A Haptic/Graphic Paradigm for the Rehabilitation of Attention in Severe Traumatic Brain Injury

BY

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B.S., Florida Institute of Technology, 2003

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Masters of Science in Bioengineering
in the Graduate College of the
University of Illinois at Chicago, 2010

Chicago, Illinois

There once was a fellow from Florida,

Who loathed life in a cubicle,

So he took out a credit card,

To travel lands afar,

Ergo, I dedicate this to Bank of America.

ACKNOWLEDGMENTS

Looking back on the development of this research for the past year and a half, it would be an incredible leap of faith to believe I could have done this on my own. It is my pleasure then to acknowledge the multitude of people who have contributed in some way to this thesis.

First, I would like to acknowledge the support and direction of my advisor, Dr. James Patton. Thank you for believing in me when I first came to you with no idea what I was doing. Thank you for the technical guidance, words of encouragement, and sound advice over the past two years, without which I would have been completely lost many times over.

Thanks to our research team with whom I've spent many hours discussing different aspects of the research: Assaf Dvorkin, Eric Larson, Felise Zollman, Sonia Pacini, Nancy Hsu, Lindsey Davitt, as well as the Rehabilitation Institute of Chicago: which altogether provided a collaborative and productive environment to work in. To my peers (in no particular order), Mary Leonard, Cari Launiere, Jamie Burgess, Felix Huang, Arno Stienen, Zach Danziger, Assaf Pressman, Mark Kovic, Minos Niu, Ian Sharp, Deivya Bansal, Justin Horowitz, Sylvester Rosario, Mark Shapiro, Devjani Saha, Ashley Greene, Farnaz Abdollahi, Molly Listenberger, Parmar Pritesh, Rayna Saito, Zachary Wright, Emily Case, Angela Chiu, Laura Zitella, Emily Mugler, Kathy Stubblefield.

Lastly, and most importantly, I would like to thank my parents, who sacrificed their own personal desires to give me a solid education, who raised me and taught me me to be a better man, and all the while putting up with me and my attitude problems.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
APT	Attention Process Training
DOF	Degrees of Freedom
GOAT	Galveston Orientation and Amensia Test
RIC	Rehabilitation Institute of Chicago
TBI	Traumatic Brain Injury
UIC	University of Illinois at Chicago
VRROOM	Virtual Reality Robotics and Optical Operations Machine

SUMMARY

Traumatic brain injury (TBI) has been known to cause deficiencies in attention and concentration which result in serious functional impairment, even at mild levels. Current models of therapy involve continuous-performance pen-and-paper tasks with a therapist, but these require prolonged investments of times by clinicians which are often not feasible. Recent research has shown that therapeutic methods involving virtual environments rich with distractions have been effective at influencing attention and concentration in the more chronic and higher functioning patients. However, to date, there have been no extended studies on how attentional training with such environments may help rehabilitate the inpatient TBI population.

Here we present a novel and previously unseen minimalist environment consisting only of a cursor and target in totally black background combined with haptic feedback via a hand-held robotic device. We tested the environment to assess and improve the attention in seventeen TBI patients with Rancho Los Amigos Levels IV-V. We used a large workspace Phantom 3.0 robot and a virtual display with a 120 degree field of view to provide the patient with a set of repetitive, point-to-point reaching tasks. Subjects visited the laboratory for two successive days, and on each day they executed two blocks of training, in randomized order, on each of three modes of haptic feedback: 1) no haptic feedback, 2) balloon effect, requiring a breakthrough haptic force to enter the target. and 3) slight haptic nudge towards the target on loss of attention as evidenced by lack of movement. We hypothesized that haptic feedback would refocus the patient's attention as well as increase attention in subsequent movements.

SUMMARY (Continued)

Our results showed that patients improve over the first day and between the first and second day, but level off on the second day, seemingly requiring more challenging tasks. We performed Tukey's Honest Significant Difference Test on a Linear Mixed-Effects Model and showed that block order and haptic nudges significantly improved performance, with p¡.0001. We showed that blocks with haptic nudges were improved even when individual movements were degraded, giving evidence that haptic nudges were able to improve attention to subsequent movements.

These findings directly support the viability of a more comprehensive study involving tasks targeting various levels of attention as well as an extensive study with repeated treatment and clinical outcome evaluations. They provide evidence that haptic feedback can be used to beneficially alter movements and attention, as well as lay a foundation for a wider family of applications that use haptic robots for rehabilitation and/or training.

1. INTRODUCTION

1.1 Traumatic Brain Injury

Traumatic brain injury (TBI) is a serious public health problem affecting approximately 1.5 million people per year in the United States. It is a leading cause of death and long term disability among children and young adults, with over 5 million people currently living with a disability as a result of TBI. The injury elicits a wide spectrum of symptoms and disabilities, ranging from the physical (loss of motor control and sensory information) to the cognitive (attention and memory deficits) to the psychological (mood swings and emotional instability). These symptoms may exist even with a lack of physical signs of injury or in the face of normal MRI and CAT scans, making diagnosis and treatment difficult (1; 2).

Because many patients suffer only from cognitive and psychological effects, themselves and their families are often unable to accept or even understand these problems, with devastating results. Traumatic brain injury has therefore been coined, "the silent epidemic". (1) Furthermore, the financial burden of civilian TBI injuries is enormous, having been estimated at nearly $50 billion per year (3). Due to our recent military conflicts and the greater use of improvised explosive devices, the incidence rate of TBI in soldiers has been on a rapid increase. The dearth of knowledge and understanding in the injury and its effects, combined with the increased incidence rates, has resulted in a current clinical crisis for the United States Veteran

Administration Hospital (4). The impact, therefore, on both civilian and military healthcare systems is large, and both stand to gain immensely from improved rehabilitative methods.

