the object in his/her hand. As soon as the cylindrical object enters the square, it disappears while another target square appears in a different random position, meaning that the subject scores one and has to reach for the next target. The task continues non-stop for 30 seconds and the subject's score is announced at the end. This exercise aims at reaching highest number of targets within a given time interval.

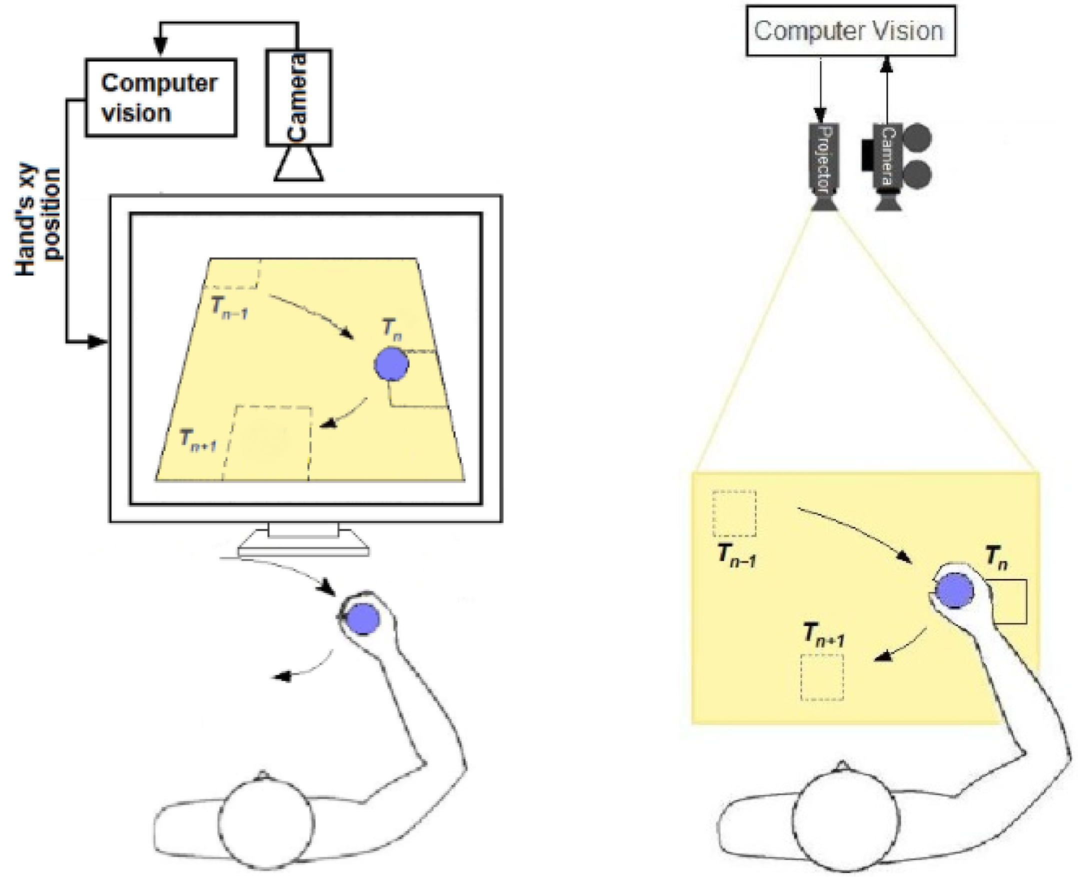
The task of pick-and-place, which is involved in many activities of daily living (ADLs), is one of the main impaired functions stroke survivors most wish to recover. It includes training of primitive postures of the hand including reaching, tilting, and grasping which need control on various hand parameters such as: range, speed, and smoothness of movement. This helps us measure several important performance features that can be used to evaluate recovery of the patient. Giving dynamic audio/visual feedbacks on performance of the user throughout the task such as playing sounds when he/she hits the target and displaying the next square target in response to the patient, the system increases the quality of patient's interaction with it.

3.3.3 Setup

We have two setups: AR and VR. Both setups share a table on which the subject performs the task. There is a camera to capture hand movements of the subject connected to a conventional computer that processes the video feed and produces audio/visual feedback in real time. This setup has the potential to be used in clinical as well as home setting (as a tele-rehabilitation system).

VR Setup

In the VR setup, the subject looks at a monitor, displaying random squares and a cursor which represents the subject's hand position while reaching the targets (3.1a). We developed a computer vision algorithm to locate and track a color marker attached to a cylindrical object which is held in the subject's hand.



(a)

(b)

Figure 3.1: (a)VR setup including a camera and monitor display; (b)AR setup including a camera and projector

AR setup

In the AR setup, instead of having a monitor, we use a projector to superimpose the virtual square targets on the tabletop. This is the same table that serves as a platform for the subject to do the pick-and-place task. Same as VR, the subject's hand movements are captured by a camera, while he is looking on the table and interact with the virtual objects superimposed on it (3.1b).

Since the key intention of this chapter was to evaluate the cognitive effect of spatial updating in VR versus AR system, we developed both systems as simple and similar as possible. That is, for VR, we developed a non-immersive system where the subject needs to coordinate his hand movement in real world while his eyes follow the visual feedbacks (i.e., relative positions of his hand and the targets) on the monitor. For AR, we used spatial augmented reality where the 2D virtual objects are projected on the tabletop (i.e., the planar workspace of the subject).

The reason for using 2D AR and VR is that some of stroke patients have difficulty with depth perception of 3D interfaces. Fluet et al. [38] showed that the subjects performed worse with 3D glasses on while looking at a 3D screen as compared to naked eyes looking at a normal screen.

3.4 Results

Performance of the subjects in both VR and AR tasks was assessed using the total number of targets that they could hit in a given time interval (30 sec). Figure 3.2 illustrates the superiority of AR scores than VRs. Figure 3.3 shows the average and STD of the scores, demonstrating that there is no overlap between extremes of means SD. The mean value of the AR scores is 19.81 with SD of 2.29. In VR score set, the mean value is 10.94 with SD of 2.41. The result of paired samples t-test analysis (p-value = 1.7291e-008, = 0.05) is statistically significant which rejects the null hypothesis; therefore the means of the samples are not equal.

In case of VR, directions of reaching trajectories of the hand toward the targets are not as accurate as AR. Hence in VR, after the reach is complete, the hand position has more often to be corrected. The source of this error is that in planning the forward command of reaching, precise position of the target is not perceived.

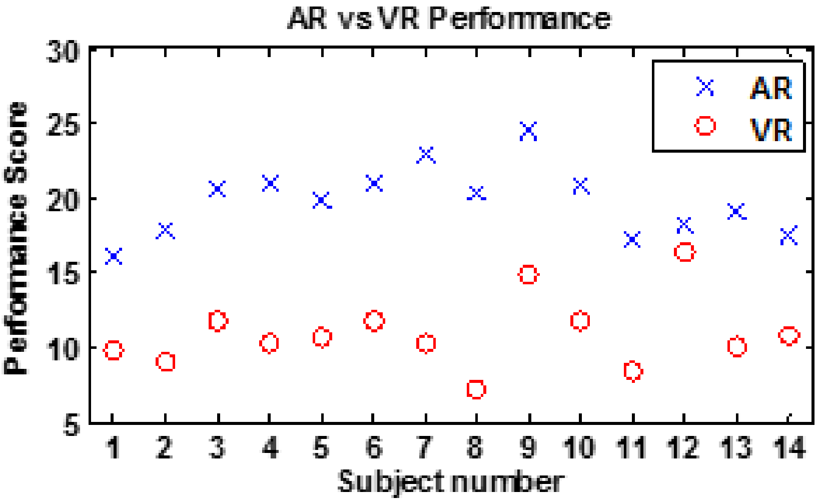


Figure 3.2: Performance of the 14 subjects in performing AR and VR tasks

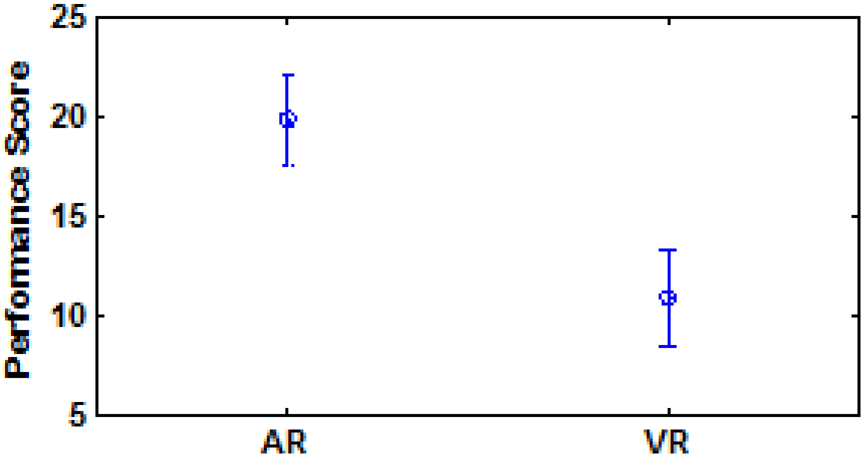


Figure 3.3: Mean and standard deviation of the 14 subjects scores in performing AR and VR tasks

Figure 3.4 shows monitored x-y hand position of a random subject while performing the VR task versus the respected target's center position. Note that the circles highlight the over/under shoots. After each over/under shoot, the subject has to take a fraction of a second to correct his hand position. As Figure 3.5 illustrates, in AR, this phenomenon is not observed. The time spent to correct one's hand position accounts for different levels of performance in AR and VR. The subjects perceive the target position inaccurately in

VR which might be due to the one extra spatial transformation that they have to perform compared to the AR task.

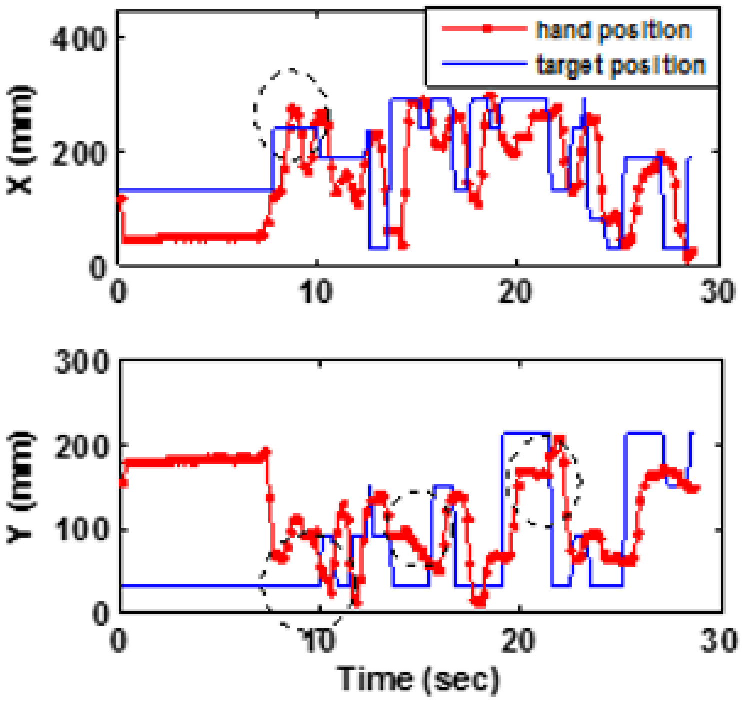


Figure 3.4: Monitored x-y hand position of a random subject while performing the VR task versus the respected target's center position. Note that the circles highlight the over/under shoots

3.5 CONCLUSION

As discussed in Section I, there have been significant amount of effort to use VR for rehabilitation. However, learning in a virtual environment can be transferred to the real environment. Transfer of rehabilitation training into real-world ADLs is even easier to accomplish if the training is conducted in as close to the real environment as possible. Spatial representation of the world and how brain deals with it as a gaze-centered transformation is one of the motivations to accept that AR could be a better medium than VR for post-stroke rehabilitation. Besides, engaging in AR therapy seems to be a cost-effective alternative to other forms of therapy such as conventional, robotic, or VR.

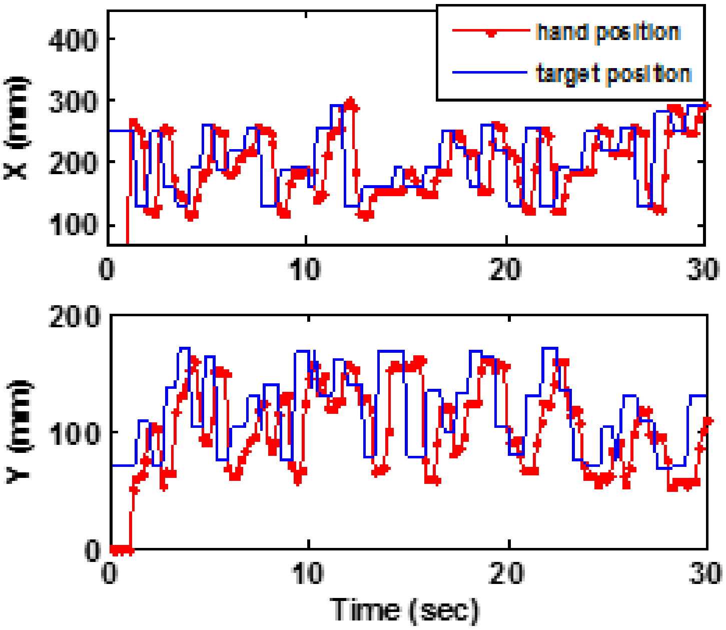


Figure 3.5: Monitored x-y hand position of the same subject as 3.4 while performing the AR task versus the respected target's center position

We designed a task of pick-and-place that is representing one of the main ADLs that post-stroke patients need to master. This exercise consists of moving an object from point to point following a target. The results show superior performance of subjects in spatial AR versus non-immersive VR setting. This could be due to the extraneous hand-eye coordination which exists in VR whereas it is eliminated in spatial AR.

Future work includes performing this exercise on stroke survivors to warrant that AR can provide a great level of clinical evidence. Furthermore, we have investigated AR perception in healthy individuals under different AR presentations [70] which has to be taken into consideration in developing AR systems for stroke patients as well.

After observing superior results of healthy subjects using spatial AR platform in this chapter, we will study another mode of interaction, i.e. free-hand interaction in 3D space, to explore how effective it can be for patients with stroke.

Chapter 4

Free-hand Interaction with Leap Motion Controller

This chapter describes collaborative work previously published at [69]. My role in that project was development of the the Fruit Ninja game using Leap Motion controller, data collection, statistical data analysis, and writing the paper.

4.1 Introduction

In recent years, the field of Human-Computer Interaction (HCI) has been advanced with many technologies, however, most are limited to healthy users. In this chapter, we leveraged the technology of free-hand interaction to rehabilitate patients with stroke. We modified the game of Fruit Ninja to use Leap Motion controller's hand tracking data for stroke patients with arm and hand weakness to practice their finger individuation. In a pilot study, we recruited 14 patients with chronic stroke to play the game using natural interaction. Their Fruit Ninja (FN) scores show high correlation with the standard clinical assessment scores

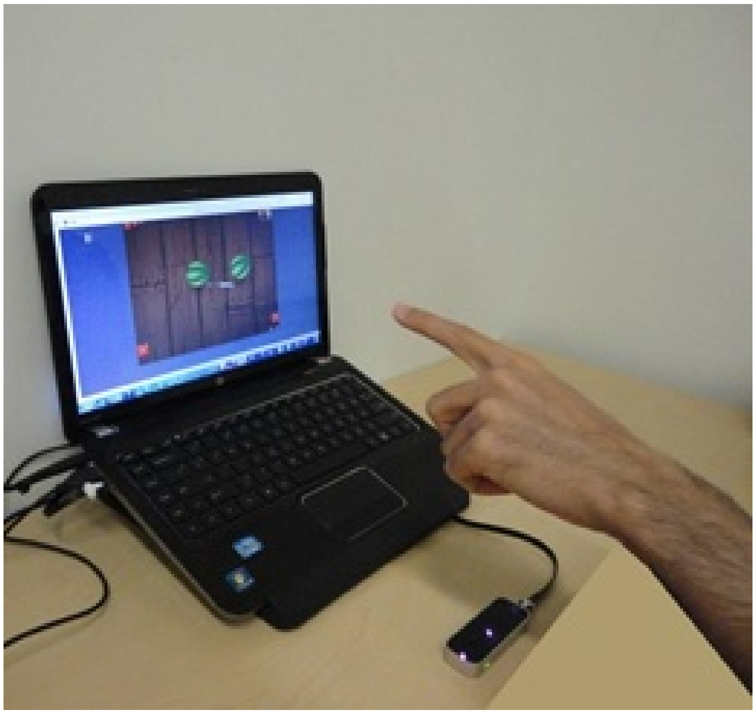


Figure 4.1: Playing Fruit Ninja using Leap Motion controller

such as Fugl-Meyer (FMA) and Box-and-Blocks Test (BBT) scores. This finding suggests that our free-hand Fruit Ninja's score is a good indicator of the patient's hand function and therefore will be informative if used in their rehabilitation.

In Human Computer Interaction, free-hand interaction has been explored for various applications such as games [71], immersive 3D modeling [72], mobile augmented reality applications [29], air painting [111], writing and sketching [121], etc.

While using free-hand interaction systems for an able-bodied user may be considered a luxury, it might serve as a great assistive technology for patients with physical disability.

One of the patient communities who may benefit largely from hand interaction are individuals with stroke. Stroke causes hemiplegia which affects motor functions in one side of the body; typically, patients lose part or full control of one of their hands. Considering that stroke is a leading cause of serious long-term disability in adults [26, 25], helping this community to retain their hand motor control, could have a significant impact on their quality of life.

4.2 Background

The human-computer interaction community has made several attempts to enhance stroke rehabilitation with HCI technologies. Hallam et al. [45] proposed an interactive glove to foster acceptance of partners after one of them is affected by stroke and help them reunite. Boulanger et al. [15] used Microsoft Surface's hand position as input of a tabletop game environment for stroke rehabilitation. The study involved exercises such as curling and uncurling fingers as well as a wrist flexion and extension of the hand back and forth about the wrist. Another example of fine motor rehab systems is PointAssist [100] which is a mouse interface that adapts to a user's level of impairment in reaching and clicking. The system could improve click success rates of individuals with fine motor impairments. Also [118] evaluated a novel click assistance technique to help users with motor impairments to click more accurately using a mouse. More specific studies focusing on finger rehabilitation include but are not limited to HandTutor [17], a glove-based treatment system which provides intensive flexion and extension movement of finger(s) and the wrist. Also MusicGlove by Reinkensmeyer et al. [40] motivates finger movements by pressing fingers against each other to play GuitarHero.

The above research shows example of touch, mouse, glove-based technologies that have been applied to stroke rehabilitation. Yet, using free-hand interaction as the most intuitive option to stroke rehabilitation has to be investigated.

4.3 Method

4.3.1 A Gaming System for Finger Individuation

We combined the game of Fruit Ninja with the Leap sensor, using open source JavaScript version of Fruit Ninja [2]. The desktop version of the game is supposed to be played with mouse events such as click and drag. Since our focus is finger individuation, we modified the game so that mouse events can be replaced by hand movements. Using the hand tracking information of the Leap sensor, we were able to trigger equivalent mouse events. We have also previously used Fruit Ninja in other stroke rehabilitation settings [55].

The setup includes a PC/notebook and a Leap sensor that is plugged in via its USB (Figure 4.1). The game runs on a browser (e.g. Google Chrome) while the hand is monitored using our java API code which is written on top of the Leap sensor's SDK.

4.3.2 Study

To determine the feasibility of free-hand interaction using Leap Motion controller for stroke rehabilitation exercises, we conducted a pilot study with 14 patients with stroke. The participants were asked to play our free-hand Fruit Ninja game. We also simplified the original Fruit Ninja so that patients with stroke with different levels of hand deficits are able to play the game for one minute.

4.3.3 Game

To avoid turning the rehabilitation exercises into boring and repetitive tasks, exercises are often gamified. For this purpose, we used Fruit Ninja, a top-ranked game in iTunes and

Figure 4.2: A snapshot from Fruit Ninja game

Google Play [1]. Fruit Ninja is not only an engaging game but also requires goal directed hand movements, which makes it appropriate for hand rehabilitation. In the original version, as the game starts, different kinds of fruits appear on the screen while the player has to slice them as fast as possible with mouse click and drag events (in the desktop version) versus touch and drag events (in the mobile version) (See Figure 4.2). If the player misses slicing three fruits, the game is over. Also, in the course of the game, several bombs appear on the screen time to time that the player has to avoid; otherwise the game is over.

We modified the Fruit Ninja game so that the patients with stroke were able to play. We changed the game-over restriction by removing the three missing fruits condition and disabling the bombs; instead we introduced a time constraint of 1 minute. This gave all the patients a similar game condition which was required for conducting a fair study and comparing their results.

4.3.4 Participants

14 patients with stroke (7 males and 7 females), aged 35-71 (M = 58.1, SD = 11) participated in the study. They were at least 6 months post stroke with different level of disability ranging from Fugl-Meyer [41] score of 19-66 (M = 48.86, SD = 17.79) and Box and Blocks Test [87] score of 0-58 (M = 30.29, SD = 20.27).

4.3.5 Experimental Procedure

Four participants had difficulty with finger movements; we strapped a stick (one of a pair of chop sticks) to the dorsum of their hand (Fig. 4.3); this was to enable them to play the game using their wrist movements (e.g., wrist supination and pronation). Since our experiment was part of a bigger study for which these four patients passed the inclusion criteria, we also accepted them to try the Fruit Ninja game. However, we took note of their special condition and did not compare their results with those of the rest of the patients.

After providing informed consent, the patients were briefed on how to play the game. They also had a warm-up round to get accustomed to the game. All the patients were asked to use their stroke-affected hand. They had three, one-minute rounds of playing the game while they were given break time in-between to rest. At the end, we asked some Likert questions on a scale of 1-4 to learn about the patients' overall satisfaction. These questions included: (i) whether the patient found the game engaging on a scale of 1 (not engaging) to 4 (very engaging); (ii) whether the game addressed a need (yes/no); and (iii) whether the patient would use the game at home on a scale of 1 (wouldn't use) to 4 (would use).

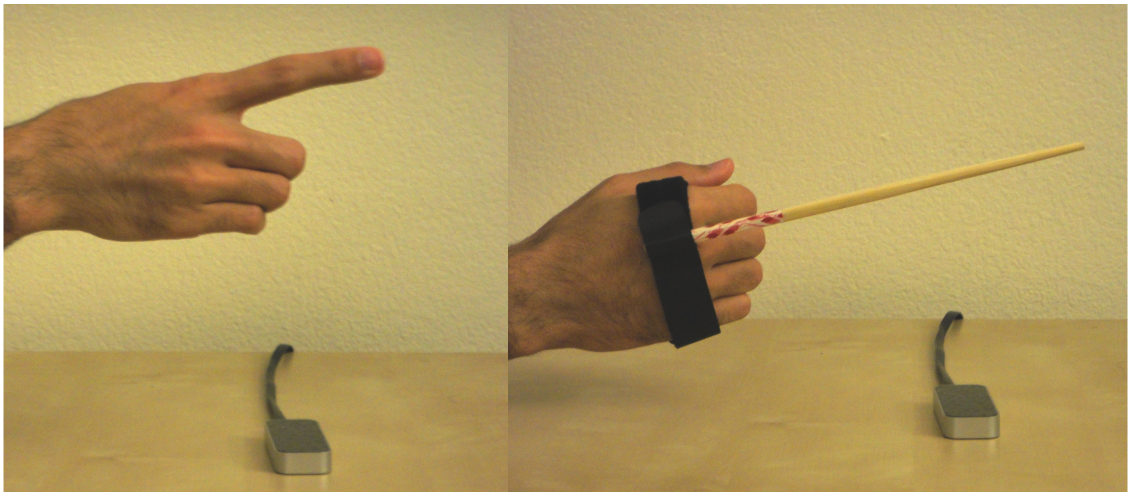


Figure 4.3: Strapping a stick to the dorsum of the hand

4.4 Results

Fig. 4 shows the game scores of our participants against their FM and BBT scores. To make an accurate comparison between patients' scores, we removed the score of four out of 14 patients who used the stick instead of their fingers. As shown in Fig. 4.4, a similar trend is observed between the patients' game (FN) scores versus clinical scores. The clinical score of FM and BBT are highly correlated ($r = 0.8157$, p¡0.01). We observed, the FN and FM scores are significantly correlated ($r=0.72$, p¡0.05), as were the FN and BBT scores ($r=0.86$, p¡0.01). Note that BBT's tasks require finer hand and fingers movements while FM tasks focus more on gross arm movements. Perhaps because the Fruit Ninja game involves fine hand/fingers control, FN-BBT scores show stronger correlation than FN-FM scores.