Traumatic brain injury is clinically classified as mild, moderate, or severe, based on variables including duration of loss of consciousness and Glasgow Coma Score. Further diagnosis is often accomplished using the Rancho Los Amigos scale and various assessment tests such as the Galveston Orientation and Amnesia Test (GOAT). The Rancho Los Amigos scale is a scale from I-VIII which assesses recovery in brain injury patients (5). The GOAT is a quantitative scale used to assess orientation to person, place, and time, and memory for events surrounding the injury (6).

All severities of TBI, from mild to severe, result in debilitating cognitive deficits, involving difficulties with organization, concentration, attention, memory, sensory information and interpretation, language processing, emotional ability, and social behavior (7; 8; 9; 10).

The loss of attentional abilities are among the most common symptoms of severe TBI. As attentional processes are also a crucial cognitive function in the execution of everyday tasks, these symptoms can be devastating to a patient and prevent full reintegration with everyday life. It is therefore imperative that in order to maximize the chances of full recovery, that assessment and rehabilitation of attention occur in a timely manner post-injury. (11; 12)

One of the primary difficulties with cognitive rehabilitation in the TBI population is that, due the emotional changes caused by TBI, patients are regularly resistant and even antagonistic towards many forms of therapy. Clinicians have reported that the population requires constantly changing and customized therapy in order to maintain the patient's focus and cooperation. It is therefore important that any proposed therapy is assessed not only for efficacy but also for tolerability by the population.

We propose a new model of attention therapy in severe TBI inpatients utilizing a virtual environment and haptic robots. Virtual environments provide various benefits, including the ability to provide a minimal, distraction-free environment specifically tailored to the task, to quickly and repeatedly present a succession of targets, and to actively monitor performance and automatically adjust environment parameters as necessary. Additionally, the use of haptic robots allows us to tirelessly and accurately measure and alter movements, as well as automatically provide physical feedback through the robot.

As no previous studies have used virtual environments for the rehabilitation of attention in this population, we first seek to demonstrate the tolerability and viability of our proposal. In our results, we show that the severe TBI inpatient population is tolerant of our methods and we are able to improve performance on our tasks by providing haptic feedback.

2. BACKGROUND

2.1 Introduction

While little research has been done using haptic robots and virtual environments for the rehabilitation of attention in severe TBI, there is a plethora of research on attention and the use of virtual environments in rehabilitation. In the following sections, I define the clinical model of attention, describe clinically proven attention therapy, identify methods to influence attention, and summarize recent research using virtual reality in rehabilitative settings. Our work starts with a virtual environment previously used in our lab, and introduces haptic effects based on studies showing methods of attention capture and redirection.

2.2 Attention

Attention is recognized as not a single distinct entity, but rather a construct of various cognitive processes. A commonly used clinical model defines attention as a componentization consisting of focused, sustained, selective, alternating, and divided attention, where each component pertains to a more complex task and is more difficult than the preceding. (13).

Many different attentional abilities are involved in routine behavior. Driving down a busy street, for instance, requires the simultaneous management of attention to multiple stimuli (divided attention), the ability to filter out stimuli (selective attention), and the ability to quickly shift attention and respond to sudden events (alternating attention). Driving down a deserted highway in the middle of the night, on the other hand, requires vigilance to maintain attention even without any external stimuli (sustained attention). Other tasks, such as getting dressed, cleaning, playing basketball, or crossing the street, all require different levels of attention to different stimuli and different management strategies to decide which stimulus gets precedence. As attention processes play a part in every task we execute, even minor degradations in performance can render an individual dangerous to himself or to those around him, further identifying attention processes as a crucial part of TBI rehabilitation. (11; 12)

A full assessment of attention is multifaceted and involves a series of tests, each targeting a different individual component of attention. For example, assessment for sustained attention involves a highly repetitive, often boring, task for an extended period of time, thereby requiring persistent vigilance to maintain accuracy and speed (13). Similarly, cognitive rehabilitation involves repeated exercises targeting specific processes. Accordingly, most rehabilitative programs for attention are comprised of a series of tasks, each exercising a given component of attention and progressively increasing in complexity and attentional demand (14; 15).

As our work is a preliminary study seeking to demonstrate the viability of our proposed model, we currently focus only on the simplest level of sustained attention.

2.3 Attention Process Training

The Attention Process Training (APT) program is a commercially available rehabilitative program in wide use across the nation built upon the aforementioned model of attention. The APT is designed as a hierarchy of tasks, such that preceding tasks must be completed in a specified amount of time and with a specified accuracy before progression may occur. When using the APT, the therapist creates a customized program based on the patient's needs and abilities, as higher functioning patients require more complex and demanding tasks in order to stimulate deficient processes (13; 16; 17).

One common example of a sustained attention task is shown in Figure 1. The patient is directed to mark all entities of a certain color and shape. While the task is relatively simple, it requires constant vigilance, especially when multiple sheets are provided consecutively. Those suffering from TBI often lose focus and forget the original task. (13)

As both assessment and rehabilitation constitute of a series of extended continuous performance tasks, often requiring additional customization per patient, even preliminary treatment requires large investments of time by clinicians and rehabilitation professionals, which, due to their increasingly demanding schedules, may not be practical or even feasible in routine practice. Additionally, these tasks are based on static media (pen-and paper or tape/cd) and therefore unable to dynamically adapt based on patients' immediate performance. Technology provides the advantage of not only automating highly repetitive therapy but also being able to alter therapy and provide progress reports based on real-time results. (18; 13).

2.4 Activation of Attention

Spatial attention has been shown to be crossmodally linked between vision and touch, such that activation in one causes an automatic and involuntary activation in the other. For example, when a bee lands on a person's finger, his visual attention is automatically diverted to the point of touch. Studies involving haptic cues and eye tracking have shown that this behavior is involuntary ant not ignorable (20). Therefore, if a haptic device and visual target

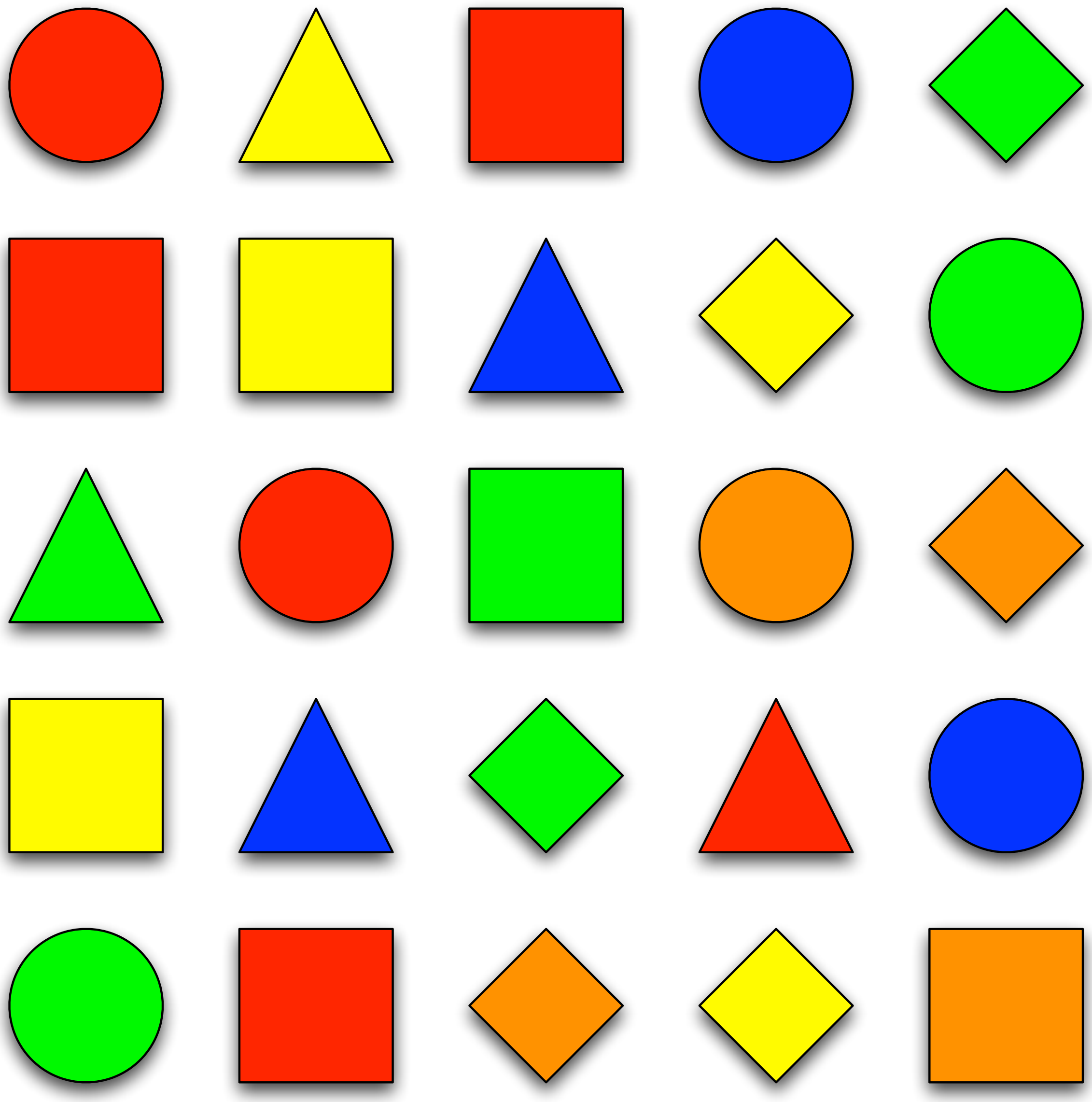


Figure 1. Example of a sustained attention test. Subject is directed to mark all red circles. Test requires constant vigilance to stay on task.

shared the same physical space, it would be possible to direct attention towards the target by providing a tactile cue (19; 20).

In cases where patients are suffering from attention process deficits, the repeated activation of those processes could, theoretically, help with rehabilitation. While doing this in typical therapy settings may be difficult, with a large three-dimensional virtual environment which augments real physical entities with virtual entities, it would be possible to place any entity in any space, including those already containing a physical entity. Our work further hypothesizes that not only will attention be captured and redirected to the task on hand, but said attention will persist to subsequent tasks.

2.5 Virtual Reality

Virtual reality (VR) is technology which allows the user to interact within a computer-generated environment, with a human-computer interface translating movements between the physical and virtual environments. The virtual environment is usually visual in nature, though it may also utilize haptic and auditory senses. VR allows alterations of objects' characteristics in space, and so, allows easy customization of environments and scenarios relative to the patients' needs, even those that may prove to be difficult in real life. Additionally, input data can be analyzed real-time in order to provide appropriate feedback and/or manipulate the environment, hence encouraging more effective and timely therapy.