In response to whether the game was engaging for the patients, 11 out of 14 subjects gave 4/4 (very engaging). Also 10 of them agreed that the game was addressing a need, i.e., the game provided practicing the movements that can be generalized to daily functions. In response to the question whether the patients would be willing to play this game if provided at home, 12 of them picked 4/4 (would use) while the other two participants gave 1/4 (wouldn't use). Two of the patients (P6-male and P1-female) who enjoyed playing the Fruit Ninja commented

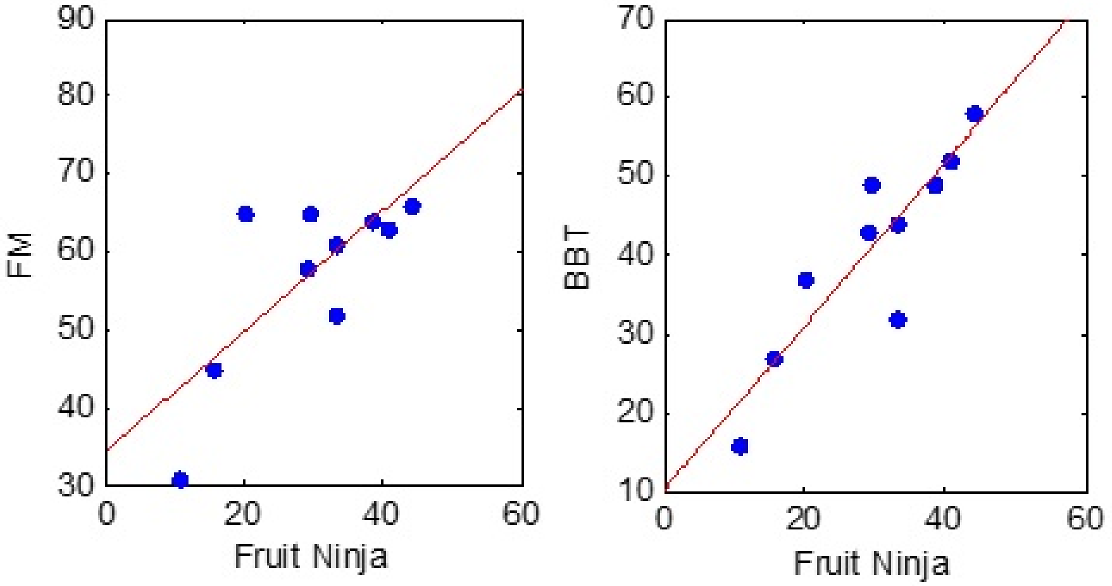


Figure 4.4: Performance in Fruit Ninja versus FM and BBT clinical tests

that the game provided hand-eye coordination which is very important in activities of daily living (ADLs). Also, three participants (P8-female, P13-male, and P7-male) mentioned that the game was not very responsive in terms of tracking their hand.

4.5 Discussion

Following up the tracking issue mentioned in previous section, we revisited the data of those particular patients (P8-female, P13-male, and P7-male) and found out that they had difficulty individuating their index finger to make a pointing gesture. Instead, they played the game with all the fingers extended. The Leap sensor assigns temporary ID's (1-5) to different fingers, for example, moving from frame n to n+1, the index finger may or may not be assigned to ID = 2. This creates a subtle confusion while showing the trace of slice on the screen (the trace may appear with jittering). Note that this event may happen in few percents of the frames (around 1%).

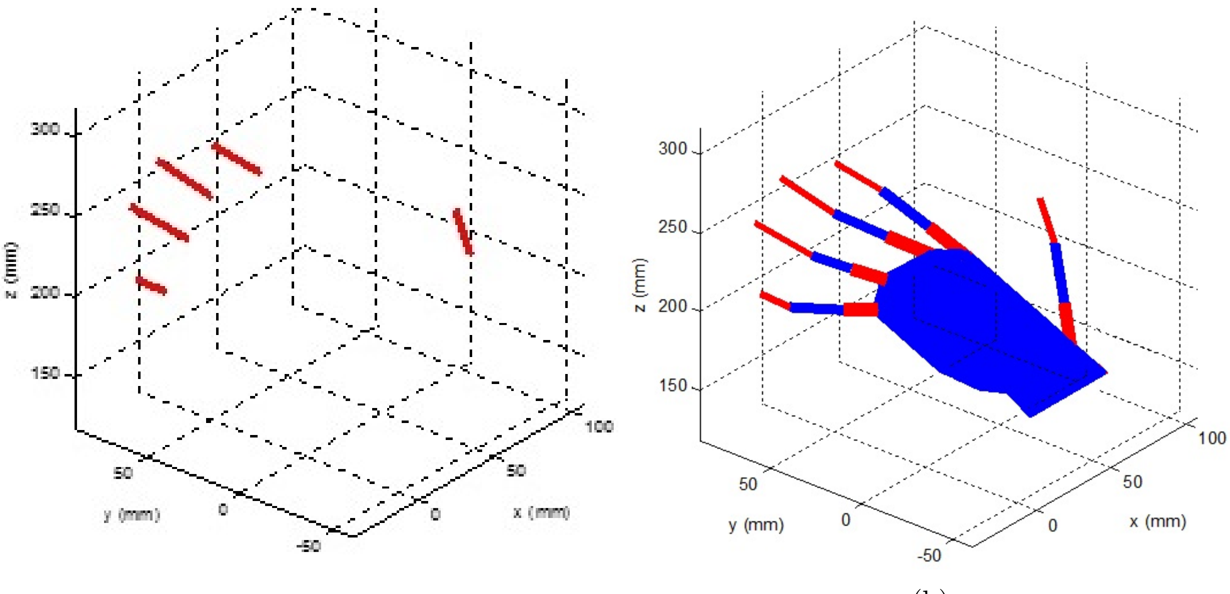
To solve this problem, we propose a 3D model of the hand that includes specific ID's for each finger and contains all skeletal parameters of the hand. Given that Leap's data is limited to fingertip position and direction vector, palm center position, normal, and direction vector, we used inverse kinematics to extract finger joint angles.

The human hand has 27 Degrees of Freedom (DoF) [79] where each joint contributes to 1-3 DoF. The wrist has 3 Cartesian DoF (x, y, and z) and 3 rotational DoF (roll, pitch, and yaw). Finger joints include the metacarpophalangeal or MP, proximal interphalangeal or PIP, and distal interphalangeal or DIP joints. The thumb has 5 DoF including 1 at the DIP, 2 at the PIP, and 2 at the MP. Each other finger (i.e., index, middle, ring, and fifth) has 4 DoF, including 1 at the DIP, 1 at the PIP, and 2 at the MP.

Of these 27 DoF, Leap SDK directly provides only the 3 from wrist rotations but it provides enough data to compute the rest. We used inverse kinematics to calculate the MP, PIP, and DIP angles by going through fingertip position and direction vector of each finger to the palm's center. Fig. 4.5b shows the completed hand skeleton based on the Leap's data shown in Fig. 4.5a. The hand skeletal model not only increases the robustness, but also enables us to record and reconstruct hand movements in a realistic way for medical assessments. Besides, the model can be used for simulating patients' hand movements in a virtual environment (i.e., games or computerized therapeutic exercises) where patients manipulate objects.

4.6 Conclusion

The HCI advents have not been fully explored in the field of patient-computer interaction. We used the cutting-edge technology of free-hand interaction with Leap Motion controller for stroke rehabilitation. We modified the Fruit Ninja game to use the Leap sensor's hand tracking data. The combination was prepared for patients with stroke to practice their fine



(a) (b)

Figure 4.5: (a)Fingertip position and directions provided by Leap sensor; (b)Full hand skeleton made by applying inverse kinematics on hand's anatomical model and Leap's data

motor control. We conducted a pilot study with 14 patients with stroke to evaluate feasibility of using this system for rehabilitation of upper extremity. The results demonstrated significant correlations between scores generated from the Fruit Ninja game and standard clinical outcome measures, such as the Fugl-Meyer Arm assessment and Box-and-Blocks Test. The qualitative evaluation of the system was also proved successful. To make the system more accurate and responsive, we also proposed a kinematic model of the hand. Using this model allows us to incorporate 3D parameters of the hand in tracking which in turn makes tracking more robust.

Free-hand interaction in 3D space proved to be an effective mode of training for highly functional patients. In next chapter, we will use our 2D AR platform and compare it with conventional mode of training to examine its usability for a wider range of patients.

Chapter 5

Comparing Direct and Indirect Interaction

This chapter describes collaborative work previously published at [52]. My role in that project was design and development of the platform for both direct and indirect modes of interactions, data collection, statistical data analysis, and writing the paper.

5.1 Introduction

Advances in technology are providing new human-computer interfaces to promote brain repair after stroke. These technologies may provide direct interaction (DI), where subjects interact with virtual objects in the real world, or indirect interaction (IDI), where subjects interact with a virtual environment indirectly. This study compares DI and IDI in patients with stroke.

The traditional approaches in stroke rehabilitation have several limitations; they are expensive, labor-intensive, time-consuming, and subjective [83]. Currently, computer-assisted technology plays a key role in enhancing traditional physical and occupational therapy, improving healthcare service, and decreasing the associated limitations [92, 122]. Conventionally, the patient interacts with the computer with or without a robot involved. Upper extremity motions are captured by robots or sensors (camera or accelerometers) and are used as user command input to the computer. Good examples of such systems are niVR rehab systems that display representations of the world and the patient on the computer screen [99].

Exercising with such systems, the patient masters a task, such as hitting a target, which may generalize to ADL to some extent. In seeing the results of their actions on the computer screen, however, patients need to perform a non-trivial cognitive transformation that of mapping their arm movements in physical space to effects in the virtual space represented on the screen. While the additional cognitive load may be negligible in healthy people, it may provide an additional challenge for people with stroke, hampering the effects of these new computer-assisted therapies.

Spatial Augmented Reality (spAR) supports interaction with virtual objects displayed in the physical world with no interference of any screen (e.g. goggle or mobile devices). These technologies have great potential to build upon traditional, non-computer-assisted, rehabilitation techniques and thereby overcome some of the limitations associated with current forms of niVR systems that are widely used in stroke rehabilitation. A chief example is the use of a high ecology environment that is maximally relevant to functional goals. Performing tasks in a spAR environment can be expected to generalize to real life settings to a greater extent than with other approaches, including other computer-based methods. As an extension of this, object affordance can be directly adjusted in therapy based on spAR, with real objects incorporated into tasks as desired. This approach can also provide a means for a therapist or patient to control the therapy environment with precision, for example, by minimizing (or increasing) extraneous distractions and consequences associated with real life stroke therapy environments, or by modulating the cognitive demands of therapy, for example, by changing how many extraneous objects are included in various therapy trials. Involving the patient in direct simulations of ADL is expected to have the additional advantage of fostering a more positive psychological approach to the rehabilitation experience.

As important factors in stroke rehabilitation, both niVR and spAR therapies provide many benefits over non-computer-assisted therapies, namely: (i) adaptable audio-visual feedback; (ii) customization/flexibility in terms of providing complexity/challenge based on patients specific need/conditions; and (iii) engagement by providing an engaging experience to keep patients involved. As [12] investigated, about 65% of patients are likely to give up their physical therapy rehabilitation session. Further, Tinson [116] provided evidence that stroke patients within a clinical unit spent only 30 to 60 minutes per day for actual therapy while 40% of their time, they are not engaged with any activity. In stroke rehabilitation, it is a key factor to have the patient involved with the training exercises frequently; otherwise the desired level of recovery will not be achieved. The distinguishing feature of spAR environments is direct interaction with virtual objects, whereas in niVR patients interact only indirectly with those objects.

We contribute experimental work on use of direct and indirect interaction in stroke rehabilitation. In indirect interaction, hands are off the output medium whereas in direct interaction, hands are manipulating the virtual objects in output medium. For instance, using mouse is considered an indirect interaction between the user and the output medium (screen) whereas using finger to touch an iPad surface is a direct interaction.

Patients played DI and IDI versions of a popular video game that requires goal-directed arm movements. Across the two versions, movement demands were identical but cognitive demands differed. In the DI version, the game was projected onto the tabletop, where subjects viewed the game plus their arm movements, at the same time and in the same visual coordinate space. The IDI version imposed greater cognitive demand, as subjects moved their arm on the tabletop to control the game but viewed the game by looking at a computer monitor.

Among 18 patients with chronic hemiparesis after stroke, the DI game was associated with 21% higher game scores (p=0.0001), 19% faster reaching times (p=0.0001), and 15% less movement variability (p=0.0068), as compared to the IDI game. Correlations between game score and arm motor status were stronger with the DI version.

During the DI-based game, as compared to IDI, scores were higher, movements were faster and more consistent, and performances were more tightly linked with arm motor status. Differences are likely due to greater cognitive demands imposed by the IDI game. These findings inform how choice of human-computer interface can guide rehabilitation therapy choices for individual patients.

5.2 Background

5.2.1 HCI Studies in Stroke Rehabilitation

Prior HCI research in stroke rehabilitation ranges from behavior change through design and persuasive technology to developing systems for compensation control and upper extremity rehabilitation [63, 44, 19, 42, 73, 62, 28, 20, 64, 10, 112, 43]. Balaam et al. [11] reported on their experiences with building systems that keep patients with stroke motivated to engage in upper limb rehabilitation exercise. Alankus et al. [5] focused on reducing compensatory motions which can hinder the recovery progress and cause new health issues for patients with stroke. Digital box and blocks [128] was built as an in-home assessment apparatus for individuals with stroke. This is an example of rehab games that leverage indirect interaction, i.e., patients need to manipulate the blocks in real-world while the effect of their action can be monitored indirectly in a screen. In another study, Alankus et al. [6] reflected on the lessons they learnt about what makes games useful from a therapeutic point of view including increasing social connectedness, connecting with family members and friends. Usem [14] presented a watch-like device that provides feedback to patients regarding the usage of their impaired arm hand in relation to their non-affected upper extremity in order to motivate them to use their affected arm more. Comparing our work to the above research, we evaluate quantitatively the impact of interaction techniques within the practical domain of stroke rehabilitation.

5.2.2 Augmented Reality Therapy in Stroke Rehabilitation

Several Augmented Reality (AR) systems were designed to recover certain impaired functions of individuals with disabilities. Luo et al. [85, 84] measured the force and assist finger extension using mechanical devices. They presented a training environment for rehabilitation of hand opening in stroke survivors. This environment integrated AR with assistive devices for the process of repetitive training of grasp-and-release tasks. One potential criticism of the system is that therapist intervention was necessary, as the patient needed to wear equipment that would be hard to don without assistance. Correa et al.

[23, 24] developed GenVirtual, an AR musical game , that provided a natural, fingertip/toe tip-based interaction. This chapter tended to help patients with motor coordination. On the other hand, GenVirtual had little effect for individual with low mobility. Alamri et al. [4] proposed a framework that takes advantages of the AR-based rehabilitation processes

with a 2-D web camera and fiducial markers. The system supported the training of daily activity, though, due to use of fiducial markers, the setup can be complex in the absence of a therapist.

5.2.3 Benefits of AR Therapy

AR superimposes a computer-generated image on a user's view of the real world. It not only preserves some benefits of niVR applications such as fully controlled setting and measurable feedbacks, but also needs less computation time to model the 3D environment [104]. In AR, patients experience a more engaging and natural interaction rather than niVR. Virtual objects can be manipulated in an intuitive and natural way to maximize learning ADLs [51]. The haptic feeling [66] of the real objects could bring on a more natural interaction. In addition, patients do not need to don external devices attached to their hand or body.

There is consensus amongst therapists that as the interaction of patients with the physical environment is reduced, their ADLs recovery starts to deteriorate [98]. Thus an essential factor to successful recovery is to increase the patients level of interaction with their environment. AR environments are flexible enough to provide customization in terms of complexity and required feedbacks of the exercises based on patients particular needs [50]. This is especially important, considering that physical conditions of the patients change regularly, and thus adjusted systems should be easily provided.

In addition, AR games have been reported highly engaging for patients undergoing therapy because they can provide interesting and engaging tasks that are more motivating than formal repetitive therapy [80].

5.2.4 Cognitive Perception of Direct and Indirect Interaction

Human brain constructs a stable spatial representation to interact with ADL objects [35]. In goal-directed interactions (e.g. reaching, pointing, or manipulating objects), the brain needs to translate the location of the target relative to the hand into a common coordinate. The conventional explanation suggests that the spatial coding of goal-directed actions is performed in sequential transformations of reference frames into a common body-centered representation [108, 37]. For example, the location of an observed target is coded in retinal coordinates which is transformed to head-centered coordinates by adding the information of the eye/head relative position. Finally, by considering the head position relative to the body, this representation is transformed into body-centered coordinates. When both the viewed target and the hand are represented in a body-centered reference frame, the hand-target-difference vector can be calculated and an action can therefore be taken place.

To interact with an object in niVR environments, the user needs to perform an additional transformation (besides the aforementioned chain of transformations) to translate the virtual worlds coordinates to the body-centered coordinates. This extra transformation is not required in a spAR environment because the user can interact with the objects directly. For patients with stroke, adapting this extra transformation may be unnecessary to recover ADLs. Moreover, such modulations in cognitive demand are known to have significant effects on motor behavior after stroke [30].

5.2.5 Direct versus Indirect Interaction: HCI Studies

Direct and indirect interactions have been the subject of research interest in different domains of human computer interaction such as large displays, pen input, 2D-3D spaces, multi-display environments, etc. Here, we discuss a few examples from each domain.

One area of interest for the HCI community to explore the effect of these two interaction modalities has been large displays. Schmidt et al. [101] studied direct and indirect interaction in multi-touch input for large displays. They examined the two modes of interaction in terms of quantitative performance, qualitative observation, and user preference. The results indicated performance loss in indirect interaction due to blindly keeping arms and hands at distance to the input device [101]. Cheng et al. [21] developed a system to use an infrared laser pointer and an infrared tracking device to achieve a more direct interaction with large displays. Their main argument was that large scale display systems usually provide users with an indirect interaction which is in line with the use of conventional desktop-oriented devices to control the wall-sized display. However, they showed direct interaction with the laser pointer and infrared tracking device reduced the cognitive load of the user and improved their mobility.

Another domain of interest is stylus input and tactile interfaces. For example, Forlines et al. [39] explored the effects of direct versus indirect pen input on pointing and crossing selection tasks. They investigated users performance with pointing and crossing interfaces controlled via two input devices, i.e., when the pen-input and display are separate (indirect) and co-located (direct). They concluded that direct input significantly outperforms indirect input for crossing selection, but the two modalities are essentially equivalent in pointing selection.

As an example of a study in 2D-3D spaces, Knoedel et al. [75] investigated the impact of directness on users performance for multi-touch RST (rotation, scaling, and translation) in 2D and 3D spaces. This study showed that direct-touch reduces completion times, but indirect interaction improves efficiency and precision specifically in 3D visualizations. The study also presented that users trajectories in 2D/3D space with direct/indirect interaction are comparable which proves that indirect RST control may be of value for interactive visualization of 3D content.

In the domain of multi-display environments, the Ubiquitous Cursor system [126] provided direct between-display feedback for perspective-based targeting. In a study that compared Ubiquitous Cursor with indirect feedback Halos and cursor-warping Stitching, Xiao et al. showed that Ubiquitous Cursor was faster than indirect feedback approaches. This work confirmed the added-value of direct feedback for cross-display movement.

Although direct interaction has been generally preferred in the above domains, indirect interaction has variety of advantages depending on the application domain too. For example, Malik et al. [89] and Moscovich et al. [86] suggested indirect interaction can be of help in the following conditions: (i) when distant interaction is required; (ii) when multiple users need separate input interfaces; (iii) when avoiding occlusion is necessary; or (iv) when one surface serves as an input to multiple displays.

Although the above studies shed light on the usage of direct and indirect interaction based on specific domains, stroke rehabilitation research lacks studies on usage of direct and indirect interaction modalities. Our paper is the first to study the effect of such interaction in rehabilitation of patients with stroke. Also, there are only few studies that quantitatively analyzed the two modes of interaction in other domains as we did. Besides, our study provides design implication for the research community and developers to change the paradigm of using niVR, as the major mode of interaction, to spAR in developing computer-assisted therapeutic systems.

The current study examined this issue by having a cohort of patients with chronic stroke play a popular video game using two different formats, one DI-based and one IDI-based.

The IDI-based version employed the approach commonly encountered in computer gaming, whereby the subject used a game controller on the tabletop while looking up at a computer monitor to view the game. In the DI-based version, the subject again used a game controller on the tabletop, but instead of looking up at a monitor the subject looked at the same tabletop onto which the game was projected. Arm movement kinematics required for game play were thus identical across the two game versions. The main difference was that playing the IDI-based game, but note the DI-based game, required subjects to perform an additional visuospatial transform. Given this, we hypothesized that the IDI-based game, as compared to the DI-based game, would be associated with lower game scores and with movements that were less efficient and less correlated with arm motor status.

5.3 Method

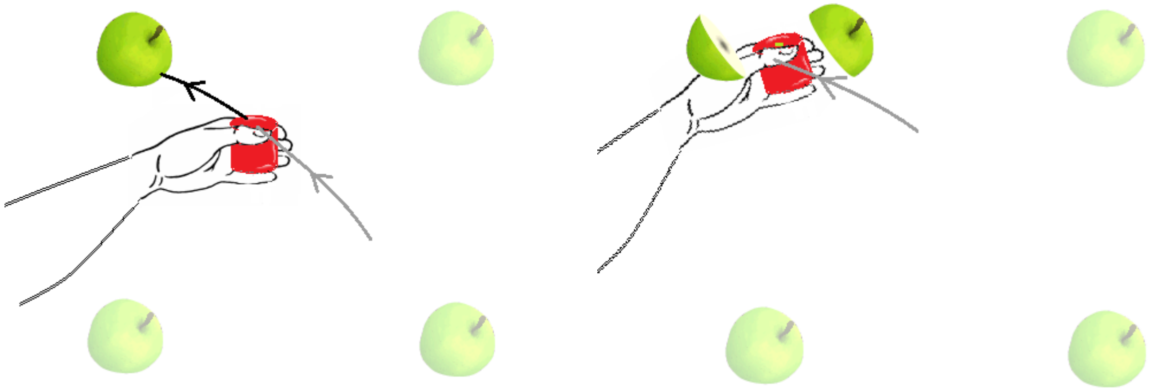
5.3.1 Subjects

Patients with chronic stroke were recruited from the community. This study was approved by the Institutional Review Board, and all subjects signed informed consent. Entry criteria were age ≥ 18 years, history of stroke with onset ≥ 6 months prior, and arm weakness operationally defined as Fugl-Meyer (FM) total arm motor score [102] of 15-55 (out of 66) plus at least 5 degrees active range of motion in either wrist or index finger metacarpophalangeal joint on the stroke-affected side. Exclusion criteria were severe cognitive, attentional, or language deficits; a non-stroke diagnosis that affected arm or hand function; and co-existent major neurological or psychiatric disease.

After signing consent, medical history was reviewed, followed by a brief exam that included a measure of loss of body/function, the FM arm motor scale [102] as well as a measure of activity limitations, the Box & Blocks test (BBT) [87, 31]. Subjects then played the DI-based and IDI-based versions of the game with the paretic arm, as below.

5.3.2 Game design

To design a game for comparing direct versus indirect interaction, we were inspired by the Box and Blocks Test (BBT), a measure of gross manual dexterity often used as a post-stroke assessment [48], [49]. The standard BBT does not require computer assistance. To perform the BBT, the patient is seated at a table, facing a rectangular box with two square compartments and a barrier in between. Several wooden cubes are placed in one compartment. The patient is asked to grasp each block one at a time, transport it across the barrier and release it in the other compartment. The test is administered by a therapist and scored by counting the number of blocks that are successfully transferred within 60 seconds.



(a) (b)

Figure 5.1: Reaching (left) and hitting (right) the fruit target

We developed a simple version of Fruit Ninja, a top-ranked game in iTunes and Google Play (it was on one-third of US iPhones in May 2012) [50]. Our game includes repeated goal-directed wrist/hand reaching tasks which are similar to distal and proximal movements in BBT. Subjects held a cup-shaped color-marker in the paretic hand, then reached for a virtual fruit target that is sliced in two when the color marker overlapped the target (Figure

5.1). Then the next fruit target appeared in a different random corner, cueing the subject to reach for the next target. The game continued non-stop for 1 minute while the subjects score was displayed on the screen. The games goal is to slice as many virtual fruits as possible within the specific amount of time (1 min). This game was implemented in both direct and indirect interaction settings, with identical movement demands across the two conditions.

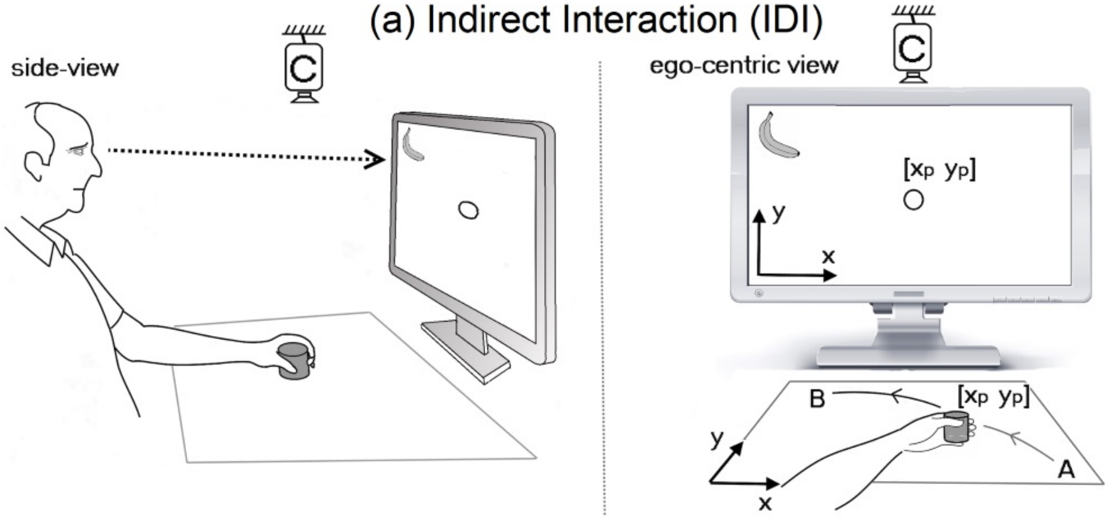
Subjects were seated and introduced to the DI and IDI versions of the game. A fruit target would then appear in one of the four corners of the tabletop and start moving around the workspace. The subject was to use the stroke-affected hand to move the cursor onto the fruit (which would slice the fruit in half, make a noise, and score 1 point) before the fruit disappeared (which would score 0 points). Once the fruit was sliced, or disappeared unsliced, a new fruit target would appear in one of the four corners, the sequence of which was pseudo-randomized. Subjects were instructed to slice as many fruits as possible within the allotted time. The score was presented throughout each game. One round of each game was 90 seconds long.

Subjects played one practice round each of the DI and the IDI game, which were not recorded or analyzed. Next, study data were acquired as the subject played three rounds of either the DI or the IDI game, the order of which was randomly assigned across subjects, followed by three rounds of the other version of the game. Subjects were provided with a brief break between each round.

5.3.3 DI vs. IDI Game Setup

All game features and arm movement demands were identical across the two versions of the game and required that the subject move the stroke-affected hand around the tabletop to slice fruit. Subjects sat in the same chair at the same table. Both game versions used the same overhead camera (Microsoft LifeCam VX-2000 Webcam, 30 fps, 720p HD capture)

(a) Indirect Interaction (IDI)



(b) Direct Interaction (DI)

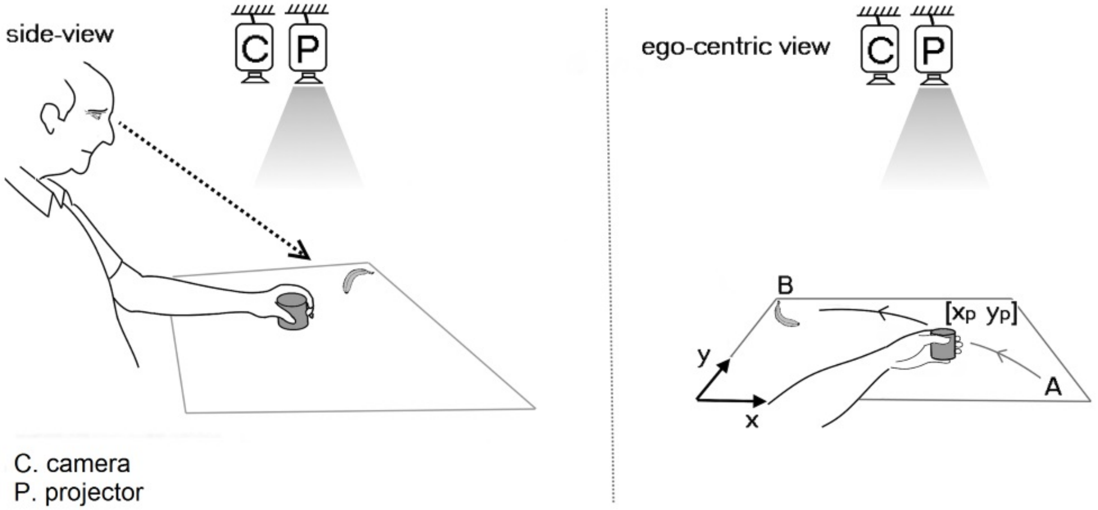


Figure 5.2: A patient playing the [a] IDI and [b] DI versions of the Fruit Ninja game. Game features and movement demands were identical across the two versions of the game. Both required that the subject move the stroke-affected hand across the tabletop in order to control the movement of a cursor that earned points by slicing fruit targets. Both versions of the game leverage the same camera; however in the IDI version, game activity was displayed using a compute r monitor, while in the DI version, game activity was displayed on the tabletop using a projector. This difference imposes two key differences: (1) During IDI play but not DI play, subjects must perform an extra spatial transform in order to convert the coordinates of tabletop hand movements to the coordinates of the cursor movements seen on the monitor, and (2) During IDI play subjects receive only proprioceptive feedback (gaze is directed at the monitor not the hand), while during DI play subjects receive both visual and proprioceptive feedback. These differences likely account for the significantly poorer motor performances seen with IDI play.

to capture the subject's tabletop hand movements, which moved the game's fruit-slicing cursor. These camera images were fed to a computer running a program that tracked the color-marker and that provided real time audiovisual feedback.

IDI set-up (Figure 5.2(a)): The subject was instructed to gaze straight ahead at a 15-inch computer monitor whose position was fixed throughout the experiments. This monitor displayed the fruit targets as well as the cursor, a circle that represented the real time position of the subject's hand. With the IDI setup, the subject's hand was 45 degrees away from his/her direction of gaze.

DI set-up (Figure 5.2(b)): The subject was instructed to gaze directly at the tabletop, onto which images appeared from a projector (P4-X Pico Projector, AAXA Technologies, Tustin, CA); the monitor was not used and remained blank. The projector thus displayed (720p HD) fruit targets, and the workspace with four corners, directly onto the tabletop. With the DI setup, the subject gazed directly at his/her hand as it moved to slice the virtual fruit targets.

5.3.4 Performance Metrics

The primary metric was game score. Three secondary metrics were extracted from game performance to aid interpretation of game scores:

1. Game score: The number of fruit targets successfully sliced during a 90-seconds round of game play. The three rounds of DI were averaged, as were the three IDI rounds. This produced a single DI score and a single IDI score.
2. Reaching time: The amount of time between reaching one fruit target and reaching the next fruit target.

3. Movement time consistency: The coefficient of variation of reaching times.
4. Response latency: The amount of time between display and target reaching, recorded for the first fruit target only in each round of the game.

5.3.5 Statistical Data Analysis

Data were analyzed using JMP 10.0 (SAS, Cary, NC) and used two-tailed testing at alpha of 0.05. Parametric methods were used to analyze data that were normally distributed or could be transformed to a normal distribution, otherwise non-parametric methods were used. The primary, plus three secondary, game performance metrics were compared between the DI and IDI game setups. Next, the relationship between game scores and motor status (BBT score and FM score) were calculated; secondary analyses also considered FM sub-scores. Finally, in an exploratory analysis, reaching times were compared according to the quadrant of visual space in which the fruit target first appeared, separately for each of the two game versions, and according to side of stroke. Quadrants were defined in egocentric space, i.e., either near or far from the body, plus either ipsilateral or contralateral to the stroke-affected arm.

5.4 Results

A total of 18 patients were recruited. All completed the study protocol, with no adverse events reported including no fatigue. Enrollees were on average 57 years old, 70 months post-stroke, and had mild-moderate motor deficits (Table 5.1).

Note that originally we had 22 patients but four of them were unable to hold the color-marker object, therefore the object was strapped to their hand. Figure 5.3 shows sketches

Table 5.1: Subject characteristics. Values are mean±SD or percentages

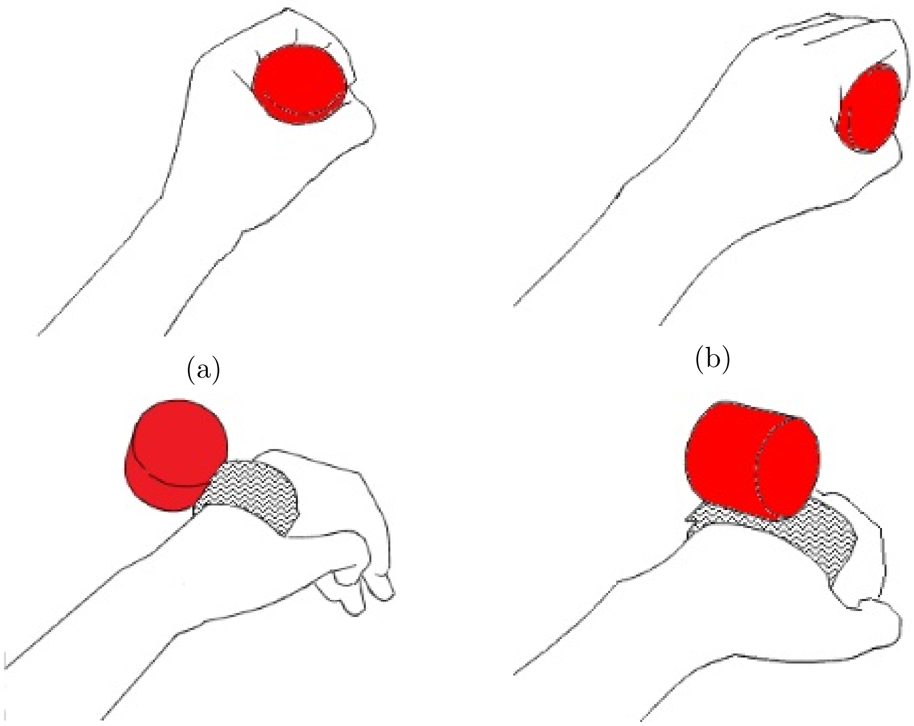
n	18
Age	57 ± 14 years
Gender (F/M)	8/10
Dominant hand (R/L)	12/6
Stroke-affected Side (R/L)	12/6
Time post-stroke	70 ± 73 months
Hypertension	61%
Diabetes mellitus	22%
Atrial fibrillation	5%
FM total score	56 ± 11
FM hand/wrist subscore	21 ± 5
FM proximal subscore	30 ± 7
BBT score	
Affected arm	38 ± 14
Affected/unaffected arm	0.66 ± 0.25

of patients hands in pronation and supination poses with the color-marker object being held or strapped to the hand.

Strapping the color-marker object to the hand makes the game easier because the patient does not need to maintain a specific wrist posture while reaching. For example in Figure 5.3, a patient without hand strap needs to maintain the posture (a) and avoid (b) whereas a patient with hand strap can play the game with both postures (c) and (d); note that wrist postures in (b) and (d) are both pronation. Those patients who used the strap (i.e., with lower FMA & BBT scores compared to other patients) scored equally or higher in the game. Later, to keep the comparison accurate, we excluded their data from the study.

5.4.1 Motor Performance with DI vs. IDI

By all measures, motor performance while playing the DI-based version of the Fruit Ninja game was superior to the IDI-based version. Game score, the primary metric, averaged 58±10 targets/game ($mean \pm SD$; range 42-78) with the DI-based version, 21% higher (p=0.0001)



(a) (b) (c) (d)

Figure 5.3: The patients' hand in pronation and supination pose while holding (a and b) or being strapped to (c and d) the color-marker object.

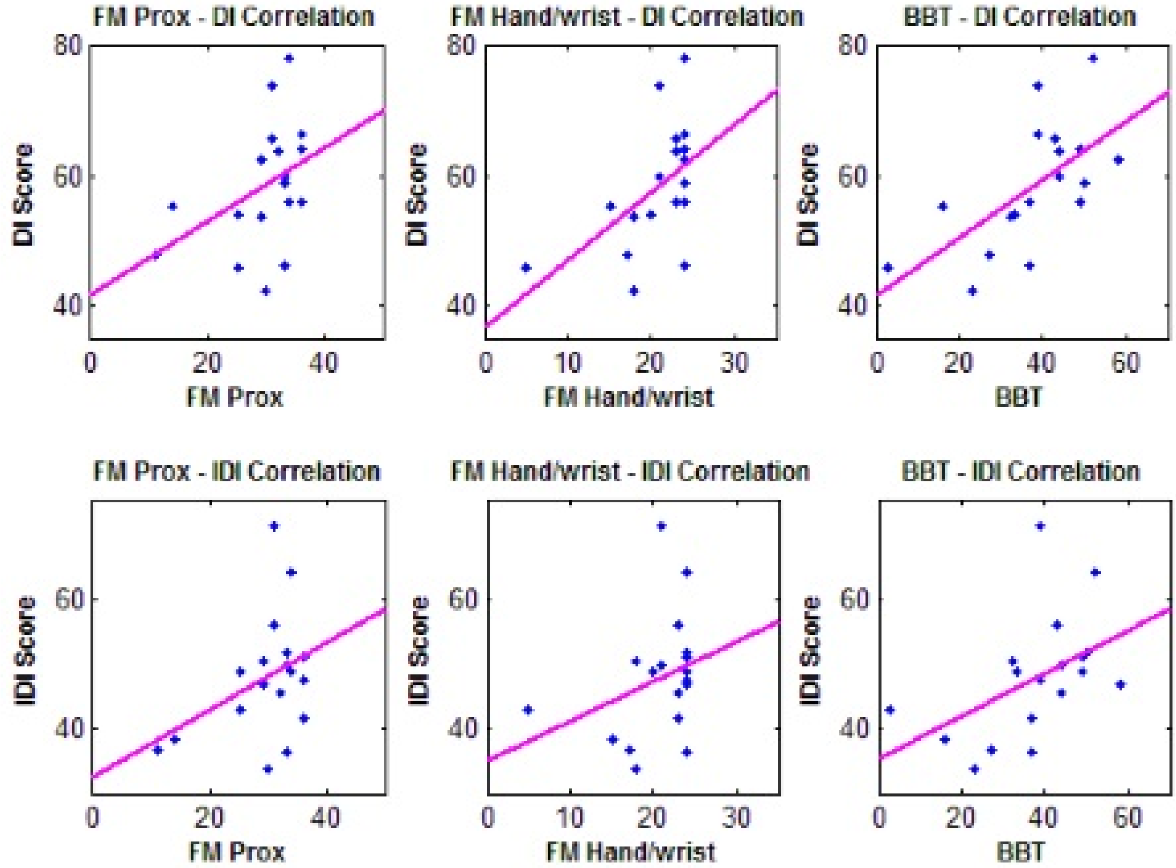


Figure 5.4: The top row shows correlation of DI scores with FMA proximal, FMA hand/wrist, and BBT scores from left to right; the bottom row shows correlation of IDI scores with FMA proximal, FMA hand/wrist, and BBT scores from left to right.

than when the same patients played the same game but using the IDI-based version (48 ± 10 targets, range 34-71). Three secondary metrics were also significantly different between DI and IDI and provided insight into these game scores. Reaching times with DI were 19% faster than with IDI (870 ± 350 vs. 1070 ± 510 msec, p=0.0001). Movement time consistency was better with DI, showing 15% less variability compared to IDI (0.41 vs. 0.48, p=0.0068). In addition, response latencies were 15% shorter with DI as compared to IDI (1.71 ± 0.66 vs. 2.01 ± 0.79 sec, p=0.0249). Visual inspection was consistent with these analyses, indicating that movements during the DI-based game were more consistent and less erratic vs. the IDI-based game (Figure 5.4).

Table 5.2: Behavioral correlates of DI and IDI scores

Behavioral Measure	DI r	DI p	IDI r	IDI p
FM hand/wrist sub-score	0.5635	0.0149	0.3552	0.148
FM proximal sub-score	0.521	0.0266	0.3198	0.1957
BBT score, affected arm	0.6406	0.0042	0.481	0.0433

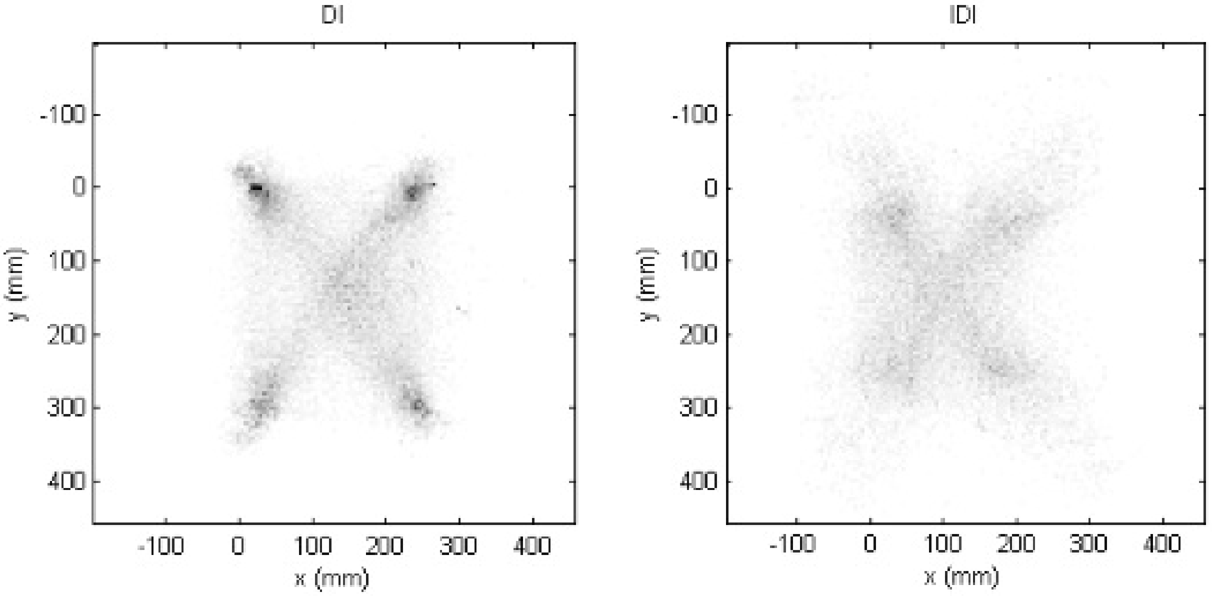


Figure 5.5: Distribution of hand position for all patients playing the [A] DI and [B] IDI versions of the Fruit Ninja game. The target locations and straight trajectories between targets are more prominent in DI. Also, IDI movements are more inconsistent and erratic, consistent with quantitative values for game metrics.

5.4.2 Behavioral Correlates of DI and IDI Scores

DI scores correlated significantly with all four affected arm motor assessments (Table 5.2, and Figure 5.5), particularly the BBT score, while IDI scores were related to motor status in only one instance, and to a weaker degree. If a formal Bonferroni correction is applied to correct for multiple comparisons, only DI scores remained significantly related to motor status.

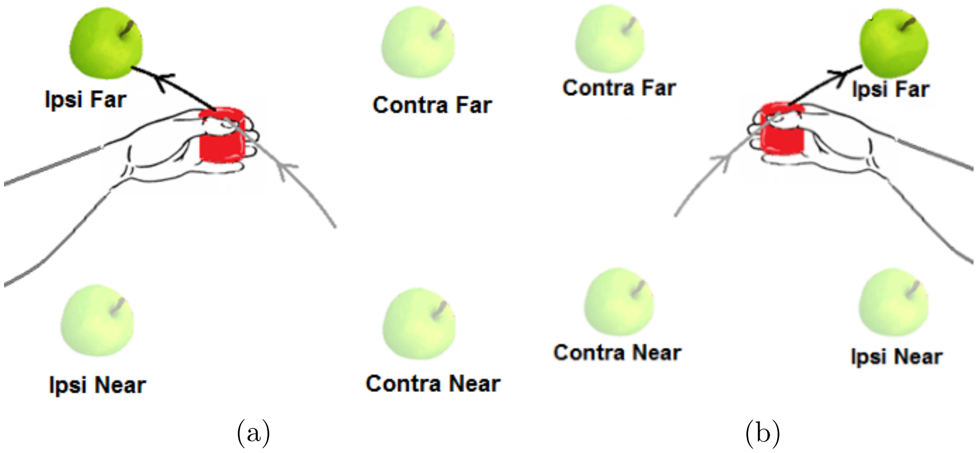
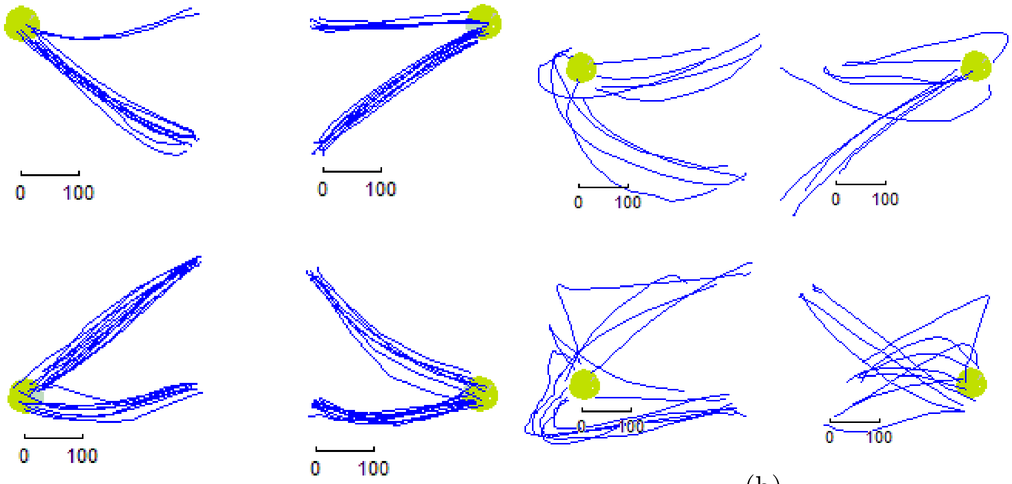


Figure 5.6: The four targets with subject-centered labels from perspective of (a) left and (b) right-hand affected patients.