Virtual reality has been demonstrated as a viable tool in both assessment and rehabilitation of a variety of injuries (21). It has been used in the restoration of cognitive and motor functions in stroke and TBI, (22; 23; 24; 25) functional evaluation of TBI therapy (26; 27) and assessment of cognitive processes damaged by TBI (28; 29; 30; 31). Studies have shown strong correlation between the results of VR-based assessment and real-world performance, and were able to reliably differentiate between healthy and TBI individuals. Furthermore, virtual reality has been shown to be both enjoyable and motivating, both of which increase the efficacy of rehabilitation (25; 32; 33). Virtual environments, however, have not previously been used for the rehabilitation of attention in severe TBI.

Overall, the benefits of virtual reality and haptic robots in rehabilitation involve the ability to fully control the visual environment, the ability to accurately record and transform movements, and the ability measure real-time performance and provide both visual and physical feedback or adjust environment parameters.

2.6 VRROOM

In the past number of years, our lab has developed a virtual reality system encompassing a large workspace three-dimensional viewport and a haptic device (VRROOM). Custom software has been developed to allow manipulation and recording of the visual and tactile environments. The VRROOM has been successfully used to help restore motor function in stroke survivors as well as assess attention deficits in TBI patients (23; 24; 31).

We expand on the VRROOM and present a number of enhancements to the platform based on previous studies linking spatial and visual attention (19; 20). Our enhancements provide haptic feedback when focus is lost and when task is near completion. Due to the complex and componentized nature of attention, we initially target only sustained attention and aim to show a preliminary viability of the platform in treating attention in TBI. Furthermore, due to the general difficulty of treating TBI patients, we also seek to demonstrate the the therapy is well-tolerated by the population.

We hypothesize that the therapy is well-tolerated, that haptic cues during focus loss, as evidenced by lack of movement, will capture and redirect attention to the task on hand, and that any haptic feedback will promote sustained focus across multiple tasks, such that overall performance will be improved in blocks with haptic effects.

3. METHODS

3.1 Subjects

Sixteen TBI patients were recruited from the inpatient population at the Rehabilitation Institute of Chicago. Eligibility criteria included traumatic brain injury, Rancho Los Amigos levels of IV or V, and a right upper extremity strength of at least 4 out of 5 Exclusionary criteria included visual field defects or hemispatial neglect that prevented perception of test stimuli, left hand dominance, an inability to understand the required task, or participation in any other clinical study. Patients were free to withdraw from the study at any time if they felt any discomfort (ie: caused by fatigue) and investigators were able to withdraw a patient for any reason whatsoever. All subjects were screened by a primary treating physiatrist and gave informed consent in accordance with the Institutional Review Board of Northwestern University. Personal and clinical data for the patients is listed in Table I.

3.2 Apparatus

A three-dimensional, large-workspace haptics/graphics system called the Virtual Reality and Robotic Optical Operations Machine (VRROOM) was used in this study (Figure 2). VRROOMs visual display subsystem, the Personal Augmented Reality Immersive System (PARIS), developed at the University of Illinois at Chicago, allowing users to view virtual objects superimposed onto the real world. A cinema-quality digital projector (Christie Mirage 3000 DLP) displays the images over five-foot-wide 1280x1024 pixel image resulting in a 110° wide view-

Subject	*Sex*	*Age*	*Rancho Level*	*Weeks Since Injury*	*GOAT Day 1*	*GOAT Day 2*
TBI 1	M	23	IV	4	76	88
TBI 2	M	34	V	3	56	NA
TBI 3	M	39	V	32	94	93
TBI 4	M	59	V	2	6	6
TBI 5	M	22	V	10	35	50
TBI 6	M	26	V	2	85	80
TBI 7	M	45	IV	4	15	30
TBI 8	M	27	IV	4	62	65
TBI 9	M	24	IV	4	70	83
TBI 10	F	72	V	4	60	69
TBI 11	M	67	V	5	95	NA
TBI 12	M	21	V	4	55	74
TBI 13	M	73	V	6	78	72
TBI 14	M	40	V	7	78	41
TBI 15	M	19	V	6	96	91
TBI 16	M	36	V	6	53	64
TBI 17	M	24	V	6	95	95
TBI 18	M	56	V	71	48	25

TABLE I

PERSONAL AND CLINICAL INFORMATION FOR TBI PATIENTS

ing angle. A 6-degree of freedom PHANToM Premium 3.0 robot (SensAble Technologies) is capable of generating 3 Newtons (N) with transient peaks of 22 N and provides a workspace measuring 900 x 900 x 300 mm. Its hardware-resident controller runs asynchronously with the computer for stable, uninterrupted control. The correct perspective and stereo projections for the view of the scene were computed using values for the current position and orientation of the head (6 DOF) supplied at 100 Hz by a tracking sensor (Flock of Birds, Ascension Technology) attached to the stereo shutter glasses (Crystal Eyes, StereoGraphics Inc.) worn by the subject.

The immersive virtual environment consisted of a minimal environment with no background textures and only a cursor and a target (generated as 3D virtual ball-shaped targets with a 1 cm radius) in the field of view. Targets could be both seen (using VR technology) and felt (using robotics to render haptic sensation) (Fig. 1b). Subjects sat in a dark room on a chair placed in front of the VRROOM system, grasping the handle of the robot with their right hand.

3.3 Procedures

Subjects were required to hold the handle of the robot and reach towards a spherical target that appeared in a minimalist virtual environment displaying only a cursor and target in order to minimize visual distractions. The set and order of targets were predefined such that all targets appeared within a field of view previously determined by a study in our lab on targeted reaching (23). Furthermore, the physical distance between all pairs of consecutive targets was identical. Each movement was allotted a maximum time of ten seconds, and was marked as complete when either the cursor had intersected with the target for 250ms or the time limit had expired. After completion of a movement there was a delay of 500ms after which the next target would be shown. Each patient was given four minutes to complete as many targets as possible (a block).

Subjects visited the lab on two consecutive days. Each visit consisted of three treatment phases with one of the haptic characteristics described below, and each treatment phase consisted of two four-minute blocks. The order of treatment phases was randomized on both days. In order to reduce fatigue, patients were allowed short breaks (1 minute) after each block and a longer break (1-4 minutes) after three. The set of possible haptic effects was defined as follows:

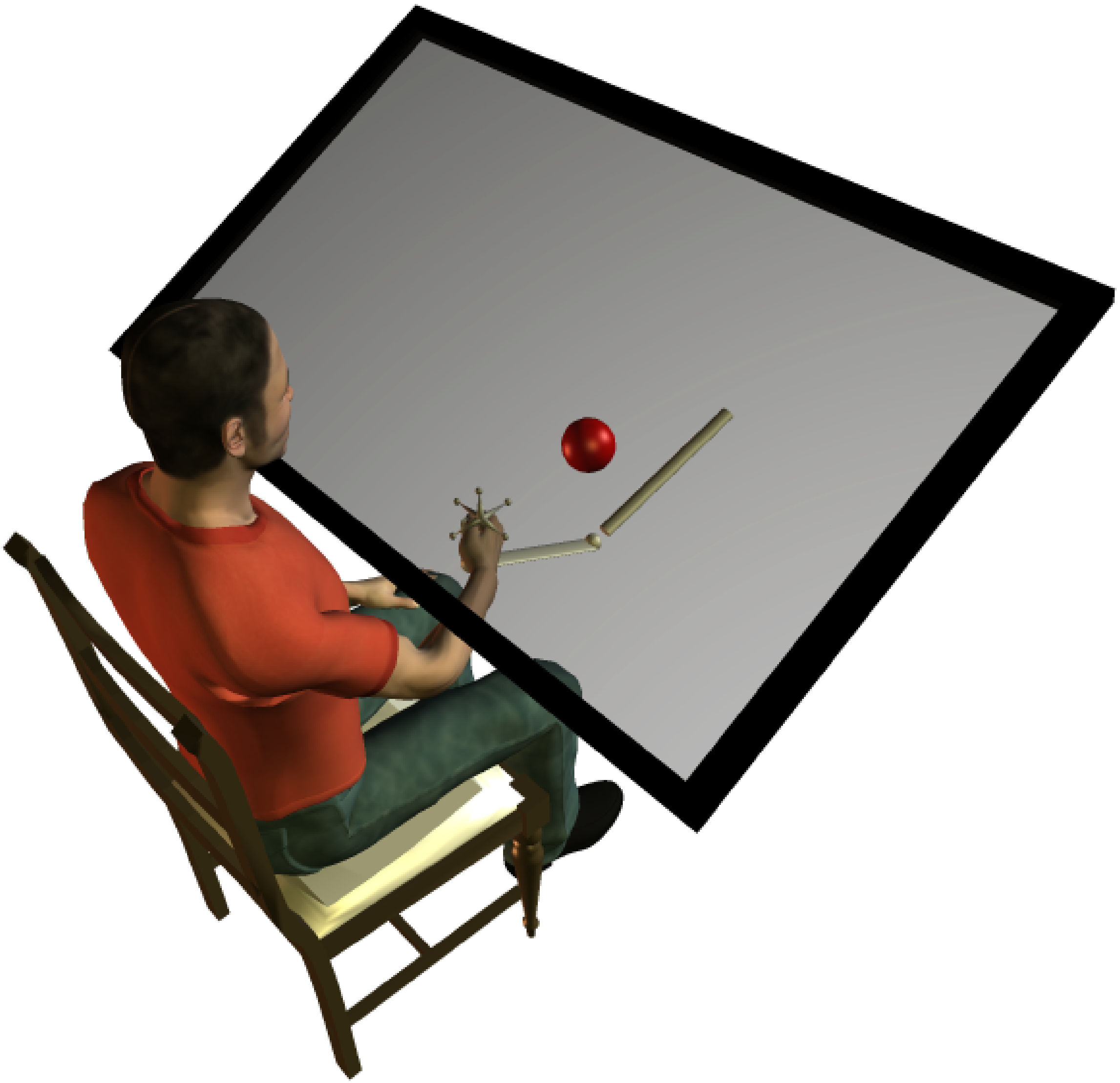


Figure 2. Rendering of user sitting at VRROOM system with cursor and target. Cursor, in the shape of a jack, is spatially colocated with hand, but hand and haptic device are not visible through glass.

- **Control** No haptic feedback
- **Balloon** A 0.5 N breakthrough haptic force was required to enter each target sphere, similar to popping a balloon. Forces were exerted according to the gradients of a trivariate Gaussian function. As the subject approached the target, he encountered a repulsor force at 1cm from the center of the target. Once this force was overcome, it gave way to an attractor force that pulled the cursor towards the center of the target. Furthermore, as the cursor approached the center, the attracter force was reduced to zero.
- **Nudge** A 1 N, 250 ms nudge, exerted in the direction of the target, was applied if the system detected no movement above 0.05 m/s in a one second period, thus providing a haptic cue to the patient to continue with the task.