5.4.3 Motor Performances in Relation to Quadrant of Visual Space

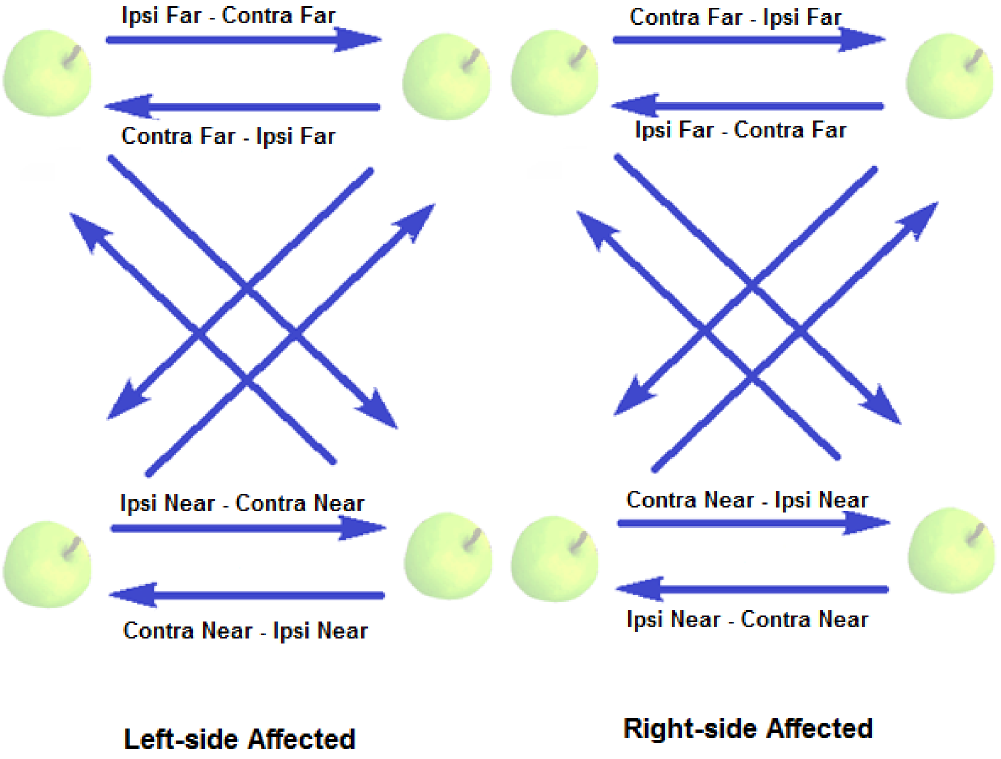
During game play, fruit targets appeared from one of four corners. These were labeled by classifying as either near or far from the body, and as either ipsilateral or contralateral to the stroke-affected arm. During game play with the DI setting, patients with right arm motor deficits (n=12) showed the fastest reaching times when targets appeared in the near-contralateral quadrant, significantly faster vs. targets appearing in any of the three other quadrants ($p = 0.0001$-0.0002). The same was true when patients with left arm motor deficits (n=6) played the game with the DI setting, with reaching times being fastest for targets appearing in the near-contralateral quadrant as compared to each of the other three quadrants ($p = 0.0001$-0.0007). For both right arm and left arm groups, reaching times did not differ in relation to quadrant of space of target origin when the game was played using the IDI setting.

Figure 5.6 illustrates the four targets with subject-centered labels from patients perspective. For example, Ipsi Far for a left-hand affected patient is the target on the top left corner of (a) while for a right-hand affected patient, it is on the top right corner of (b). Figure 5.7 illustrates a patients hand trajectories when separated based on the four targets in DI and IDI settings.



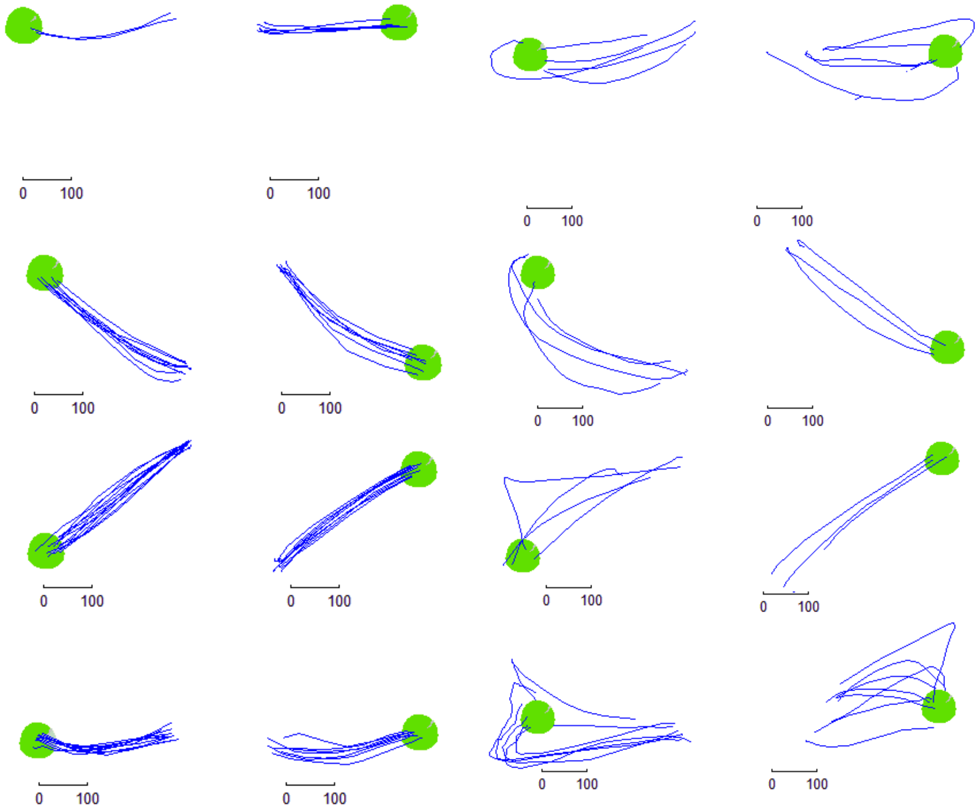
(a) (b)

Figure 5.7: Hand trajectories when separated based on four targets in (a) DI and (b) IDI (the scale bars show 100mm)



(a) (b)

Figure 5.8: The eight movements with subject-centered labels from perspective of (a) left and (b) right-hand affected patients.



(a) (b)

Figure 5.9: Hand trajectories when separated based on eight movements in (a) DI and (b) IDI (the scale bars show 100mm)

5.5 Discussion

In the current study, patients with chronic post-stroke hemiparesis used the affected arm to play the same game (Fruit Ninja) using two different human-computer interfaces, one with IDI and one with DI. During the DI-based game, as compared to IDI, scores were higher, movements were faster and more consistent, and performances were more tightly linked with arm motor status. These differences are likely due to the additional cognitive demands imposed when playing the IDI-based game. Many different types of human-computer interface are available when designing a stroke rehabilitation protocol, and the current findings underscore how different choices influence task demands and thus behavioral effects.

Although movement demands were identical across the two versions of the game, cognitive demands were not. For both versions of the Fruit Ninja game, subjects needed to make movements that required rapid integration of visual and somatosensory inputs [107, 105]. During DI version play, subjects looked directly at their hand as it moved to control gameplay, but during IDI version play subjects instead looked at a computer screen, which increases cognitive demand. This increase in cognitive demand can be understood in terms of a difference in the spatial congruence between movement goal and motor output [36], an uncoupling between eye and hand movements [78], or the imposition of an added sensorimotor transformation [88]. Regardless, the higher cognitive demand associated with playing the IDI-based version of the game reduced game scores by 21% compared with the DI-based version (p=0.0001), associated with slower an less consistent arm movements. Modulations in cognitive demand is particularly important to behavior after stroke, as demand increases having a negligible effect in healthy subjects can exceed cognitive reserve and degrade behavioral performance in subjects with stroke [78, 55, 74, 109].

Although increasing cognitive demand in the IDI-based game reduced movement quality (lower scores, slower reaching, less consistent movement), in some cases this might nonetheless be a preferred approach to rehabilitation given the increased emphasis that the IDI game provides on visuospatial skills. The brain constructs a stable spatial representation of the workspace environment [35], transforming hand and target positions into a common body-centered space [27, 37, 108]. The DI game exists in this same space–spatial transforms for game play are the same as those used during real world activities–but the IDI game plays out on the computer monitor, which has its own coordinate space. As such, with an IDI-based approach, the patient must perform at least one extra spatial transform to convert the virtual world's coordinates into body-centered coordinates. An IDI approach may thus be useful to promote cognitive recovery after stroke. Furthermore, increased cognitive demand modulates activity in brain motor networks and can enhance motor learning in healthy subjects and in subjects with stroke [120, 117, 30, 32], and so might be a desired feature for some types of motor rehabilitation. Therefore, future studies might test the hypothesis that sustained practice of the IDI game, as compared to the DI game, may be associated with greater motor recovery after stroke.

5.6 Conclusion

Advances in technology are providing many new types of computer interface to promote brain repair after stroke. The current study examined two forms, IDI and DI, incorporating the popular Fruit Ninja game into each. An IDI approach to gaming substitutes a virtual environment in place of the real world [13], directing the subject's attention towards the virtual world (here, the computer monitor) rather than to the real world (here, the paretic hand as it moves towards across the table) [61]. A DI approach to gaming overlays computer-generated virtual objects into the real world. Such real world activities may be more intuitive than many IDI-based approaches, which might promote massed practice. A DI approach may also allow patients to practice real-life functional tasks safely, for example, a patient might work on being independent in the kitchen by working with computer-generated objects and thus with zero risk of spilling, burning, or electric shock. On the other hand, an IDI-based approach might nonetheless have advantages, for example, to promote recovery of visuospatial skills, or by using modulation of cognitive demands to promote motor recovery. The optimal choice of human-computer interface varies across individuals, over time, and according to specific goals. The current study provides insights into how different human-computer interfaces affect motor performance and thus might influence motor recovery and motor skill acquisition after stroke.

Since DI proved to be more effective for training of patients, we are going to use it for developing neruo-games in next chapter.

Chapter 6

Neuro-game and System Design to Improve Cognitive Control

This chapter describes collaborative work under publication. My role in that project was design and development of neuro-games, implementation of the AR platform, conducting pilot studies, statistical data analysis, and writing the paper.

6.1 Introduction

New therapies for stroke rehabilitation have taken advantage of advances in computer and robotic technologies. One area of particular interest is that of computer games, as they have the potential to make physical and neural rehabilitation more engaging than traditional rehabilitation procedures, therefore leading to potentially more efficient therapies. Over the past several years, we have been designing and assessing such games with stroke patients. We developed our games using a projector-based platform and conducted pilot studies to evaluate these therapies. This study focuses on the many issues of game design for this particular population: stroke patients. Designing games for this group is considerably different than designing games for general entertainment. Specifically, the design of these games has concrete objectives such as improvement of motor and cognitive control that are not important for healthy gamers. As such, game design needs to be informed by a deep knowledge of specific areas of the brain that play a crucial role in cognitive control, and the physical movements in the game need to stimulate those areas. We contribute a new perspective to game design by considering the brain's neuro-anatomical function, given specific objectives. Also to evaluate our study, we report on a patient with stroke results before and after training with neuro-games.

6.2 Background

Previous studies on games for patients with stroke targeted theoretic aspects of rehabilitation. Alankus et al [5] developed a method to sense compensatory torso motion. Hocine et al [48] proposed a game adaptation technique that sought to improve the training outcomes of stroke patients during a therapeutic session. Xu et al [127] developed a virtual reality Ten Pin Bowling game to create a simulated environment for the patients with stroke to retrain their motor function. Also, there is a wide spectrum of games designed for stroke rehabilitation which mainly tried to leverage technology that tracks body movements and reactions [94, 60]. The scope of this study differs from above works in the sense that it explores largely cognitive and motor skills.

A few studies looked into controlling game variables to encourage cognitive control. For example, Taheri et al [113] modulated the subject's success rate at the game to stay at a hypothetical optimal challenge point which results in highest gain. Gazzaley et al [8] investigated the neurobiological correlates of more effective cognitive control techniques. They showed that there is a difference in EEG of younger vs. older adults which may explain their different performance in standard tests. When they trained the healthy elderly subjects with multi-tasking neuro-games, their EEG patterns resembled those of the younger adults and they showed significant gain in standard cognitive tests which also remained for the next six months. Cramer et al. [125] showed that cortical connectivity between specific areas of the brain, namely prefrontal, pre-motor, parietal, and primary motor cortex in healthy young individuals plays an important role in their motor learning capabilities. Building on the work of Gazzaley et al [8] and Cramer et al. [125], we focus on the same areas of the brain to study game-assisted learning in patients with stroke. This paper focuses not on the clinical assessment of our game-based therapies, but on the game design decisions that have been made along the way. We report on the lessons we learned on what makes games useful from a neuroanatomic learning point of view. We believe the insights gained during this design process can inform many others designing games for specific groups of users, especially those with disabilities.

6.3 Method

Our design process follows Delft design approach [9] with the following steps: (i) context of use, (ii) defining the design challenge, (iii) generating ideas, and (iv) evaluating and testing the concept. We discuss the first three steps in this section. The last step will be discussed in the result section.

6.3.1 Context of Use

Traditional robotic and computerized rehabilitation solutions [49, 58] are designed to engage and entertain patients and provide clinicians with information for objective assessment. However, they lack the advantages of targeting specific parts of the brain which are found to

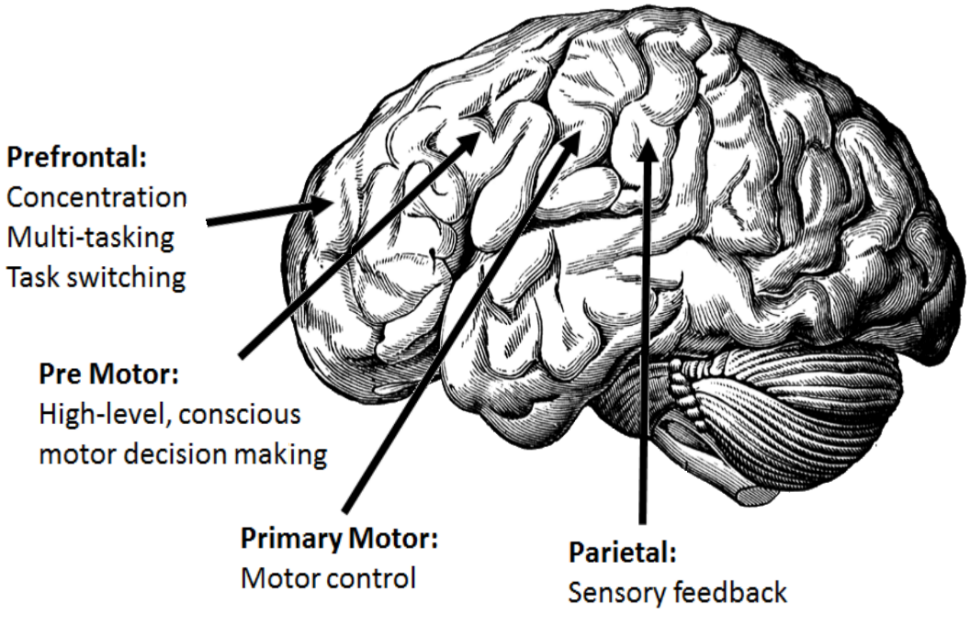


Figure 6.1: Areas of interest in the brain

be crucial in motor learning and cognitive control [125, 8]. Over the past several years, we have been designing games to activate four areas of the brain: (i) prefrontal, (ii) pre-motor, (iii) primary motor cortex, and (iv) parietal areas (illustrated in Figure 6.1).

Although the neuroanatomical functions of these brain areas are subject to debate, in the context of our study, we rely on the consensus of opinions among neuroscientists [46, 90, 91] which relates the tasks in Table 6.1 to the above-mentioned areas.

Game Platform

Since our work involves installation of a tele-rehab platform in patients' home, the platform has to be inexpensive, portable, and easy to setup/operate with minimal to no assistance. We used a projector-based platform to support direct interaction while playing the games. The setup consists of a projector that projects virtual entities on a tabletop as well as a camera that tracks patients' hand movements. Figure 6.2a shows the setup. We built a

Table 6.1: Brain areas of interest, their corresponding functions and game requirements

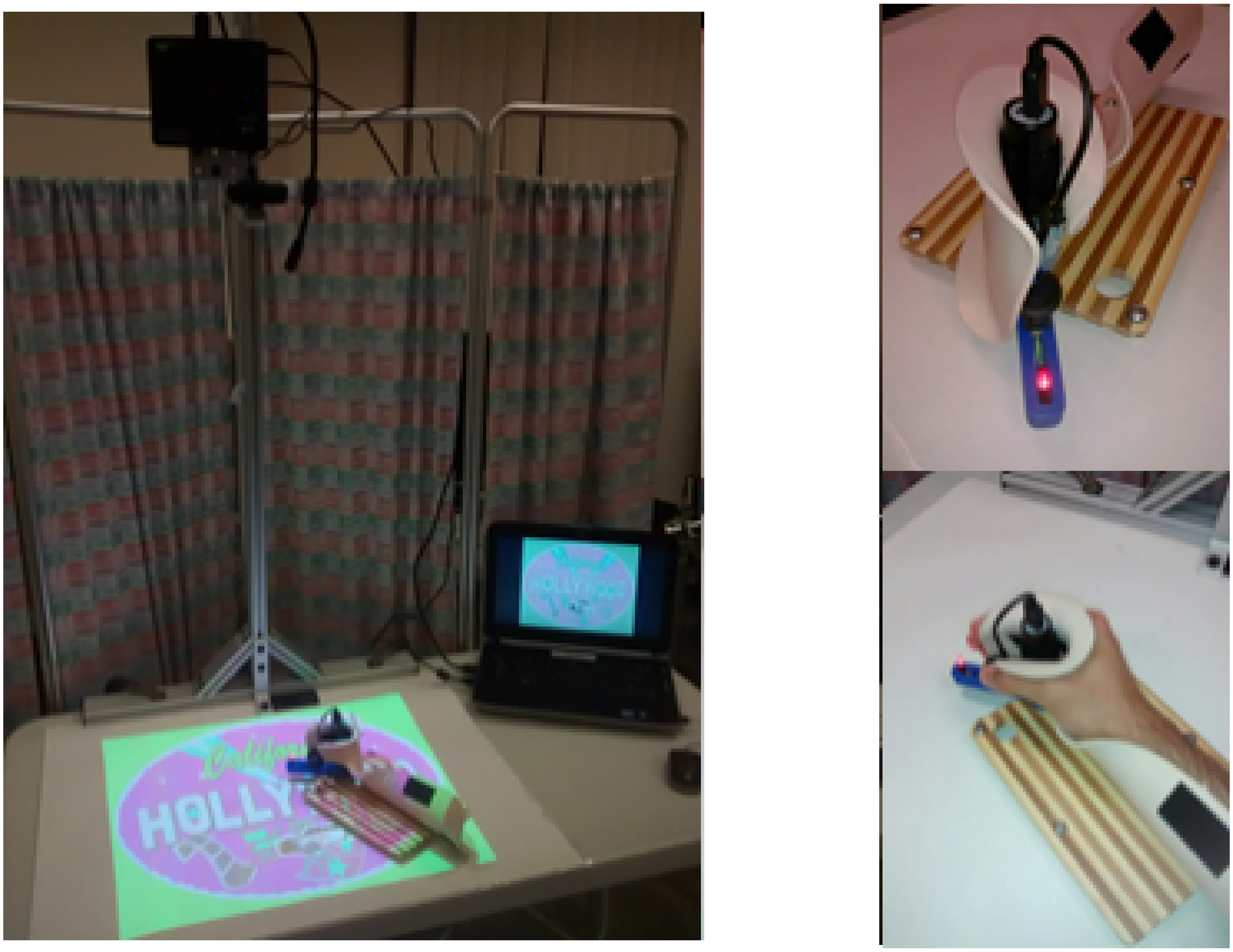
Brain area	Function	Game requirement
Prefrontal	Concentration Multi-tasking Task-switching	Selective attention Concentration
Pre-Motor	Conscious decision making for movements	Decoding visual clues Obstacle avoidance
Primary motor cortex	Execution of movements	Goal-directed upper limb movements
Parietal	Fusion of visuospatial feedbacks	Visuospatial transformation

splint unit (Figure 6.2b) for patients to help them with smoother movements across the play-area without having to bear their hand's weight. The splint unit includes a rolling board with four wheels beneath it to facilitate movement, a battery-powered LED for the camera to track, and a wrist splint to help patients maintain neutral supination/pronation wrist posture. Therefore, all movements fall on shoulder plus a bit of elbow.

Training Program

The goal of the design is to develop games that lead to both behavioral and neurological improvements. In order to assess whether the goal was achieved or not, we designed a study that have patients play the games for one week, measuring specific behaviors before and after that week. The entry criteria is to have medium control of the upper limb (i.e. BBT score of 3 or more). The patient is admitted on the first day of the week, i.e. Monday morning.

Assessing whether the games meet the goal for which they were designed is a non-trivial task. There are two batteries of tests namely pre-training and post-training which are identical in order to show improvement, or lack thereof. In both pre- and post-training phases, we use three standard tests: (i) Resting-state EEG [125], (ii) Box and Blocks Test (BBT) [87], and (iii) Trail test (Trail A) [96]. These are well-established procedures that can give an accurate state of the patient. Additionally, we carefully designed two other tests: (i) speed test, and



(a) (b)

Figure 6.2: (a) AR game setup, (b) splint unit to ease patients' hand movements on tabletop

(ii) tracking test. The former is essential to initialize the games with a patient-customized speed only performed during pre-training phase while the latter is a baseline assessment to observe behavioral changes performed both pre- and post-training.

After pre-training tests, the patient is trained on the usage of the system. Our staff members monitor how the patient plays the first 30-minute session which includes all games. Each game lasts around 3-min and there is a 2-min break in between. In the afternoon , the system is delivered to the patient's home. Then the patient undergoes the 2nd session of games under supervision of one of our staff. This is to ensure that everything works smoothly at the patient's home and the patient has no issue regarding operating the setup and playing the games. During the next 3 days, i.e. Tuesday, Wednesday, and Thursday, the patient plays two sessions of the games, with at least a 4-hour break in between sessions. We enforced this condition in the system so the next round cannot be started with less interval. Note that the order of games is consistent across the system and all patients.