3.4 Data Analysis

The VRROOM system is capable of recording events occurring in the scene (e.g., appearance of a target, application of forces), as well as the subject's arm position in space at any given time (via the robotic arm) at approximately 100 Hz. From our raw data, we calculated the distance to the target as well as instantaneous velocity at each recorded moment. We performed significance analysis on a linear mixed-effects model in order to remove within-patient differences and understand effects caused by ordering and haptic feedback.

4. RESULTS

4.1 Tolerability

Two of our eighteen patients requested to withdraw from the experiment. One of those had refused all previous therapy from our clinicians, so the request was not unexpected. The other withdrew halfway through the first visit. A third patient was unable to complete all of the blocks on his first visit due to fatigue, but he returned and completed all trials on the second visit.

We requested feedback from our patients for their opinions regarding the experiment. The primary, and most repeated, complaint was that the experiment became too easy and thereby boring. This identified a need for more complex tasks that target higher orders of attention as performance improves. The idea of progressively more demanding tasks parallels clinically proven rehabilitation paradigms, such as the APT, which increase difficulty as performance improves (13).

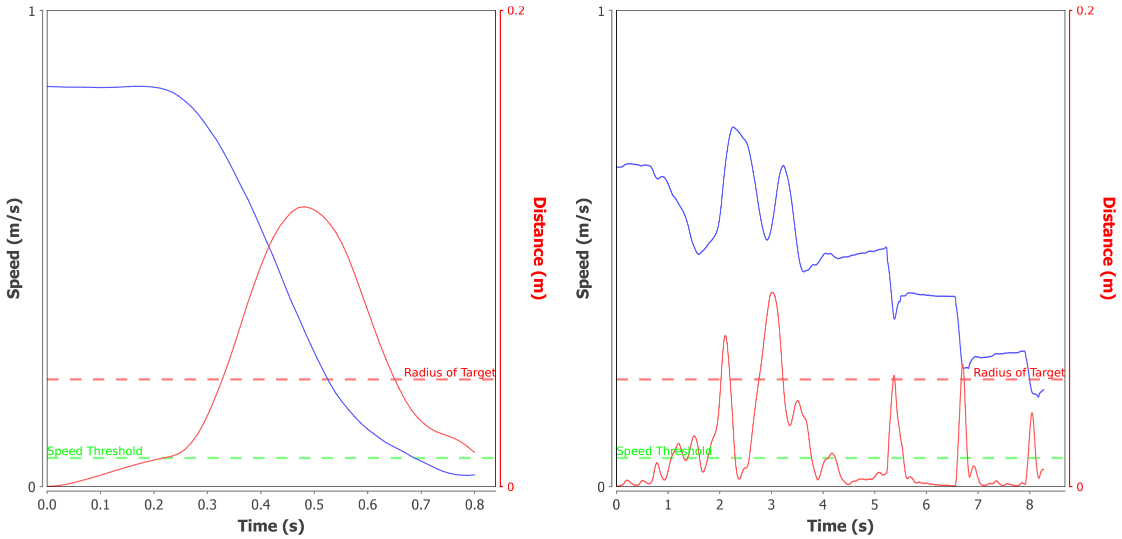
4.2 Overview Analysis

Although we limited our subjects to Rancho IV-V, we witnessed a wide range of performance, spanning from the minimally functional to the almost fully functional, relative to our tasks. We were able to identify problematic movements that showed repeated stops and difficulties completing even a simple point-to-point movement (3(b)). These transient pauses were believed to be due to loss of attention, though an assertion isn't possible without specific monitoring of attentional processes. We also identified problematic movements which were aided by the application of a haptic nudge (3(d)) as well as movements which were inhibited by exertion of a breakthrough force (3(c)).

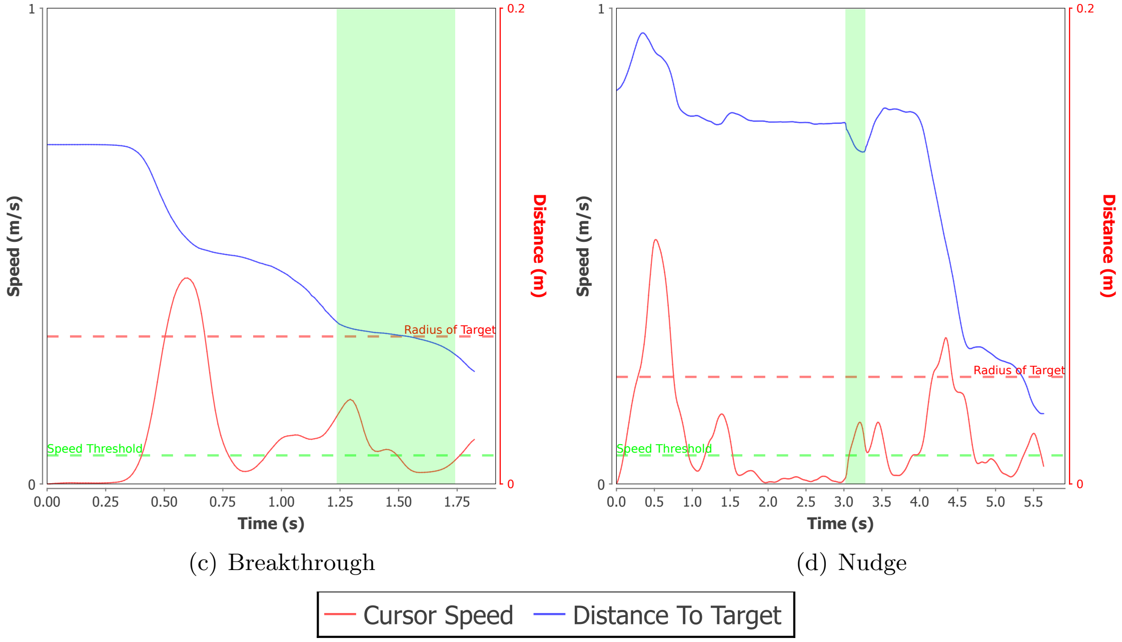
Eleven of the patients received less than ten nudges and five of the patients received more twenty nudges. No patients received between 10-20 nudges (Figure 4). A few nudges could be attributed to becoming adjusted with the environment, not understanding directions, and losing contact with the robot. Because the total number of trials depended on performance, the actual difference was more than twofold. Those receiving less than ten nudges had rates of 0-.5% of total trials, whereas those with greater than twenty nudges had rates of 3-20%. Further analysis showed a distinct separation of performance and response to haptic effects between the two groups. For purposes of identification in this study, they are henceforth known as "high-performing" and "low-performing". These terms do not necessarily relate to any clinical outlook or diagnosis.