On the last day of the week, i.e., Friday, the patient is admitted in the lab again and performs post-training tests which include tracking test, trail test, BBT, as well as a resting-state EEG similar to pre-test phase.

There are a lot of factors to determine why we run the study as explained above. We refer our readers to [93] for further information since the current study follows the same protocol. For instance, the 30-minute practice time, one-week duration of home-based therapy, and other factors were selected based on previous experience with similar studies to ensure observance of both behavioral and brain-activity change.

6.3.2 Subjects

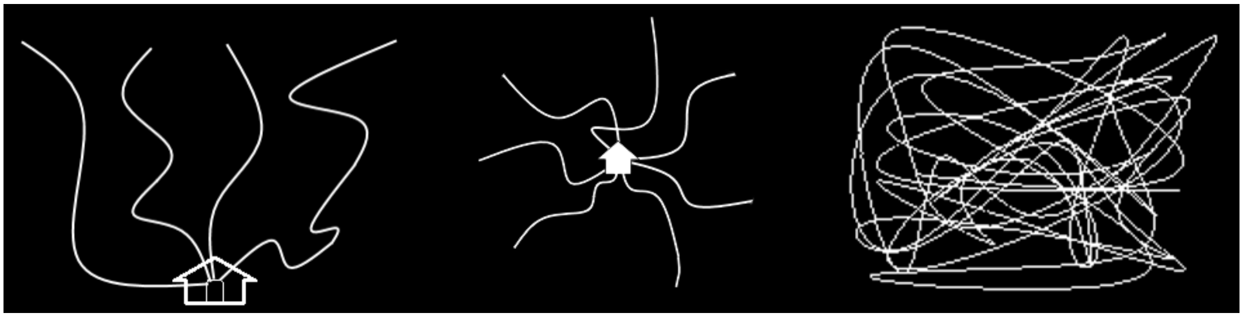
We recruited four healthy subjects (one female and three males) as well as one patient with stroke (male). We used our healthy subjects' results during formative evaluation to examine functionality of our platform and games. Later, we used the data of our patient with stroke for clinical validation of our study.

6.3.3 Design Challenge

We want to develop games that work on visuospatial tracking skills of patients with components of decision making and obstacle avoidance. To motivate patients continue playing, we needed to develop several games to ensure patients wouldn't get easily bored. For the visuospatial tracking, we needed to come up with some game ideas to have patients follow a moving target as close as possible. However, given the disabilities of these patients, in our design, we had to consider the following criteria:

- What is the size of the play-area?
- What is the tracking target?
- What is the size of the target?
- What is the game piece controlled by the patient?
- What is the size of the user-controlled object?
- What is the speed of the moving target?
- What is the trajectory of the moving target?
- What constitutes success?

Beside the above-mentioned factors, games should be engaging and fun. They should also be similar in terms of cognitive requirements (i.e. visuospatial perception) because this study aims at enhancing this capability of patients with stroke that is controlled by parietal area. Some of the games should also incorporate decision making and obstacle avoidance controlled by premotor area. Multi-tasking, controlled by prefrontal area, has been proved to help significantly with cognitive control improvement [8]. All of our games require coordinated movements which encourages coherence between primary motor cortex and the above-mentioned brain areas.



(a) (b) (c)

Figure 6.3: Different designs of game trajectory

6.3.4 Generating Ideas

We had a team of researchers with computer science as well as medical backgrounds. We met weekly to brainstorm ideas and discuss progressively generated pilot results.

Game Trajectory Ideas

All games are based on trajectories that were generated in a pseudorandom fashion. We started off with simple trajectories such as circles which were predictable and therefore could affect patients' performance. We then tried forward and backward paths to and from a home port (Figure 6.3a) which wastes time in the backward path. We then moved to center-out complex trajectories from a home port (Figure 6.3b) similar to but more complex than those used in robotic studies [103]. The problem with these trajectories was that they were anticipatable and not usually crossing the center-line making subjects waste a lot of time at the home port. Finally, we developed non-predictable pseudo random continuous paths (Figure 6.3c). These trajectories proved to be suitable for the task of visuospatial tracking as we planned.

When designing the trajectories, there were other issues to consider as well. For example, weight of elbow poses extra shoulder work when hand is in the space near one's body.

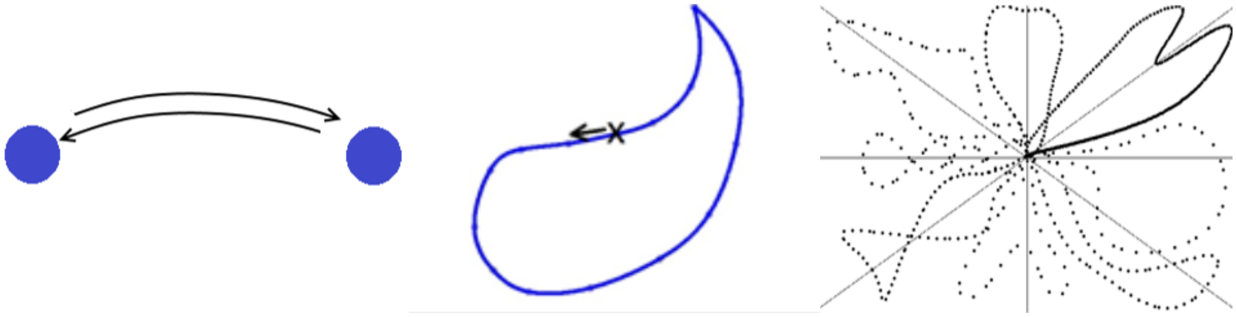
Therefore, we designed the splines of trajectory such that percent time that one plays in the space near the body is lower to prevent shoulder muscle fatigue. Also, the splines were generated such that the hand does not cover the target as it moves around the play-area.

We also needed to adjust target speed in trajectories based on the average maximum speed of each patient based on the findings of Wu et al [125]. However, we advanced their method to minimize the subjectivity of the test. We then initialized the games according to the measured speed. Our pilot study showed that this speed needs to be increased by a small percentage (i.e. %5) to maximize the effect of learning as measured by the tracking test pre- and post-training.

The main question was how to design a speed test that shows subjects' maximum functional arm speed. We went through so many iterations of prototyping and evaluating through pilot studies to come up with a proper test that can output a reasonable arm speed for each subject.

As a first step, we studied previous work on the same topic. Wu et al [125] asked subjects to move between two circles at the right and left sides of the play-area as fast as possible over 10 seconds as shown in Figure 6.4a. Our pilot study with four healthy individuals showed that this design does not reflect the true speed level of subjects to be used in the games because this task does not require movement accuracy while the games do. Also, the subjects' freely-chosen paths across the play-area did not resemble the similar level of complexity required by the games.

In our second design, we developed a more complex trajectory-based speed test which required following a curvilinear path for five laps; the subjects were asked to move along the perimeter of the shape shown in Figure 6.4b as fast as possible. We repeated the pilot experiment on our four healthy subjects and learned that they challenged themselves to different levels which differed from their game performance. For example, we observed that a



(a) (b) (c)

Figure 6.4: Difference designs of speed test

Table 6.2: The game characteristics

Gameitem	*Specification*
Play-area size	2x2 feet
Target object	Game-customized
Target size	2x2 inches
User-controlled object	Game-customized
User-controlled object size	2x2 inches
Target speed	Patient-customized
Trajectory	Pseudo-random splines
Success	50% overlap between target and user-controlled object

subject with low speed during this test, showed significantly higher functional speed during the games. This could be attributed to the self-paced nature of the test and the difference between the complexities of the trajectories.

Finally, we designed an objective speed-test with similar cognitive and motor demand to the games as shown in Figure 6.4c. In the final test, the subjects were asked to track an object with increasing speed moving on an unpredictable trajectory as accurately as possible while we recorded their performance and found the speed at which they failed. Figure 6.5 illustrates that each of the four subjects started with a maximum accuracy and as the speed increased, their accuracy fell. We fit a sigmoid curve to the accuracy-speed graph to find the speed at which the subjects showed 60% of their personal maximum accuracy. This number was selected after iterative pilot studies.

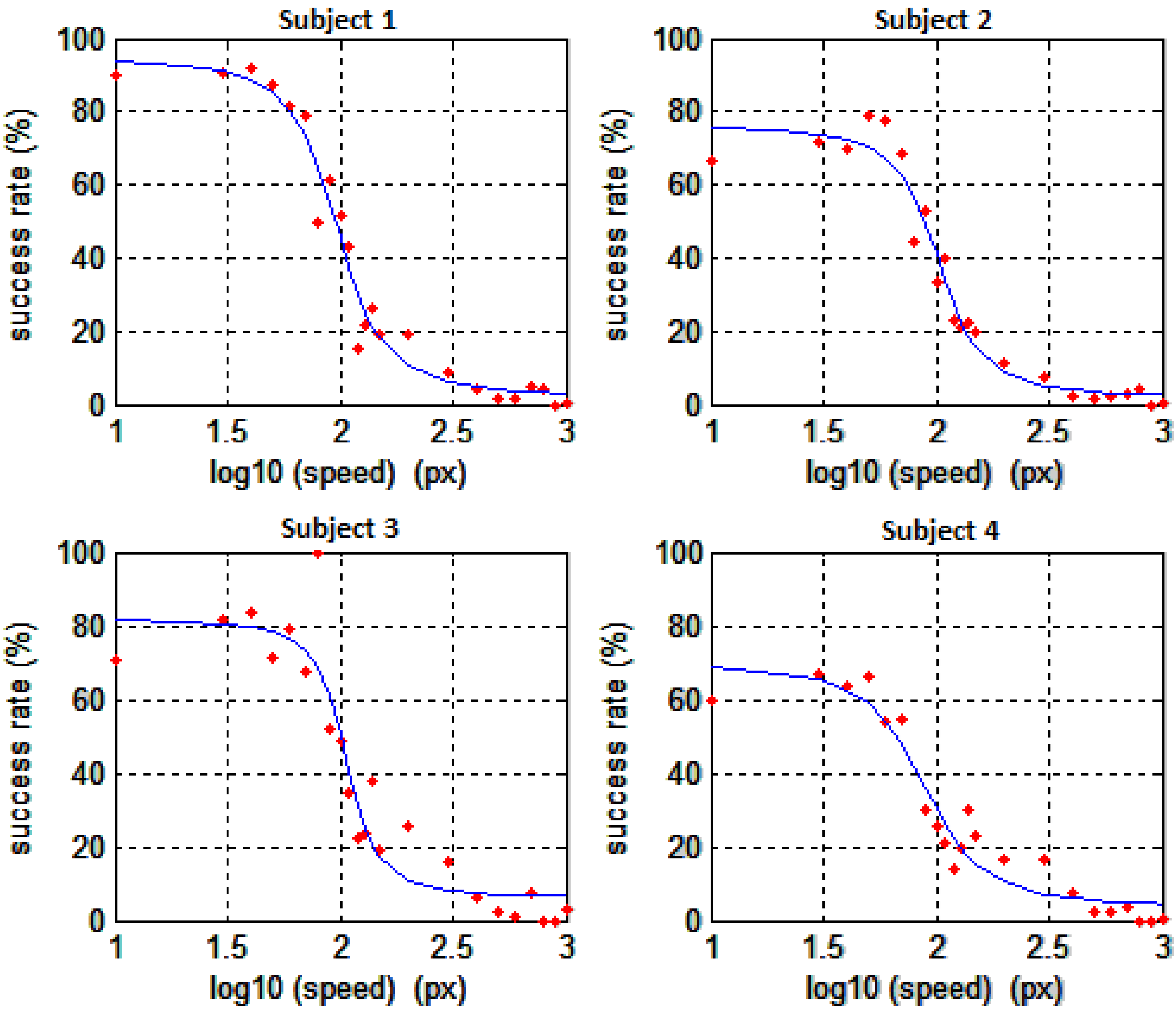


Figure 6.5: Speed-accuracy trade-off on four healthy subjects

Game Ideas

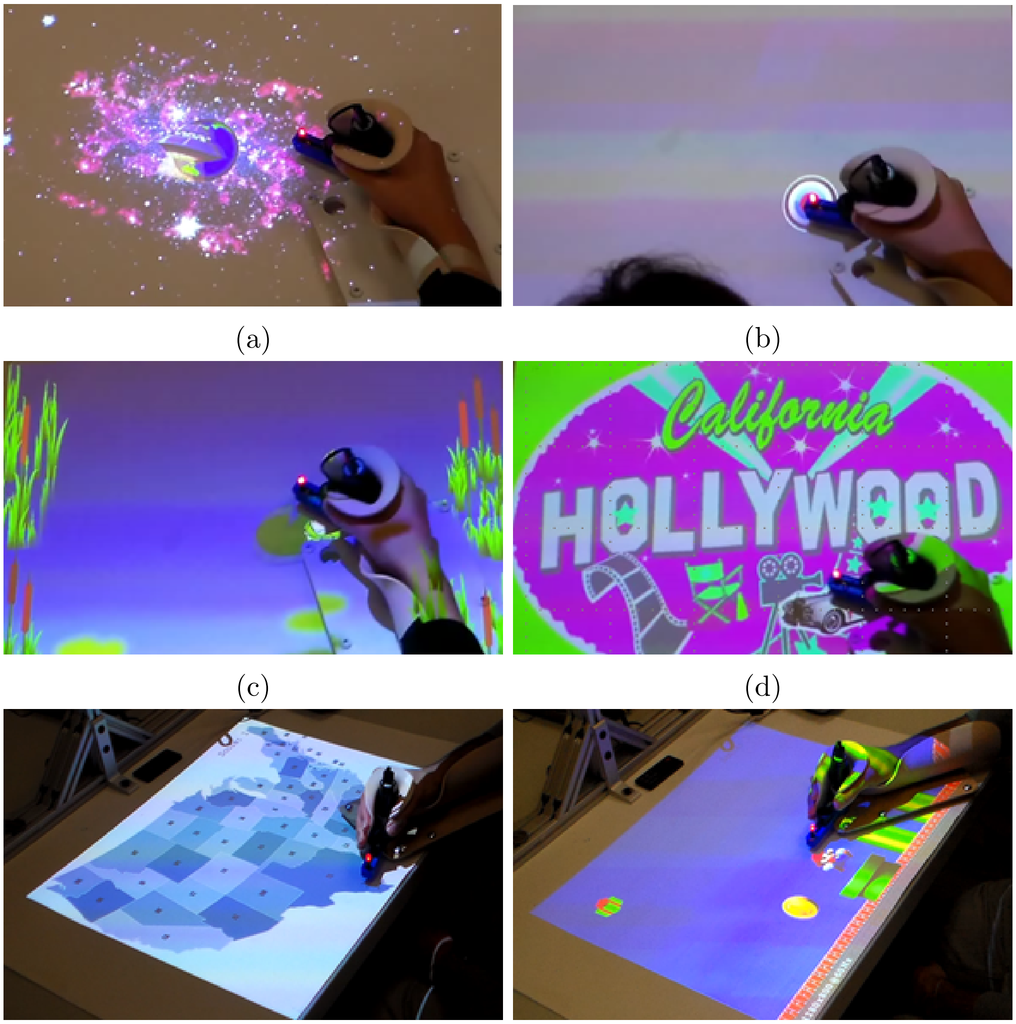
Designing process for the games was iterative; we went through many versions and based on multiple pilot experiments, we concluded our findings in Table 6.2.

We wanted the games to challenge cognitive and motor abilities of the patients yet be engaging and fun. A few examples of the early game ideas that were piloted are as follows:

Candy Hunt game has a candy as target which moves along a fast, speed-varying trajectory and the player chases it as close as possible by controlling/moving a frog which is projected on top of the LED shown in Figure 6.2b. This game requires high moderate to high cognitive effort.

Calligraphy has a black circle as target that moves along a speed-varying trajectory that forms a word in cursive font; the player chases the circle as close as possible by moving the LED. At the end of each round, the player can see the written attempt compared to the model. This game requires moderate cognitive effort. After the early pilots, we learned that there could be different preferences across different games and players. For example a game could require fast with low accuracy movements or slow with high accuracy movements. We also learned that both cognitively intense games as well as lighter versions are needed. We needed to offer consistent instructions across all subjects in form of a brief ($\leq 10s$) audio-visual recording. Although, we originally started with a lot of informative visual cues in the games, we noticed they could mislead the player. Therefore, we kept minimal number of visual cues necessary to follow the games.

Also having little pop-up surprises kept people focused and engaged. We also noticed that it is important to distribute trajectories equally among four quadrants of the play-area. Changing the difficulty of the games a bit (e.g. %5 increase in the target speed) to keep subjects engaged showed helpful in our pilots. The above lessons helped us modify the existing games to improve the training.



(a) (b)

(c) (d)

(e) (f)

Figure 6.6: Games: (a) Space invaders, (b) Etch a sketch, (c) Alligator Bite, (d) Paparazzi, (e) Soaring over the US, and (f) Mario adventure

6.4 Results

6.4.1 Designed Games

Our design process led to development of six games namely Mario Adventure, Soaring over the US, Space Invaders, Alligator Bite, Etch a Sketch, and Paparazzi based on the game requirements in Table 6.1.

In the following, we describe the game titles as well as the instructions to play them. While reading the instructions, notice that in all games, there is a target moving along a trajectory. The player needs to follow the target as accurate and fast as possible. This ensures training of players on their visuospatial tracking skills. Most of the games have a surprise pop-up component customized based on the game story to avoid losing players' concentration. Also in two of the games, i.e. Mario Adventure and Alligator Bite, we included component of decision making and task switching. Fig. 6.6 shows a snapshot of each game.

Space Invaders *Follow the spaceship until it explodes. Place the LED light on top of the spaceship and continue to follow its path. If done properly, the spaceship will eventually explode and if not, an alien will invade and appear on the spaceship. The score at the end of the game will displayed as Star Wars medals of honor.*

Etch a Sketch *Place the LED light on top of the bull's eye. Follow the bull's eye path. There will be a total of 3 rounds with different images to be drawn. At the end of each round, the model image will be on the left and the drawn attempt on the right.*

This game is slow and precise. We tried to have good amount of side loops in shapes and occasional variable speeds while keeping the slow and careful paradigm. Also, for each round of this game, a random shape is selected to avoid prediction of trajectory by subjects. Figure 6.7 shows the database of shapes that our software chooses from.

Alligator Bite *Have the frog follow the lily pad, but avoid alligator when it appears on the lily pad. The LED light will be the frog. The frog will gain points when on top of lily pad and if done properly, the lily pad will bloom into a lighter green color. Towards the bottom center of the screen, there is a lug that will randomly display a butterfly with a bubble sound that will signify the alligator's appearance. If this happens, the frog must avoid the alligator*

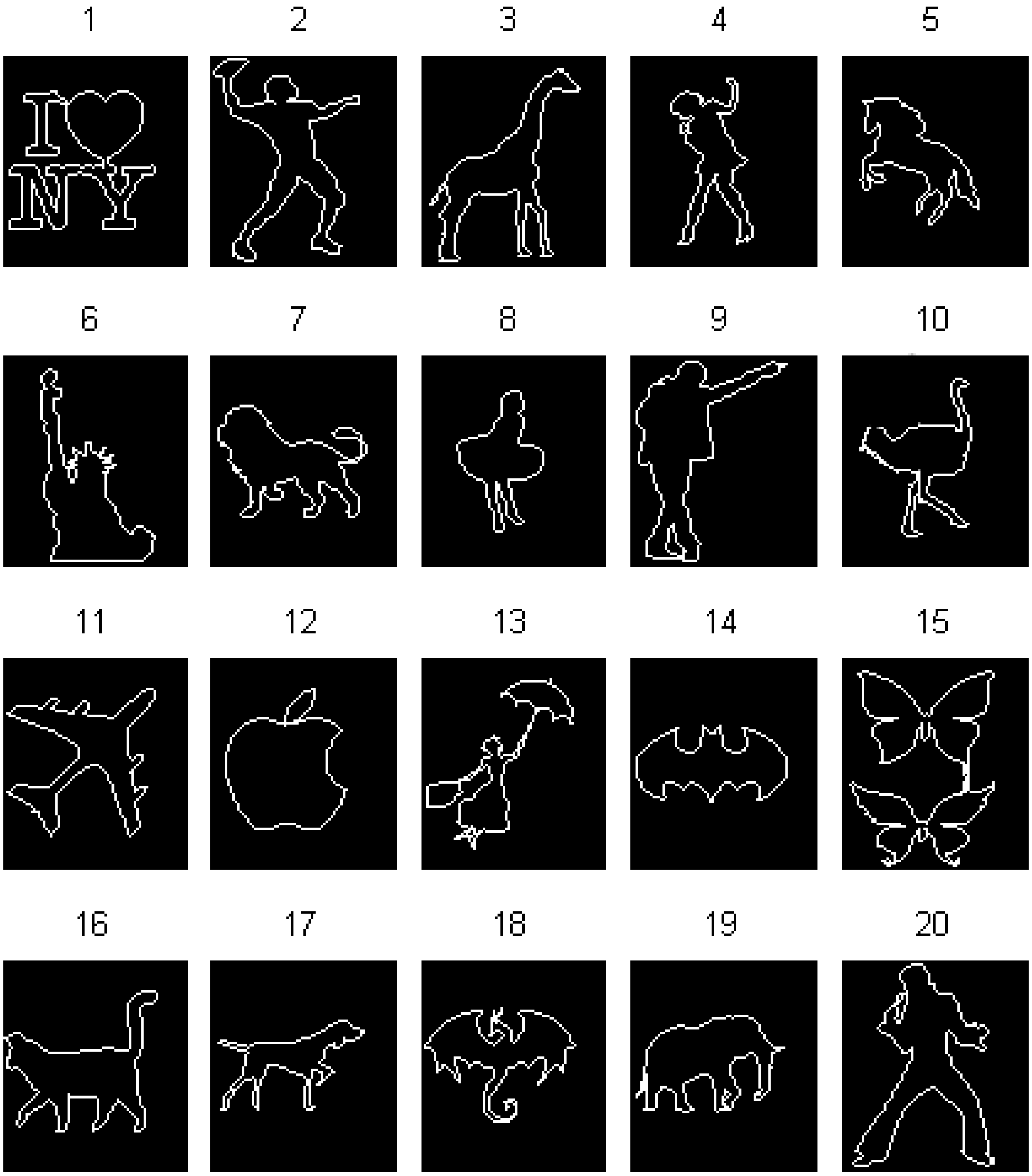


Figure 6.7: Database of images for ”Etch a Sketch” game

on the lily pad until it disappears. The lug is a safe place for the frog to hide from alligator. The score at the end of the game will be displayed as butterflies.

Alligator Bite has a moderate cognitive complexity.

Paparazzi *Follow the limo to try to capture a picture of the celebrity insides. Place the LED light on the center star of the limo and continue to follow its path. If done properly, the limo will light up bright yellow and eventually an image of a celebrity will appear on the screen. The score at the end of the game will be displayed as Oscars depending on accuracy.*

Paparazzi is a high in fun game with moderate demand.

Soaring over the US Follow the helicopter around the map to reach a destination. Place LED light on top of helicopter at all times. If done properly, the propellers on the helicopter will spin. Once the helicopter reaches a destination, a slideshow of attractions relative to the location will begin when the music starts. The score will be shown as US flags depending on the accuracy.

Mario adventure *Control Mario to try to collect as many coins as well as avoiding the red villain when present. The LED light will be Mario. Mario needs to follow the yellow coin for points. On the top region of the screen, there is a mystery box that will make a popping sound right before either a sack of coins or red villain will appear. Manoeuver Mario to follow the sack of coins to gather extra points and be sure to avoid the red villain if he appears instead. The score at the end of the game will be shown as gold coins.*

Mario adventure is cognitively the most demanding game. We've ensured that arm never obscures any of the targets. We modified the game such that it is less crowded in terms of objects to follow than normal game. Also, we changed the box trajectory to move further from coin so they never cross paths. Same for the brown shells, we kept them a bit from coin. The warning dots are also much more visibly salient like an explosion to make it easier for patients to catch.