Both groups showed consistent improvement on the first day, which may be at least partially attributable to learning. The high-performing group showed a distinct performance increase between the first and second days, after which variations in movement time decreased and performance leveled off. This provides further evidence that these patients would be prime subjects to progress to more demanding tasks. (Figure 5)

The low-performing group showed statistically significant improvement throughout both days, with improvement continuing to the end of the second day. This group would likely stand



(a) Ideal Movement (b) Problematic Movement



(c) Breakthrough (d) Nudge

Figure 3. Selected individual movements. Green shade is application of haptic effect. Green dashed line is speed threshold under which is considered no movement. Red dashed line is radius of target. (a) Ideal movement. Note time scale relative to other figures. (b) Problematic movement with no haptic feedback. Note repeated stops. (c) Movement with breakthrough force. Note temporary delay upon force near target. (d) Movement with haptic nudge. Note reinitiation of movement after nudge.

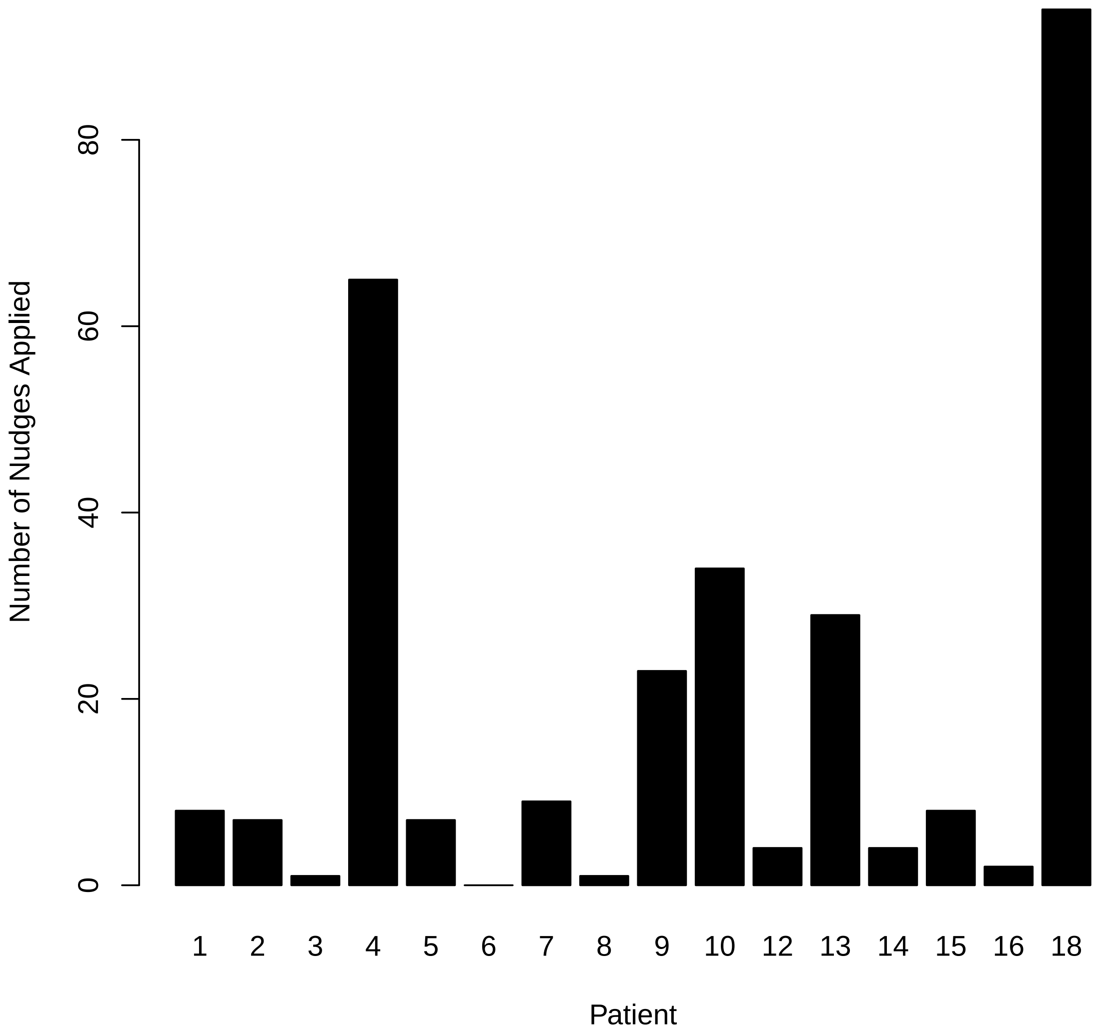


Figure 4. Number of nudges received per patient. All points are less than 10 or greater than 20, identifying a distinct characteristic between low and high-performing patients. Patients below the threshold (shown as a dashed line) were treated as high-performing patients, and atients above the threshold as low-performing patients.