6.5 Evaluation

Throughout our design process, we conducted several single and multi-session for formative evaluation. We used their results to come up with a proper game trajectory as well as speed to initialize the games. We also used their results to modify our game design ideas. However, our main baseline measure is a tracking test that is particularly helpful to measure the patient's improvement. The tracking test was conducted at baseline and at the end of training, and it is the behavioral outcome measure that we look into to assess improvement in performance. Compared to the games, this test requires similar cognitive demand on patients i.e. their visuospatial perception and coordinated upper-body movements. The trajectory used in this test is similar to Fig. 6.3c. The test comprises of tracking a bullseye on a pseudo-random trajectory. The performance metric is the distance between center of the target (i.e. bullseye) and center of the LED representing the subject hand position.

In the following, we report on pre and post-training results of our patient with stroke who underwent training for one week. First, we look at error and success rate of her performance in four of the games during the whole training. Then we show error visualization of her performance comparing the very first and last session of her training.

6.5.1 Error and Success Rate

Figures 6.8, 6.9, 6.10, and 6.11 illustrate error and success rate of the patient for the following games respectively: Space Invaders, Etch a Sketch, Paparazzi, and Soaring over the

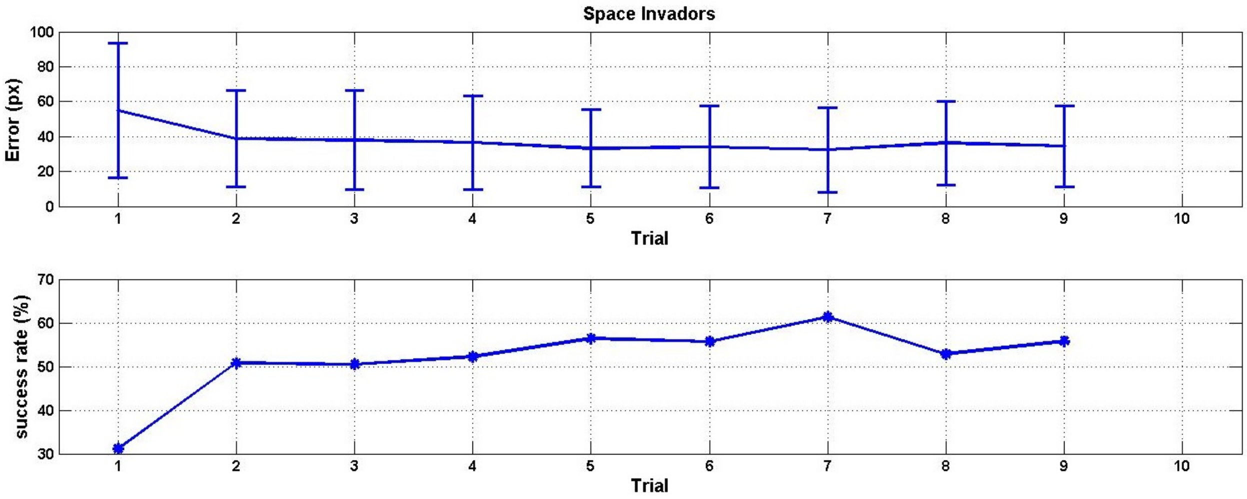


Figure 6.8: Error and success rate of the patient in "Space Invaders" game

US. The other two games, i.e., Mario Adventures and Alligator Bite have obstacle avoidance components which prevents us to analyze their error and success rate due to confounding variables. For these two games, we were mainly interested to have patients train on task switching/obstacle avoidance skills. Therefore, EEG results will cover the effect of this training.

As can be observed in the all mentioned figures, error reduces and accordingly success rate increases from session one to ten, showing improvement of the patient throughout the training program. The only different observable trend is Etch a Sketch game. The performance of patient does not show consistency. This is due to difference in complexity of sketches that are given to the patient on each round of the game.

6.5.2 Error Visualization

Figures 6.12, 6.13, 6.14, 6.15 illustrate error visualization of the patient for the first and last session of training for the following games respectively: Space Invaders, Etch a Sketch, Paparazzi, and Soaring over the US. In order to plot these graphs, we draw a circle at the

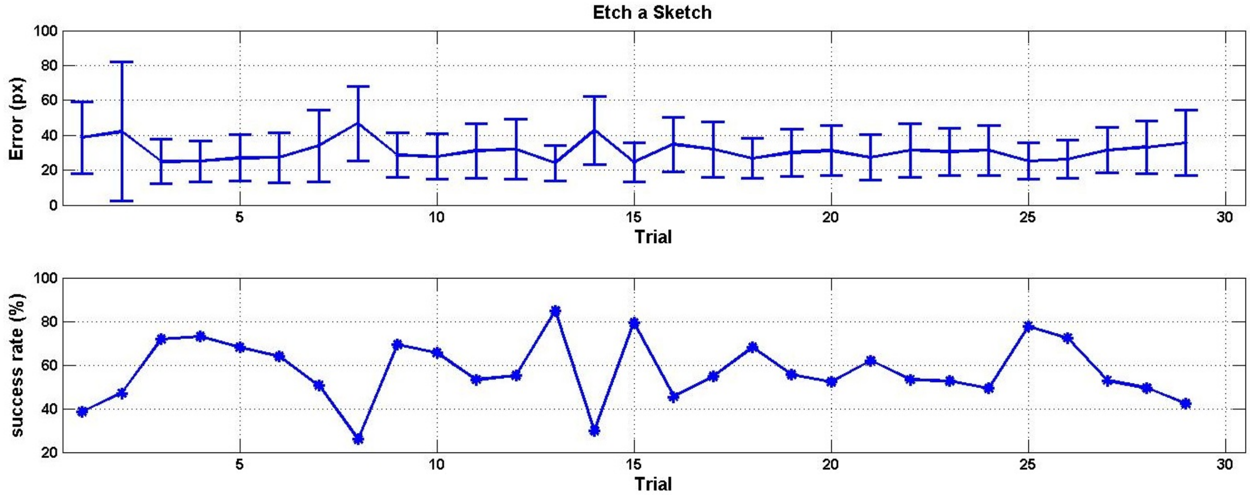


Figure 6.9: Error and success rate of the patient in "Etch a Sketch" game

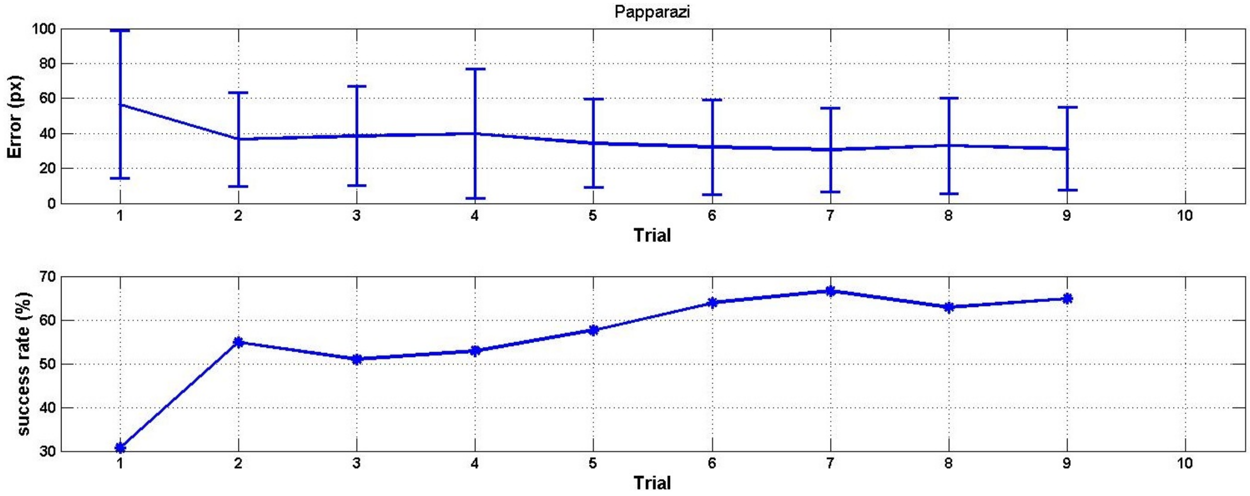


Figure 6.10: Error and success rate of the patient in "Paparazzi" game

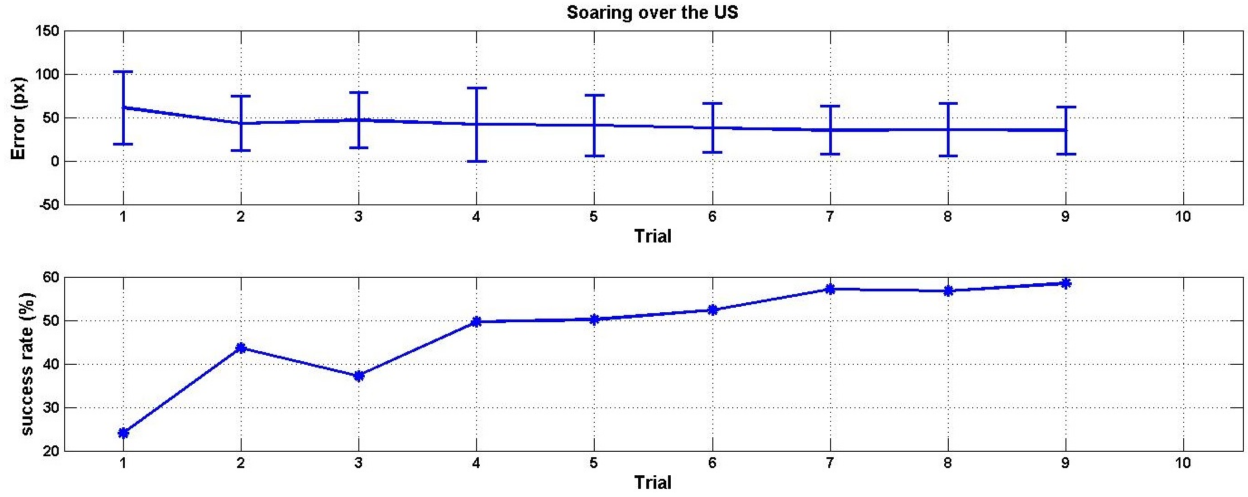


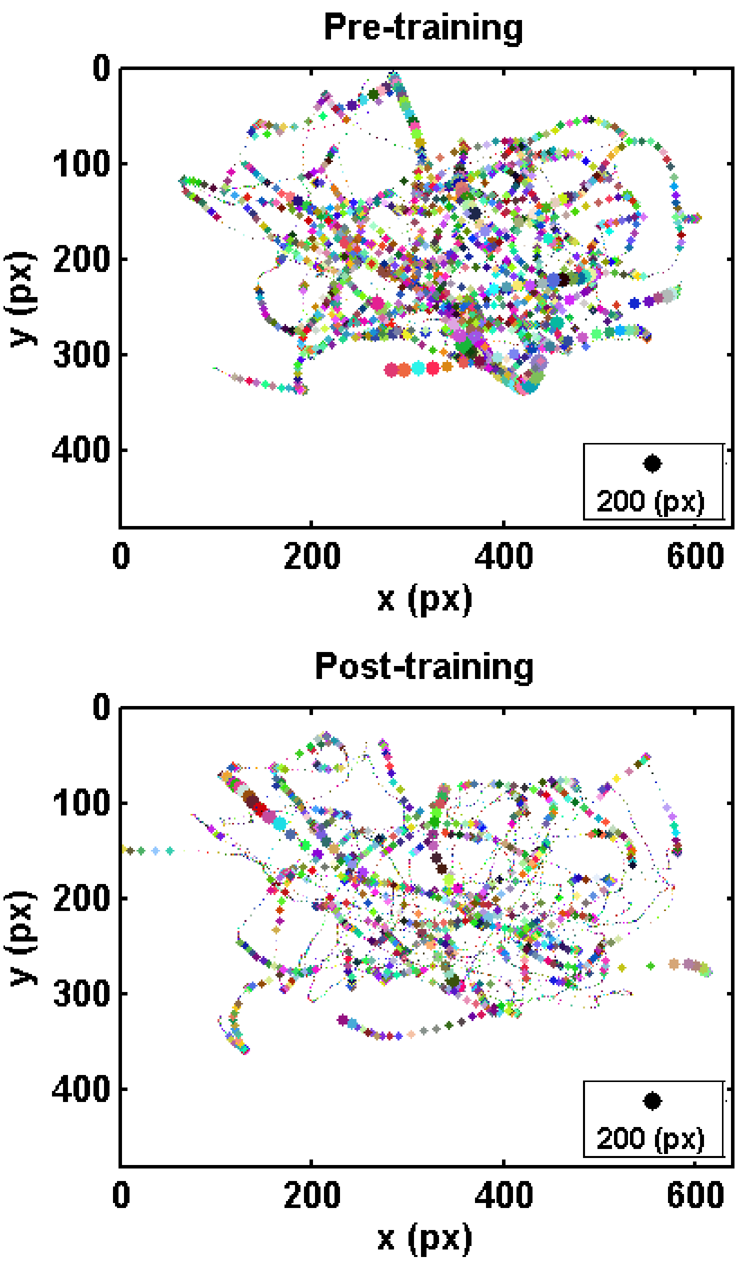
Figure 6.11: Error and success rate of the patient in "Soaring over the US" game

center of the LED position (i.e. representative of patient's hand position). The radius of the circle at each point depends on the error of the patient at that specific point, which is the euclidean distance between center of the target and the LED position. As can be seen in all the mentioned Figures, circles of the post-training test are notably smaller than the pre-training test, showing improvement of the patient.

6.6 Discussion

We report on the lessons we learned on what makes games useful from a neuroanatomic learning point of view. First, to design games with therapeutic purposes, we should make sure that games are fun and engaging for patients to play. Games should be customized to meet personal capabilities of patients. During training program, games should be adjusted based on patients' progress to keep them challenged and avoid losing their interest.

Second, during our pilots, we learned that both cognitively intense games as well as lighter versions are required because each group contributes to improvement of different levels. Briefing patients on how to play the games in form of a short audio-visual recording that is repeated before each round of the game is beneficial; we observed that in many cases, the patients confirmed understanding the rules of a game, however, they could forget the rules in the next rounds. Too many visual cues in the games tended to mislead players instead of helping them. Having little pop-up surprises keeps patients focused and engaged which keeps their prefrontal and pre-motor areas active. Trajectories should be distributed equally among quadrants of the play-area to ensure fair comparison amongst patients, especially due to visuospatial neglect present in some patients with stroke. Changing difficulty of games a bit (e.g. %5 increase in the target speed after each session) can keep patients engaged; this is critical to maintain the learning level of patients during the training program.



Pre-training

Post-training

Figure 6.12: Error visualization of the patient in ”Space Invaders” game

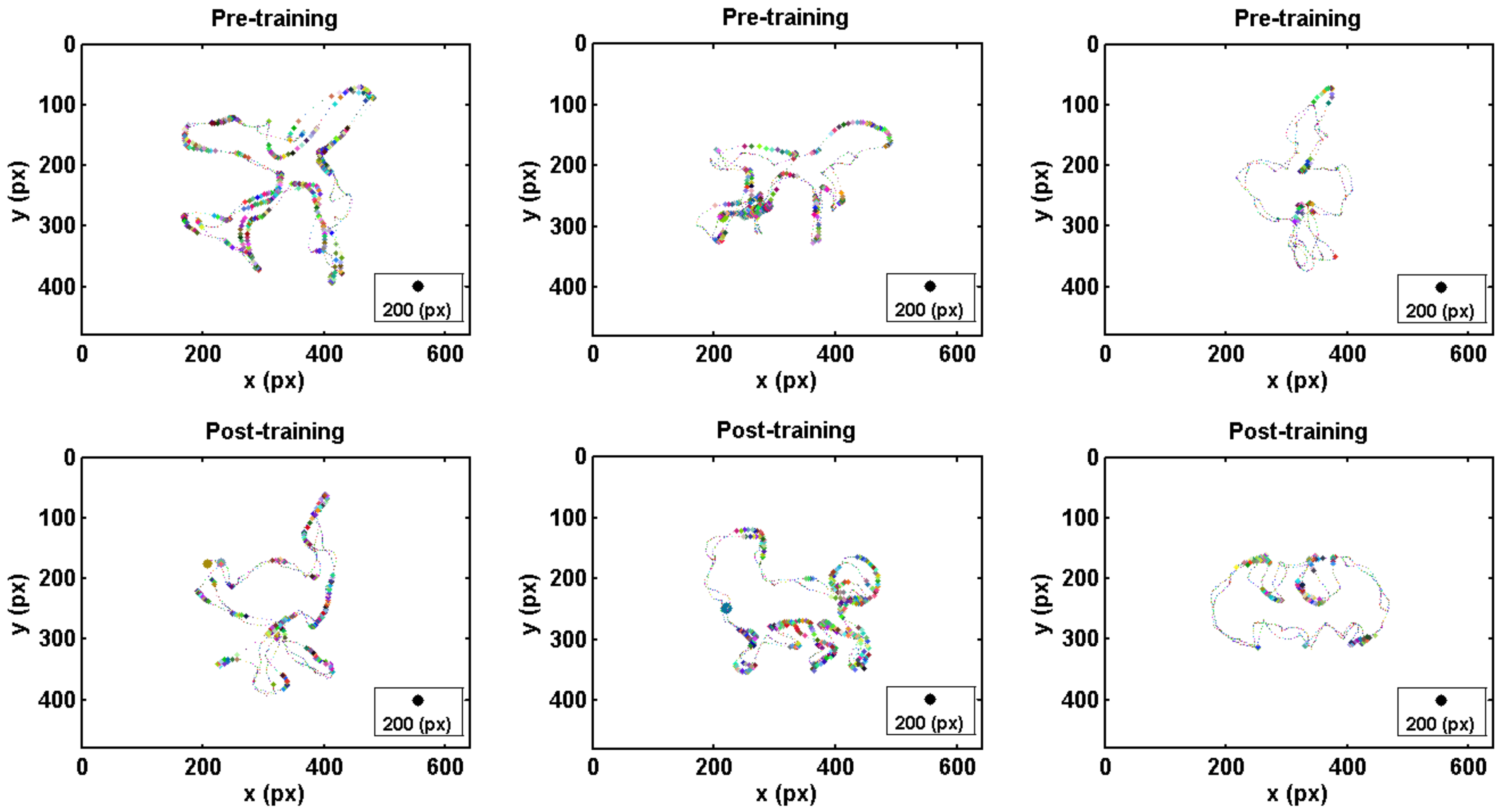


Figure 6.13: Error visualization of the patient in ”Etch a Sketch” game

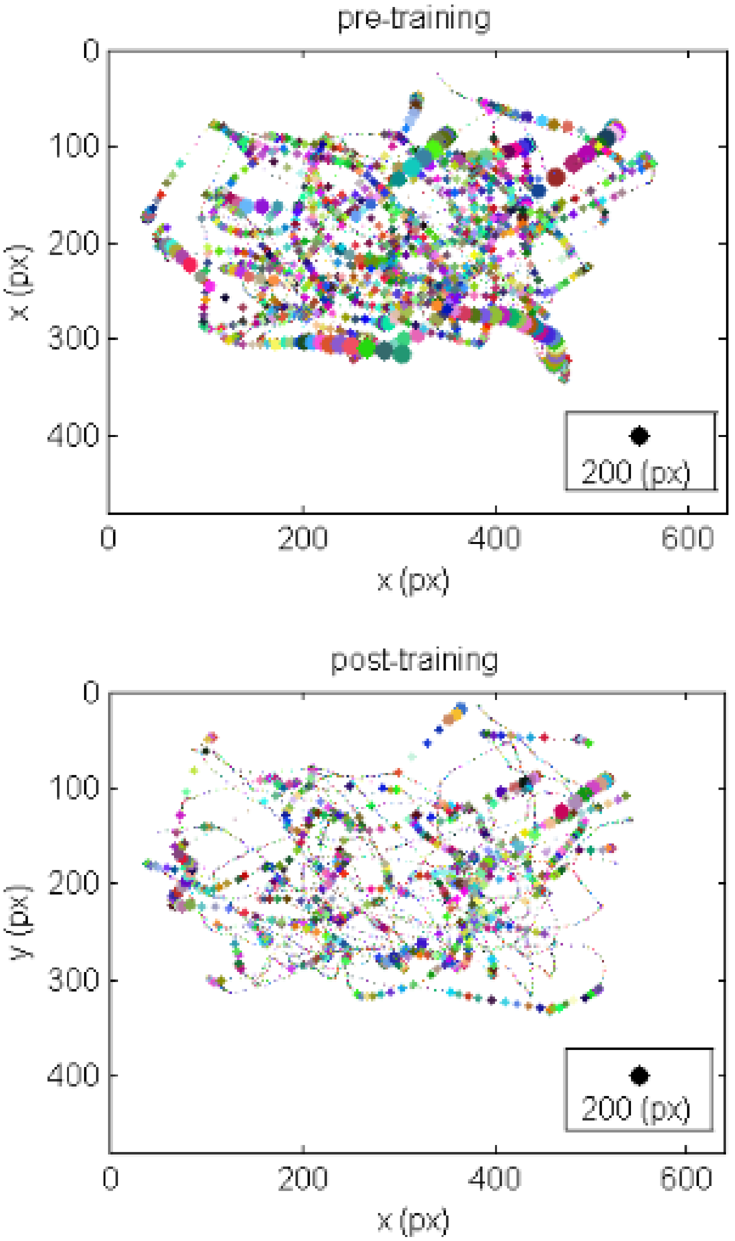


Figure 6.14: Error visualization of the patient in "Paparazzi" game

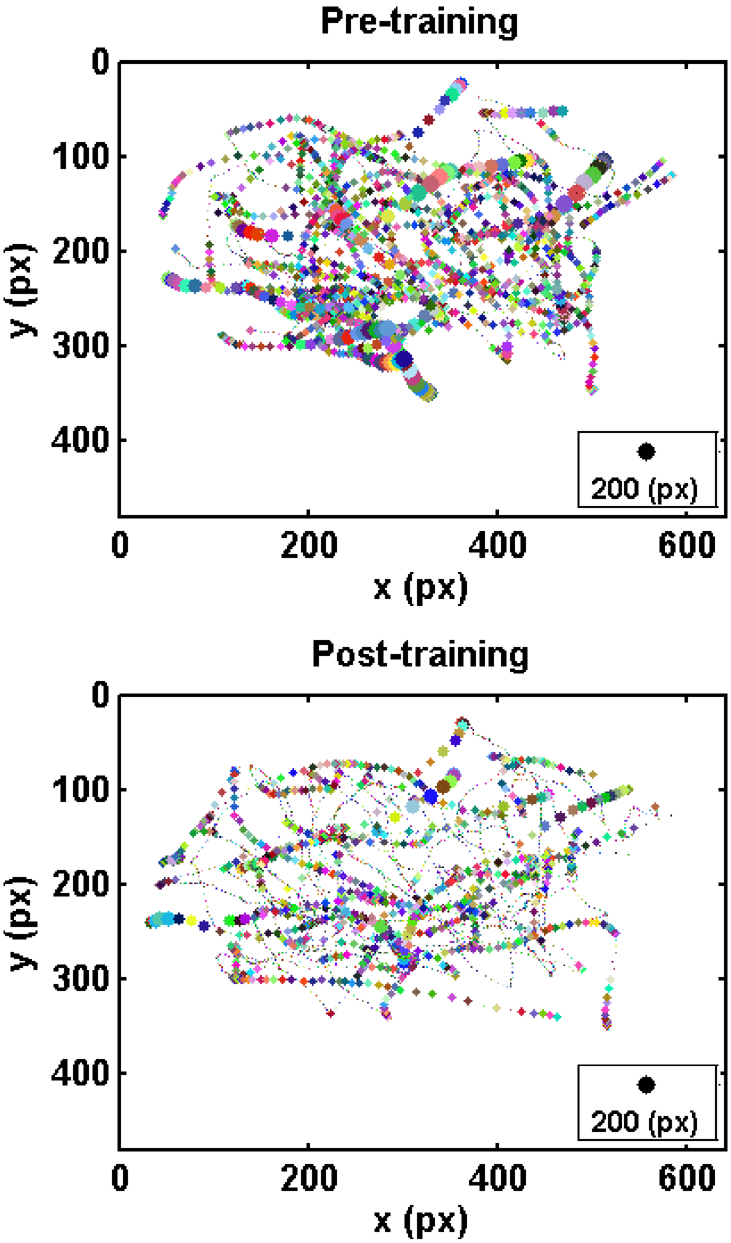


Figure 6.15: Error visualization of the patient in ”Soaring over the US” game

6.7 Conclusion

In conclusion, we explained the design process of six games and their specific characteristics for improving cognitive control in patients with stroke. We discussed different steps of our design process including: (i) context of use, (ii) defining a design challenge, (iii) generating ideas, and finally (iv) evaluating the concepts.

We also evaluated the efficacy of our study by reporting a patient with stroke's result who underwent our training program using the neuro-games. We will continue in collecting data from patients with stroke who have enrolled in our tele-rehab program. We believe the insights gained during our design process can inform many others designing games for specific groups of users, especially those with disabilities.

Next chapter will summarize the lessons that we've learned throughout our studies.

Chapter 7

Lessons Learned

7.1 Introduction

Over the past four years, our team, which includes computer scientists and medical researchers, has been designing games for post-stroke rehabilitation. Most of these studies have been described in the literature [69, 51, 55, 52, 51, 66, 68, 67, 56, 54, 57, 53, 70, 65]. We present the design process and principles used in designing those games, and discuss the challenges and opportunities of designing games specifically for neuro-rehabilitation. This chapter is an in-depth analysis of how technology, and games in particular, need to be carefully considered to support effective therapies for physical rehabilitation.

7.2 Lessons

7.2.1 Make Your Game Platform Mobile and Usable by Patients

The conventional stroke rehabilitation platforms are immobile, i.e. patients are required to visit clinic to get their exercise [82]. Also, the setup is both expensive and requires therapist supervision. Our solution is developed as a tele-rehabilitation game platform such that patients can use it without therapist involvement and at the convenience of their home. Further, our setup is very cost-effective compared to those of conventional therapy.

7.2.2 Use Games that Can Translate to Activities of Daily Living

Using a high ecology environment that is maximally relevant to functional goals is a key factor in rehabilitation. Performing tasks in an AR environment can be expected to generalize to real life settings to a greater extent than with other approaches, including other computer-based methods. As an extension of this, object affordance can be directly adjusted in therapy based on AR, with real objects incorporated into tasks as desired. In our neuro-games, we modeled visuospatial tracking tasks that train patients on their range of motion as well as accuracy both required in activities of daily living. We even had a few patients who verbally reported (not part of the study protocol) that they felt more confident and flexible in terms of range of motion after training.

7.2.3 Increase Interaction of Patients with Physical Environment

There is consensus amongst therapists that as the interaction of patients with the physical environment is reduced, their ADLs recovery starts to deteriorate [98]. Thus an essential factor to successful recovery is to increase the patients level of interaction with their environment. AR platforms are flexible enough to provide customization in terms of complexity and required feedbacks of the exercises based on patients particular needs [50]. This is especially important, considering that physical conditions of the patients change regularly, and thus adjusted systems should be easily provided. In our tele-rehab platform, we asked patients to use the splint unit as a physical object to interact with virtual ones. This helped them both with more comfortable movement across play-area as well as gave them a sense of interaction with physical world.

7.2.4 Use Direct and Natural Interaction

To interact with an object in an indirect therapy environments, the user needs to perform an additional transformation to translate the virtual worlds coordinates to the body-centered coordinates [27]. This extra transformation is not required in a direct environment because the user can interact with the objects directly. For patients with stroke, adapting this extra transformation may be unnecessary to recover ADLs. Moreover, such modulations in cognitive demand are known to have significant effects on motor behavior after stroke [30].

7.2.5 Transform Exercise to Game for Repetitive Execution

We learned that rehabilitation should provide in form of an engaging experience to keep patients involved. As [12] investigated, about 65% of patients are likely to give up their physical therapy rehabilitation session. Further, Tinson [116] provided evidence that stroke patients within a clinical unit spent only 30 to 60 minutes per day for actual therapy while 40% of their time, they are not engaged with any activity. Therefore, it is a key factor to have the patient involved with the training exercises frequently; otherwise the desired level of recovery will not be achieved. Throughout our studies, we found that the best way to make an exercise engaging is to transform it to a game.

7.2.6 Customize Games for Stroke Patient Demographic

Stroke patients are typically older than normal game players. We found it essential to pay careful attention about size of virtual objects or their color contrast in games. For instance, during our pilots, we specifically noticed that our elderly subject kept losing track of the target. We have since modified the color contrast of the objects to ensure our patients can maintain attention during their play. We also added audio information to help patients know when they are off target.

7.2.7 Ensure Therapeutic Value of the Games

From therapeutic perspective, patients are encouraged to (i) improve their accuracy and (ii) expand their Range of Motion (RoM) [7]. These may help improve their quality of life by enabling them to do ADL tasks that they could not achieve before. For example, our patients in different studies reported that they were unable to undo their bra or wipe themselves after using the bathroom. Considering the fact that these routines, yet very private, were performed seamlessly in their lives prior to stroke, one appreciates the vital need for improving accuracy and RoM. Provided that our main scientific goal was to train visuospatial cognition, concentration, and hand-eye movement coordination, we heavily incorporated both accuracy and RoM in the game requirements.

Furthermore, to keep consistency across patients, we did not calibrate the workspace to the patient's RoM but observed that through practice one patient expanded his RoM, i.e. by trying to track the helicopter as far as he can, he increased his functional RoM.

7.2.8 Address Compensatory Movements and Unwanted Postures

Patients often use compensatory movements involving abnormal body parts where they find themselves unable to perform a task that would normally use stroke-affected body parts. We observed that some of our patients with stroke used their trunk movement to reach for the far top of the screen where they could not otherwise reach. Addressing these compensatory motions is critical because we want the game to encourage movements of interest e.g. in our case, shoulder and elbow movements. For that, we eliminated environmental factors as much as we could. Instead of using any chair or worse, a swivel desk chair, we used a folding chair that is not easily moved. If our study was lab-based or in-clinic, we would strap patients using chest harness to limit compensatory trunk movement. However, we could not propose this practice at their home due to risk factors involved; we did not do the same in the lab sessions either (i.e. first and last of the nine sessions) for two reasons: (i) we wanted to maintain consistency across nine sessions, and (ii) the first session also intended to train them on how to properly use the system. For instance, we notified them about their compensatory movement such as those of trunk and unaffected arm. Most importantly, we noticed that patients showed a wide range of wrist neutral posture. For instance, one may have a near normal wrist tone and posture while another has a spastic flexed wrist. To address this issue, we replaced a hand-held LED unit used in early pilots with the splint unit (Figure 6.2b). The splint unit eliminates wrist movements and the adverse effects of spastic wrist postures, helping the patient focus on elbow and shoulder motion.

7.2.9 Adjust Games to Patients' Capabilities

Ermi et al [34] determined that challenge consists of two primary components namely the challenge of speed and cognitive challenges. Only if these challenges are balanced based on the skills of the player, the quality of gameplay will be appropriate. The need for games that are capable of keeping a patient engaged and motivated while respecting a patients' abilities will hence be desirable. Studies have shown that people only engage in an activity if the outcome matches the effort at which they perform [47, 77, 124]. Hence learners who believe that they are competent or successful have been shown to remain engaged and motivated over a longer period of time [81]. In our view, this can only be achieved if a game considers the cognitive and physical deficits of patients and incorporates a mechanism that is capable of balancing the difficulty of an exercise i.e. adapt the difficulty to the current capabilities of the patient.

7.2.10 Use Knowledge of Results and Knowledge of Performance

Feedback is considered as a key parameter, while performance of a subject is attained. The feedback can be in form of Knowledge of Performance (KoP) or Knowledge of Results (KoR)[123]. KoP is real-time information compared to KoR which indicates the success of actions with regard to an overall goal. KoP is presented both intrinsically and extrinsically whereas KoR is presented extrinsically. In our neuro-game platform, we included both types of these feedbacks. We used audio-visual information as KoP to be presented to patients while they were playing the games. We also showed final performance of patients in terms of game scores as KoR at the end of each game. It is general consensus in neuroscience that both KoP and KoR facilitate motor learning. We also found them useful in our neuro-games as long as they are not used in an obtrusive and overwhelming manner.

Here are a few examples of presenting KoP and KoR in our neuro-games:

- Subjects naturally observe location of their hand with respect to the moving target and use the visual and proprioceptive feedbacks as an intrinsic KoP.

- We provide the extrinsic KoP by changing the graphics of the moving target in realtime, informing the subject whether they are performing the task up to the required accuracy.
- We designed natural feedbacks for seamless understanding: one can naturally understand that propellers of the flying helicopter in Soaring over the US game (i.e. the moving target) should spin and it does when they are performing the task of tracking correctly i.e. KoP.
- When the helicopter lands in a US state, if tracking was successful, the subject would see a slideshow of photos of local attractions and hear a vibrant music related to that state (KoR). Otherwise, if tracking was unsuccessful, nothing pleasant happens and the helicopter flies again to start a new round.

7.2.11 Use AR Games to Engage Patients

AR superimposes a computer-generated image on a user's view of the real world. It not only preserves some benefits of virtual reality applications such as fully controlled setting and measurable feedbacks, but also needs less computation time to model the 3D environment [104]. In AR, patients experience a more engaging and natural interaction rather than VR. Virtual objects can be manipulated in an intuitive and natural way to maximize learning ADLs [51]. The haptic feeling [66] of the real objects could bring on a more natural interaction. In addition, patients do not need to don external devices attached to their hand or body. In addition, AR games have been reported highly engaging for patients undergoing therapy because they can provide interesting and engaging tasks that are more motivating than formal repetitive therapy [80].

7.2.12 Make Games Fun

There are different factors to make games fun. Using proper audio and visuals are definitely important. We learned in early pilots that our music motivated subjects and drew their attention; one of the patients reported that while using the tele-rehab game platform at home, he sang with the music tracks and memorized those that he hadn't known before. This is an example of subjects tendency to creatively challenge themselves in other aspects such as verbal memory when provided with a game that they find interesting. Among our six games, patients enjoyed specifically playing Soaring over the US and gave us great feedback on our music choice. This game in particular came with a collection of music based on different states of US.

7.2.13 Use Popular Games

Customizing familiar games can help. Sometimes, patients already know a game or have heard about that. This makes it easier for them to learn the rules. We observed the effect of using popular games in our Leap Motion study with the popular game of Fruit Ninja, which was a top-ranked game in iTunes and Google Play [1]. At the same time, we do not want to use the existing games exactly because some patients may be avid gamers and this might introduce confounding variable to our studies.

7.2.14 Keep Games Challenging

Similar to other players, as patients get used to the games, they may feel bored unless difficulty of games gradually change. To address this issue, we added a gradual difficulty to our games by increasing the speed of target around 5% per day. This kind of difficulty adjustment can provide satisfactory challenge and maintain consistent attention of patients during the training program.

7.2.15 Provide Interfaces for Both Therapists and Patients

The current platform provides a friendly graphical user interface for patients which is very simple to use (patients need to use a single keyboard space bar to navigate between games). Therefore, our interaction at patients end went very smoothly. There is also a pseudo graphical user interface for therapists to use our neuro-game platform. This will help with evaluation of patients in an easier and more prompt manner.

7.3 Things That Did not Work

7.3.1 Hardware Installation Could Be More User-friendly

Although our tele-rehab platform is very easy to use by patients, it still requires us to set it up at their home before they can use it. We foresaw the installation process for up to 40 patients with stroke which required one or two staff members from our lab delivering all the equipments to and from patients' house; all pieces of equipment fit inside the trunk of a compact Sedan. Our setup was designed to be safe to be operated by patients with minimal/no risk. Above all, patients could contact us 24 hour with their question/concerns in case of any problem. Although we planned and delivered the above without a major concern, the ideal situation would be to have a plug-and-play system that can be up and running by patients' family/friends.

7.3.2 Games' Difficulty Could be Dynamically Adjusted

One of the key factors in our tele-rehab games is speed of the moving target. Due to the wide range of disability of patients, this speed needs to be calculated and adjusted per patient. We designed and developed a method to find the maximum functional arm speed of patients and used this number as speed of the moving target to initialize our games. As the patient progressed during the training program, we increased the speed of moving target by 5% after each training day. However, the ideal way to balance difficulty of games based on patients' progress would be using dynamic adjustment. We were not able to leverage this method in our study because we wanted to have control over different parameters. However, in a setting where rehabilitation is the only goal, we recommend to have neuro-games with dynamic difficulty adjustment.

7.3.3 Hardware Could be More Robust

Our tele-rehab platform composes of a display, computer vision, processing, and splint unit that form a closed loop. Our design proved robust for all above units except for an occasional failure in computer vision. This was due to our system being sensitive to ambiance lighting. For instance, once we delivered the system to a patient's house who wanted us to set it up in her patio. Due to extra bright lighting during day time, the system was not responsive, although it was working fine in the evening.

It is always recommended to design the hardware as resilient as possible. Another patient reported that his pet cats jumped up and down on our system while he was training and he had to lock them away. Fortunately, our setup was not affected, however, one can see the potential hazards.

7.3.4 Patients May Not Follow the Instructions

Despite several times of patient training and having brief video instructions included before each game, we still observed discrepancy between what patients were supposed to do and what they were asked for in few cases. This was due to patients' problem with memory or concentration. In these cases, help of a close family member to remind the patient with the instruction while playing is desired.

7.3.5 Patients' Perceived Goal May Not be the Study's Goal

One of our main goals in using neuro-games was to train visuo-spatial tracking skills of patients. We developed our games such that they are fun to avoid patients' frustration. In few cases, we observed that patients were more focused on the fun part of playing the games rather than concentrating on their tracking accuracy. Therefor, justifying patients about motivation of the study is very important. Our experience with patients showed that a lot of them are very interested to know about the concepts behind the study and why they should be doing what they are asked for.

7.3.6 No One May Speak for Patients

We spent six months on designing the neuro-games with collaboration of both computer and medical researchers. Besides, we ran many pilots with both healthy young and elderly individuals to find the potential error/flaws of the system. However, in the first exposure of the system to patients, we found that the system's required range of motion might not be suitable for many of them. This could have been a major exclusion criteria for our study which could have limited it to very highly functional patients. Therefore, we modified the range of motion such that the moving target could be always accessible for patients with our original inclusion criteria. We learned that only patients can represent their true needs and abilities.

Chapter 8

Conclusion and Future Work

8.1 Summary of the Results

In this dissertation, we focused on human computer interaction in stroke rehabilitation. The overall research question that we tried to address is whether HCI can support the design of more effective rehabilitation therapies. Here, the benefit of using HCI is twofold: (i) it can introduce advanced computer technology that can be customized to specific patients' needs; and (ii) it can provide new methods to help patients with their ADL, both in terms of their behavioral change as well as functional capabilities. We designed several HCI studies to address the main concerns regarding the current problems with state-of-the-art computerized rehabilitation therapies. The main activities of this dissertation can be summarized as follows:

- Designing and developing a spatial augmented reality system for assessment and training of upper extremity in patients with stroke. The result of two normal subjects proved functionality of the system.

- Developing Augmented Reality (AR) and Virtual Reality (VR) setups to compare performance of healthy individuals in the “Pick-and-Place” task, which is part of many activities of daily living (ADL’s) and one of the major affected functions stroke patients mainly expect to recover. Superior performance of our 14 healthy subjects in AR setup motivated us to follow up with running our study on patients with stroke.

- Developing and evaluating 3D free hand interaction for training high-level hand functions in patients. The performance of 14 patients with stroke correlated strongly with their clinical assessment, showing validity of using 3D free hand interaction as a good measure of patients’ performance in their rehabilitation program.

- Proposing a new patient-computer interaction mode and comparing it with the conventional computerized stroke rehabilitation. The result of 18 patients with stroke confirmed superiority of our proposed interaction mode to conventional methods.

- Developing a tele-rehabilitation game platform designed for in-home patient’s use. The setup was evaluated by both healthy and patient subjects.

- Designing a study to investigate neurobiological correlates of HCI based on tele-rehabilitation neuro-game training. This included designing and developing neuro-games to enhance targeted brain functions. Our results confirmed improvement of patients in terms of behavioral changes during one-week training program.

8.2 Future Work

Following up our studies in this dissertation, there are different directions to continue this line of work.

8.2.1 Increasing Subject Population

We are interested to recruit more patients and have them undergo our tele-rehabilitation program using the neuro-game platform. With every new patient completing the training, we have been able to improve our tele-rehabilitation platform. Also, since there is a wide range of deficits in patients with stroke, having our program validated by larger number of patients can lead to a more solid and reliable training program.

8.2.2 Behavioral Correlations of Cortical Plasticity

In our tele-rehab study, we recorded a 3-min resting state brain activity of patients using EGI-256 dense array EEG recording system. This was done before and after training at the very beginning of the first and last sessions. Otherwise, if EEG recording was done after the sessions, the patients' brain would be noisy due to recent activity. The EEG data can give us the opportunity to study brain activity and observe possible cortical connectivity change in our patients. To use the EEG data, it should be first cleaned up by removing the artifacts e.g. (i) EMG signals generated by head and neck sub-skin muscles, (ii) eye blink signals, and (iii) eye movement signals. We plan to use Independent Component Analysis (ICA) as well as frequency and magnitude methods to locate and remove these artifacts. After data cleaning, we will investigate the cortical connectivity i.e. coherence between brain regions of interest before and after training. For instance, in our neuro-games, we hypothesized that activity in Parietal and Pre-frontal lobes is essential in playing the games. An increase in coherence between Primary Motor Cortex and these brain areas after training can validate the hypothesis.

8.2.3 Productization of the Neuro-game Platform

Our neuro-game platform can currently be used at home by patients without intervention or monitoring of a therapist. However, we need to deliver the equipment and set it up at patients' home. Our hardware setup can be modified such that it can be delivered to patients as a plug-and-play package; therefore family members of patients can be able to set it up by following a simple instruction.

Also, currently, the data analysis part of the study is done offline, i.e. after the training is completed. However, for productization of our tele-rehabilitation platform, we need to modify it such that patients can see the analyzed result in form of chart/graphs in a graphical user interface. We also plan to send a summary of patients' performance to the clinic for the therapist's reference. The advantage of having such a system is twofold: (i) it can inform and motivate the patients by giving them daily feedback, and (ii) it enables the caregivers to monitor patients performance as they progress. This is of great importance since caregivers can be informed about possible problems and resolve them in a timely manner.

Bibliography

[1] Fruit ninja.

[2] Fruit ninja github.

[3] J. Adamson, A. Beswick, and S. Ebrahim. Is stroke the most common cause of disability? *Journal of Stroke and Cerebrovascular Diseases*, 13(4):171–177, 2004.

[4] A. Alamri, J. Cha, and A. El Saddik. Ar-rehab: An augmented reality framework for poststroke-patient rehabilitation. *Instrumentation and Measurement, IEEE Transactions on*, 59(10):2554–2563, 2010.

[5] G. Alankus and C. Kelleher. Reducing compensatory motions in video games for stroke rehabilitation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2049–2058. ACM, 2012.

[6] G. Alankus, A. Lazar, M. May, and C. Kelleher. Towards customizable games for stroke rehabilitation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2113–2122. ACM, 2010.

[7] A. W. Andrews and R. W. Bohannon. Decreased shoulder range of motion on paretic side after stroke. *Physical Therapy*, 69(9):768–772, 1989.

[8] J. A. Anguera, J. Boccanfuso, J. L. Rintoul, O. Al-Hashimi, F. Faraji, J. Janowich, E. Kong, Y. Larraburo, C. Rolle, E. Johnston, et al. Video game training enhances cognitive control in older adults. *Nature*, 501(7465):97–101, 2013.

[9] v. B. Annemiek, D. Jaap, v. d. S. Roos, and Z. Jelle. *Delft Design Guide: Design Strategies and Methods.* BIS Publishers, 2014.

[10] N. Bagalkot and T. Sokoler. Unboxing the tools for physical rehabilitation: embracing the difference between the clinic and home. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*, pages 597–606. ACM, 2012.

[11] M. Balaam, S. Rennick Egglestone, G. Fitzpatrick, T. Rodden, A.-M. Hughes, A. Wilkinson, T. Nind, L. Axelrod, E. Harris, I. Ricketts, et al. Motivating mobility: designing for lived motivation in stroke rehabilitation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3073–3082. ACM, 2011.

[12] S. F. Bassett. The assessment of patient adherence to physiotherapy rehabilitation. *New Zealand journal of physiotherapy*, 31(2):60–66, 2003.

[13] O. Baus and S. Bouchard. Moving from virtual reality exposure-based therapy to augmented reality exposure-based therapy: a review. *Frontiers in human neuroscience*, 8, 2014.

[14] L. Beursgens, F. Boesten, A. Timmermans, H. Seelen, and P. Markopoulos. Us' em: motivating stroke survivors to use their impaired arm and hand in daily life. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems*, pages 1279–1284. ACM, 2011.

[15] C. Boulanger, A. Boulanger, L. de Greef, A. Kearney, K. Sobel, R. Transue, Z. Sweedyk, P. H. Dietz, and S. Bathiche. Stroke rehabilitation with a sensing surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1243–1246. ACM, 2013.

[16] J. Broeren, L. Claesson, D. Goude, M. Rydmark, and K. S. Sunnerhagen. Virtual rehabilitation in an activity centre for community-dwelling persons with stroke. *Cerebrovascular Diseases*, 26(3):289–296, 2008.

[17] E. Carmeli, S. Peleg, G. Bartur, E. Elbo, and J.-J. Vatine. Handtutortm enhanced hand rehabilitation after stroke: a pilot study. *Physiotherapy Research International*, 16(4):191–200, 2011.

[18] D. Carroll. A quantitative test of upper extremity function. *Journal of chronic diseases*, 18(5):479–491, 1965.

[19] L. Chao, X. Le, C. Bin, and W. Jin-wu. A novel pnf-based rehabilitation robot for upper-limb of stroke patients. In *Proceedings of the 4th International Convention on Rehabilitation Engineering & Assistive Technology*, page 21. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre, 2010.

[20] Y. Chen, H. Huang, W. Xu, R. I. Wallis, H. Sundaram, T. Rikakis, T. Ingalls, L. Olson, and J. He. The design of a real-time, multimodal biofeedback system for stroke patient rehabilitation. In *Proceedings of the 14th annual ACM international conference on Multimedia*, pages 763–772. ACM, 2006.

[21] K. Cheng and K. Pulo. Direct interaction with large-scale display systems using infrared laser tracking devices. In *Proceedings of the Asia-Pacific symposium on Information visualisation-Volume 24*, pages 67–74. Australian Computer Society, Inc., 2003.

[22] T. Coles, D. Meglan, and N. W. John. The role of haptics in medical training simulators: a survey of the state of the art. *Haptics, IEEE Transactions on*, 4(1):51–66, 2011.

[23] A. G. D. Correa, G. A. de Assis, M. d. Nascimento, I. Ficheman, and R. d. D. Lopes. Genvirtual: An augmented reality musical game for cognitive and motor rehabilitation. In *Virtual Rehabilitation, 2007*, pages 1–6. IEEE, 2007.

[24] A. G. D. Corrêa, I. K. Ficheman, M. D. Nascimento, and R. de Deus Lopes. Computer assisted music therapy: A case study of an augmented reality musical system for children with cerebral palsy rehabilitation. In *Advanced Learning Technologies, 2009. ICALT 2009. Ninth IEEE International Conference on*, pages 218–220. IEEE, 2009.

[25] S. C. Cramer. An overview of therapies to promote repair of the brain after stroke. *Head & neck*, 33(S1):S5–S7, 2011.

[26] S. C. Cramer, M. Sur, B. H. Dobkin, C. O'Brien, T. D. Sanger, J. Q. Trojanowski, J. M. Rumsey, R. Hicks, J. Cameron, D. Chen, et al. Harnessing neuroplasticity for clinical applications. *Brain*, 134(6):1591–1609, 2011.

[27] J. D. Crawford, D. Y. Henriques, and W. P. Medendorp. Three-dimensional transformations for goal-directed action. *Annual review of neuroscience*, 34:309–331, 2011.

[28] J. Curtis, L. Ruijs, M. de Vries, R. Winters, and J.-B. Martens. Rehabilitation of handwriting skills in stroke patients using interactive games: a pilot study. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems*, pages 3931–3936. ACM, 2009.

[29] D. Datcu and S. Lukosch. Free-hands interaction in augmented reality. In *Proceedings of the 1st symposium on Spatial user interaction*, pages 33–40. ACM, 2013.

[30] A. Dennis, R. Bosnell, H. Dawes, K. Howells, J. Cockburn, U. Kischka, P. Matthews, and H. Johansen-Berg. Cognitive context determines dorsal premotor cortical activity during hand movement in patients after stroke. *Stroke*, 42(4):1056–1061, 2011.

[31] J. Desrosiers, G. Bravo, R. Hébert, E. Dutil, and L. Mercier. Validation of the box and block test as a measure of dexterity of elderly people: reliability, validity, and norms studies. *Archives of physical medicine and rehabilitation*, 75(7):751–755, 1994.

[32] L. Dodakian, K. G. Sharp, J. See, N. S. Abidi, K. Mai, B. W. Fling, V. H. Le, and S. C. Cramer. Targeted engagement of a dorsal premotor circuit in the treatment of post-stroke paresis. *NeuroRehabilitation*, 33(1):13–24, 2013.

[33] L. Dovat, O. Lambercy, B. Salman, V. Johnson, R. Gassert, E. Burdet, C. L. Teo, and T. Milner. Post-stroke training of a pick and place activity in a virtual environment. In *Virtual Rehabilitation, 2008*, pages 28–34. IEEE, 2008.

[34] L. Ermi. Fundamental components of the gameplay experience: Analysing immersion. *Worlds in play: International perspectives on digital games research*, 37.

[35] K. Fiehler, F. Rösler, and D. Y. Henriques. Interaction between gaze and visual and proprioceptive position judgements. *Experimental brain research*, 203(3):485–498, 2010.

[36] P. M. Fitts and C. M. Seeger. Sr compatibility: spatial characteristics of stimulus and response codes. *Journal of experimental psychology*, 46(3):199, 1953.

[37] M. Flanders, S. I. H. Tillery, and J. F. Soechting. Early stages in a sensorimotor transformation. *Behavioral and Brain Sciences*, 15(02):309–320, 1992.

[38] M.-C. Fluet, O. Lambercy, and R. Gassert. Effects of 2d/3d visual feedback and visuomotor collocation on motor performance in a virtual peg insertion test. In *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*, pages 4776–4779. IEEE, 2012.

[39] C. Forlines and R. Balakrishnan. Evaluating tactile feedback and direct vs. indirect stylus input in pointing and crossing selection tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1563–1572. ACM, 2008.

[40] N. Friedman, V. Chan, D. Zondervan, M. Bachman, and D. J. Reinkensmeyer. Musicglove: Motivating and quantifying hand movement rehabilitation by using functional grips to play music. In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pages 2359–2363. IEEE, 2011.

[41] A. R. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scandinavian journal of rehabilitation medicine*, 7(1):13–31, 1974.

[42] J. Galliers, S. Wilson, S. Muscroft, J. Marshall, A. Roper, N. Cocks, and T. Pring. Accessibility of 3d game environments for people with aphasia: an exploratory study. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility*, pages 139–146. ACM, 2011.

[43] K. Gerling, I. Livingston, L. Nacke, and R. Mandryk. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1873–1882. ACM, 2012.

[44] F. Güldenpfennig and G. Fitzpatrick. A monitoring device as assistive lifestyle technology: combining functional needs with pleasure. In *Proceedings of the 4th Augmented Human International Conference*, pages 190–193. ACM, 2013.

[45] J. Hallam and V. Whiteley. Interactive therapy gloves: reconnecting partners after a stroke. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems*, pages 989–994. ACM, 2011.

[46] L. Heimer. *The human brain and spinal cord: functional neuroanatomy and dissection guide*. Springer Science & Business Media, 2012.

[47] T. Hill, J. Fultz, and P. M. Biner. Incidental learning as a function of anticipated task difficulty. *Motivation and Emotion*, 9(1):71–85, 1985.

[48] N. Hocine, A. Gouaich, S. A. Cerri, D. Mottet, J. Froger, and I. Laffont. Adaptation in serious games for upper-limb rehabilitation: an approach to improve training outcomes. *User Modeling and User-Adapted Interaction*, 25(1):65–98, 2015.

[49] N. Hogan, H. I. Krebs, J. Charnnarong, P. Srikrishna, and A. Sharon. Mit-manus: a workstation for manual therapy and training. i. In *Robot and Human Communication, 1992. Proceedings., IEEE International Workshop on*, pages 161–165. IEEE, 1992.

[50] M. K. Holden. Virtual environments for motor rehabilitation: review. *Cyberpsychology & behavior*, 8(3):187–211, 2005.

[51] H. M. Hondori, M. Khademi, L. Dodakian, S. C. Cramer, and C. V. Lopes. A spatial augmented reality rehab system for post-stroke hand rehabilitation. In *MMVR*, pages 279–285, 2013.

[52] H. M. Hondori, M. Khademi, L. Dodakian, A. McKenzie, C. V. Lopes, and S. C. Cramer. Choice of human–computer interaction mode in stroke rehabilitation. *Neurorehabilitation and neural repair*, page 1545968315593805, 2015.

[53] H. M. Hondori, M. Khademi, and C. V. Lopes. Monitoring intake gestures using sensor fusion (microsoft kinect and inertial sensors) for smart home tele-rehab setting. In *2012 1st Annual IEEE Healthcare Innovation Conference*, 2012.

[54] H. M. Hondori, M. Khademi, and C. V. Lopes. Use of a portable device for measuring arm's planar mechanical impedance during motion. In *Biomedical Engineering and Sciences (IECBES), 2012 IEEE EMBS Conference on*, pages 980–983. IEEE, 2012.

[55] H. M. Hondori, M. Khademi, A. McKenzie, L. Dodakian, C. V. Lopes, and S. C. Cramer. Utility of augmented reality in relation to virtual reality in stroke rehabilitation. *Stroke*, 45:1, 2014.

[56] H. M. Hondori and A. W. Tech. Smart mug to measure hand's geometrical mechanical impedance. In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pages 4053–4056. IEEE, 2011.

[57] H. M. Hondori, A. W. Tech, M. Khademi, and C. V. Lopes. Real-time measurement of arms mechanical impedance with augmented reality illustration. In *IEEE-EMBC*, 2012.

[58] S. J. Housman, V. Le, T. Rahman, R. J. Sanchez, and D. J. Reinkensmeyer. Arm-training with t-wrex after chronic stroke: preliminary results of a randomized controlled trial. In *Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on*, pages 562–568. IEEE, 2007.

[59] S. J. Housman, K. M. Scott, and D. J. Reinkensmeyer. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. *Neurorehabilitation and neural repair*, 2009.

[60] H. L. Hurkmans, G. M. Ribbers, M. F. Streur-Kranenburg, H. J. Stam, R. J. Van Den Berg-Emons, et al. Energy expenditure in chronic stroke patients playing wii sports: a pilot study. *J Neuroeng Rehabil*, 8(38):1–7, 2011.

[61] B. Imam and T. Jarus. Virtual reality rehabilitation from social cognitive and motor learning theoretical perspectives in stroke population. *Rehabilitation research and practice*, 2014, 2014.

[62] A. Jacobs, A. Timmermans, M. Michielsen, M. Vander Plaetse, and P. Markopoulos. Contrast: gamification of arm-hand training for stroke survivors. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*, pages 415–420. ACM, 2013.

[63] H.-T. Jung, Y.-K. Choe, J. Baird, and R. A. Grupen. A follow-up on humanoid-mediated stroke physical rehabilitation. In *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction*, pages 159–160. ACM, 2012.

[64] Y. Jung, S.-C. Yeh, and J. Stewart. Tailoring virtual reality technology for stroke rehabilitation: a human factors design. In *CHI'06 extended abstracts on Human factors in computing systems*, pages 929–934. ACM, 2006.

[65] M. Khademi, H. M. Hondori, L. Dodakian, S. Cramer, and C. V. Lopes. Comparing pick and place task in spatial augmented reality versus non-immersive virtual reality for rehabilitation setting. In *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*, pages 4613–4616. IEEE, 2013.

[66] M. Khademi, H. M. Hondori, C. V. Lopes, L. Dodakian, and S. C. Cramer. Haptic augmented reality to monitor human arm's stiffness in rehabilitation. In *Biomedical Engineering and Sciences (IECBES), 2012 IEEE EMBS Conference on*, pages 892–895. IEEE, 2012.

[67] M. Khademi, H. Mousavi Hondori, L. Dodakian, C. V. Lopes, and S. C. Cramer. An assistive tabletop keyboard for stroke rehabilitation. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces*, pages 337–340. ACM, 2013.

[68] M. Khademi, H. Mousavi Hondori, A. McKenzie, L. Dodakian, C. V. Lopes, and S. C Cramer. Comparing direct and indirect interaction in stroke rehabilitation. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 1639–1644. ACM, 2014.

[69] M. Khademi, H. Mousavi Hondori, A. McKenzie, L. Dodakian, C. V. Lopes, and S. C. Cramer. Free-hand interaction with leap motion controller for stroke rehabilitation. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 1663–1668. ACM, 2014.

[70] M. Khademi, H. Mousavi Hondori, and C. Videira Lopes. Optical illusion in augmented reality. In *Proceedings of the 18th ACM symposium on Virtual reality software and technology*, pages 195–196. ACM, 2012.

[71] D. Kim, O. Hilliges, S. Izadi, A. D. Butler, J. Chen, I. Oikonomidis, and P. Olivier. Digits: freehand 3d interactions anywhere using a wrist-worn gloveless sensor. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, pages 167–176. ACM, 2012.

[72] H. Kim, G. Albuquerque, S. Havemann, and D. W. Fellner. Tangible 3d: Hand gesture interaction for immersive 3d modeling. In *IPT/EGVE*, pages 191–199, 2005.

[73] M. King, J. Hijmans, M. Sampson, J. Satherley, N. McMillan, and L. Hale. Bilateral movement training with computer games for stroke rehabilitation. In *Proceedings of the 4th International Convention on Rehabilitation Engineering & Assistive Technology*, page 20. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre, 2010.

[74] L. A. Knaut, S. K. Subramanian, B. J. McFadyen, D. Bourbonnais, and M. F. Levin. Kinematics of pointing movements made in a virtual versus a physical 3-dimensional environment in healthy and stroke subjects. *Archives of physical medicine and rehabilitation*, 90(5):793–802, 2009.

[75] S. Knoedel and M. Hachet. Multi-touch rst in 2d and 3d spaces: Studying the impact of directness on user performance. In *3D User Interfaces (3DUI), 2011 IEEE Symposium on*, pages 75–78. IEEE, 2011.

[76] H. I. Krebs, M. Ferraro, S. P. Buerger, M. J. Newbery, A. Makiyama, M. Sandmann, D. Lynch, B. T. Volpe, and N. Hogan. Rehabilitation robotics: pilot trial of a spatial extension for mit-manus. *Journal of NeuroEngineering and Rehabilitation*, 1(1):5, 2004.

[77] A. Kukla. Foundations of an attributional theory of performance. *Psychological Review*, 79(6):454, 1972.

[78] Y. Lajoie, N. Teasdale, C. Bard, and M. Fleury. Attentional demands for static and dynamic equilibrium. *Experimental brain research*, 97(1):139–144, 1993.

[79] J. Lee and T. L. Kunii. Model-based analysis of hand posture. *Computer Graphics and Applications, IEEE*, 15(5):77–86, 1995.

[80] N. Lehrer, Y. Chen, M. Duff, S. L. Wolf, and T. Rikakis. Exploring the bases for a mixed reality stroke rehabilitation system, part ii: design of interactive feedback for upper limb rehabilitation. *Journal of neuroengineering and rehabilitation*, 8(1):54, 2011.

[81] A. H. Lequerica and K. Kortte. Therapeutic engagement: a proposed model of engagement in medical rehabilitation. *American journal of physical medicine & rehabilitation*, 89(5):415–422, 2010.

[82] A. C. Lo, P. D. Guarino, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, D. G. Federman, R. J. Ringer, T. H. Wagner, H. I. Krebs, B. T. Volpe, et al. Robot-assisted therapy for long-term upper-limb impairment after stroke. *New England Journal of Medicine*, 362(19):1772–1783, 2010.

[83] P. S. Lum, C. G. Burgar, P. C. Shor, M. Majmundar, and M. Van der Loos. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Archives of physical medicine and rehabilitation*, 83(7):952–959, 2002.

[84] X. Luo, R. V. Kenyon, T. Kline, H. C. Waldinger, and D. G. Kamper. An augmented reality training environment for post-stroke finger extension rehabilitation. In *Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on*, pages 329–332. IEEE, 2005.

[85] X. Luo, T. Kline, H. C. Fischer, K. Stubblefield, R. V. Kenyon, D. G. Kamper, et al. Integration of augmented reality and assistive devices for post-stroke hand opening rehabilitation. In *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*, pages 6855–6858. IEEE, 2005.

[86] S. Malik, A. Ranjan, and R. Balakrishnan. Interacting with large displays from a distance with vision-tracked multi-finger gestural input. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, pages 43–52. ACM, 2005.

[87] V. Mathiowetz, G. Volland, N. Kashman, and K. Weber. Adult norms for the box and block test of manual dexterity. *American Journal of Occupational Therapy*, 39(6):386–391, 1985.

[88] J. Messier and J. Kalaska. Differential effect of task conditions on errors of direction and extent of reaching movements. *Experimental Brain Research*, 115(3):469–478, 1997.

[89] T. Moscovich and J. F. Hughes. Indirect mappings of multi-touch input using one and two hands. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1275–1284. ACM, 2008.

[90] N. Müller and R. Knight. The functional neuroanatomy of working memory: contributions of human brain lesion studies. *Neuroscience*, 139(1):51–58, 2006.

[91] J. Nolte and J. Sundsten. *The human brain: an introduction to its functional anatomy*, volume 5. Mosby St. Louis, 2002.

[92] S.-K. Ong, Y. Shen, J. Zhang, and A. Y. Nee. Augmented reality in assistive technology and rehabilitation engineering. In *Handbook of Augmented Reality*, pages 603–630. Springer, 2011.

[93] K. M. Pearson-Fuhrhop, B. Minton, D. Acevedo, B. Shahbaba, and S. C. Cramer. Genetic variation in the human brain dopamine system influences motor learning and its modulation by l-dopa. *PLoS One*, 8(4):e61197, 2013.

[94] L. Pogrzeba, M. Wacker, and B. Jung. Potentials of a low-cost motion analysis system for exergames in rehabilitation and sports medicine. In *E-Learning and Games for Training, Education, Health and Sports*, pages 125–133. Springer, 2012.

[95] S. S. Rathore, W. D. Rosamond, L. S. Cooper, L. E. Chambless, H. A. Tyroler, and A. R. Hinn. Characterization of stroke signs and symptoms: Findings from the atherosclerosis risk in communities study. *Circulation*, 103(9):1362, 2001.

[96] R. M. Reitan. Validity of the trail making test as an indicator of organic brain damage. *Perceptual and motor skills*, 8(3):271–276, 1958.

[97] V. L. Roger, A. S. Go, D. M. Lloyd-Jones, E. J. Benjamin, J. D. Berry, W. B. Borden, D. M. Bravata, S. Dai, E. S. Ford, C. S. Fox, et al. Heart disease and stroke statistics2012 update a report from the american heart association. *Circulation*, 125(1):e2–e220, 2012.

[98] F. D. Rose, B. M. Brooks, and A. A. Rizzo. Virtual reality in brain damage rehabilitation: review. *CyberPsychology & Behavior*, 8(3):241–262, 2005.

[99] N. Rossol, I. Cheng, W. F. Bischof, and A. Basu. A framework for adaptive training and games in virtual reality rehabilitation environments. In *Proceedings of the 10th International Conference on Virtual Reality Continuum and Its Applications in Industry*, pages 343–346. ACM, 2011.

[100] G. Salivia and J. P. Hourcade. Pointassist: assisting individuals with motor impairments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1213–1222. ACM, 2013.

[101] D. Schmidt, F. Block, and H. Gellersen. A comparison of direct and indirect multitouch input for large surfaces. In *Human-Computer Interaction–INTERACT 2009*, pages 582–594. Springer, 2009.

[102] J. See, L. Dodakian, C. Chou, V. Chan, A. McKenzie, D. J. Reinkensmeyer, and S. C. Cramer. A standardized approach to the fugl-meyer assessment and its implications for clinical trials. *Neurorehabilitation and neural repair*, page 1545968313491000, 2013.

[103] R. Shadmehr and F. A. Mussa-Ivaldi. Adaptive representation of dynamics during learning of a motor task. *The Journal of Neuroscience*, 14(5):3208–3224, 1994.

[104] Y. Shen, S. Ong, and A. Nee. Hand rehabilitation based on augmented reality. In *Proceedings of the 3rd International Convention on Rehabilitation Engineering & Assistive Technology*, page 23. ACM, 2009.

[105] A. Shumway-Cook and M. Woollacott. Attentional demands and postural control: the effect of sensory context. *Journals of Gerontology-Biological Sciences and Medical Sciences*, 55(1):M10, 2000.

[106] N. R. Sims and H. Muyderman. Mitochondria, oxidative metabolism and cell death in stroke. *Biochimica et Biophysica Acta (BBA)-Molecular Basis of Disease*, 1802(1):80–91, 2010.

[107] S. J. Sober and P. N. Sabes. Multisensory integration during motor planning. *The Journal of Neuroscience*, 23(18):6982–6992, 2003.

[108] J. Soechting, S. Tillery, M. Flanders, et al. Transformation from head-to shoulder-centered representation of target direction in arm movements. *Cognitive Neuroscience, Journal of*, 2(1):32–43, 1990.

[109] S. Subramanian, L. A. Knaut, C. Beaudoin, B. J. McFadyen, A. G. Feldman, and M. F. Levin. Virtual reality environments for post-stroke arm rehabilitation. *Journal of neuroengineering and rehabilitation*, 4(1):20, 2007.

[110] L. E. Sucar, G. Azcárate, R. S. Leder, D. Reinkensmeyer, J. Hernández, I. Sanchez, and P. Saucedo. Gesture therapy: A vision-based system for arm rehabilitation after stroke. In *Biomedical Engineering Systems and Technologies*, pages 531–540. Springer, 2009.

[111] J. Sutton. Air painting with corel painter freestyle and the leap motion controller: a revolutionary new way to paint! In *ACM SIGGRAPH 2013 Studio Talks*, page 21. ACM, 2013.

[112] T. Swann-Sternberg, A. Singh, N. Bianchi-Berthouze, and A. Williams. User needs for technology supporting physical activity in chronic pain. In *CHI'12 Extended Abstracts on Human Factors in Computing Systems*, pages 2441–2446. ACM, 2012.

[113] H. Taheri, J. B. Rowe, D. Gardner, V. Chan, D. J. Reinkensmeyer, and E. T. Wolbrecht. Robot-assisted guitar hero for finger rehabilitation after stroke. In *Engineering in medicine and biology society (EMBC), 2012 annual international conference of the IEEE*, pages 3911–3917. IEEE, 2012.

[114] G. T. Thielman, C. M. Dean, and A. Gentile. Rehabilitation of reaching after stroke: task-related training versus progressive resistive exercise. *Archives of physical medicine and rehabilitation*, 85(10):1613–1618, 2004.

[115] J. Tiffin and E. J. Asher. The purdue pegboard: norms and studies of reliability and validity. *Journal of applied psychology*, 32(3):234, 1948.

[116] D. Tinson. How stroke patients spend their days: an observational study of the treatment regime offered to patients in hospital with movement disorders following stroke. *Disability & Rehabilitation*, 11(1):45–49, 1989.

[117] E. Todorov, R. Shadmehr, and E. Bizzi. Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *Journal of motor behavior*, 29(2):147–158, 1997.

[118] S. Trewin, S. Keates, and K. Moffatt. Individual responses to a method of cursor assistance. *Disability and Rehabilitation: Assistive Technology*, 3(1-2):2–21, 2008.

[119] C. A. Trombly and C.-Y. Wu. Effect of rehabilitation tasks on organization of movement after stroke. *American Journal of Occupational Therapy*, 53(4):333–344, 1999.

[120] A. Turolla, M. Dam, L. Ventura, P. Tonin, M. Agostini, C. Zucconi, P. Kiper, A. Cagnin, and L. Piron. Virtual reality for the rehabilitation of the upper limb motor function after stroke: a prospective controlled trial. *J Neuroeng Rehabil*, 10:85, 2013.

[121] S. Vikram, L. Li, and S. Russell. Writing and sketching in the air, recognizing and controlling on the fly. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*, pages 1179–1184. ACM, 2013.

[122] J. Waterworth. Virtual reality in medicine: a survey of the state of the art. *Sweden, Jul-1999*, 1999.

[123] C. J. Winstein. Knowledge of results and motor learningimplications for physical therapy. *Physical therapy*, 71(2):140–149, 1991.

[124] R. A. Wright. Perceived motivational arousal as a mediator of the magnitude of goal valence. *Motivation and Emotion*, 6(2):161–180, 1982.

[125] J. Wu, R. Srinivasan, A. Kaur, and S. C. Cramer. Resting-state cortical connectivity predicts motor skill acquisition. *NeuroImage*, 91:84–90, 2014.

[126] R. Xiao, M. A. Nacenta, R. L. Mandryk, A. Cockburn, and C. Gutwin. Ubiquitous cursor: a comparison of direct and indirect pointing feedback in multi-display environments. In *Proceedings of Graphics Interface 2011*, pages 135–142. Canadian Human-Computer Communications Society, 2011.

[127] Z. Xu, H. Yu, and S. Yan. Motor rehabilitation training after stroke using haptic handwriting and games. In *Proceedings of the 4th International Convention on Rehabilitation Engineering & Assistive Technology*, page 31. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre, 2010.

[128] C. Zhao, C.-P. Hsiao, N. M. Davis, and E. Yi-Luen Do. Tangible games for stroke rehabilitation with digital box and blocks test. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*, pages 523–528. ACM, 2013.