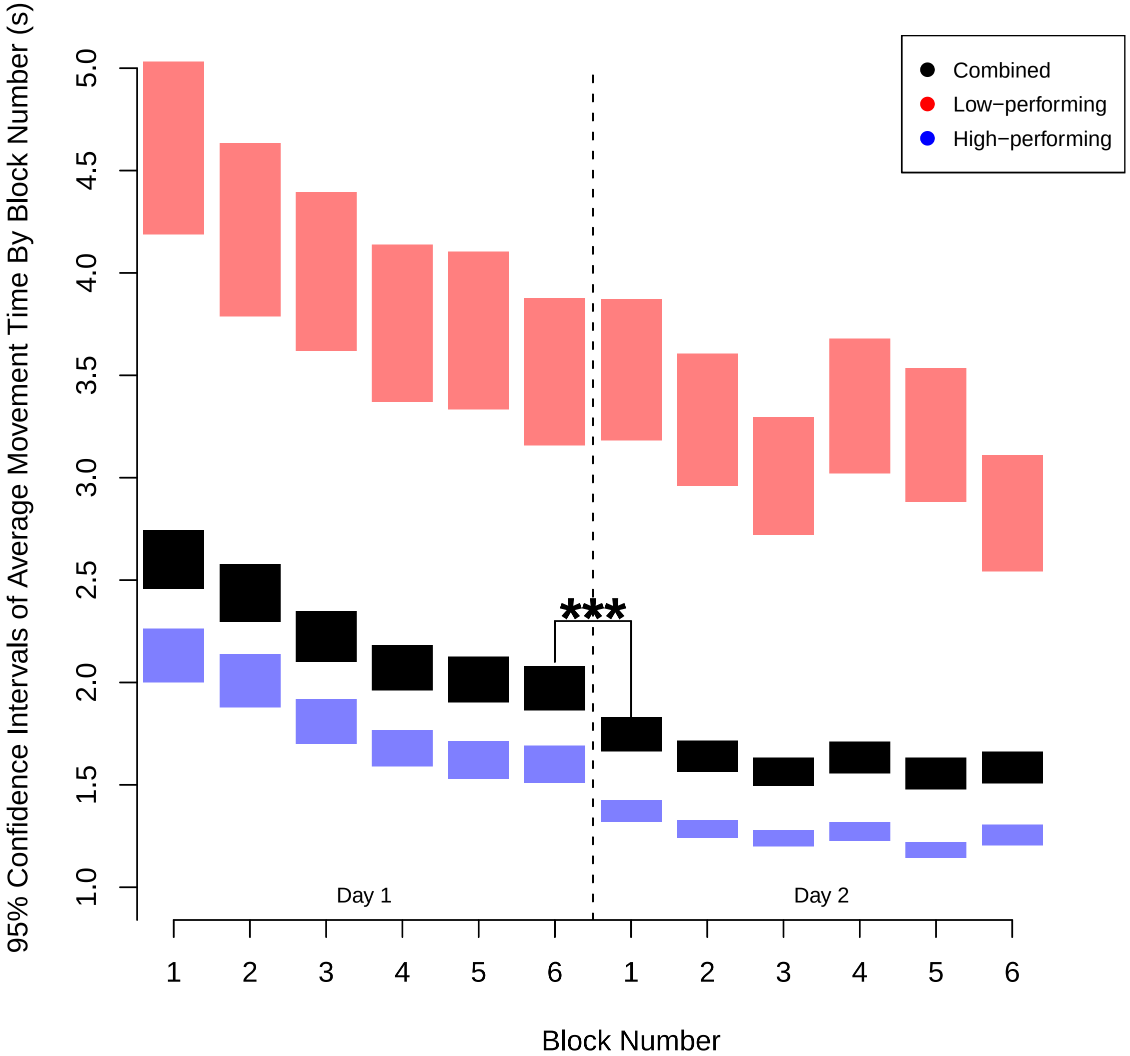


Figure 5. 95% confidence intervals of movement time vs block number show consistent improvement throughout the first day and beginning of second day, major improvement between first and second days, and level off by end of second day, distinct difference in performance between two groups of patients, identifies strong ordering effect.

for more of the same tasks until performance is similar to that of the high performing group. (Figure 5)

In comparing performance vs haptic effect, the high-performing group showed little variance within each block type. However, the balloon effect caused a performance degradation, and nudges, on the other hand, resulted in slightly better performance. Since this group received only a few nudges, on the order of less than 0.6%, it would be expected that the performance measures would be the same across the Nudge and No Effect blocks. The low-performing group showed high variability within each block. Balloon effects had no effect on performance. As there is some improvement in the nudged blocks, it provides support for our hypothesis that the nudges will improve lasting performance. (Figure 6)

Nudges, however, significantly improved performance. This population had nudge rates between 3-20%. The performance in the Nudge blocks for low-performing patients provides greater support that nudges do help the patient in overall task completion. (Figure 6)

4.3 Interaction Analysis

In order to identify the core factors affecting performance, we first created an interaction plot for time vs visit and block type, for both high- and low-performing patients. The performance during Nudge blocks was better in every case, while there was no significant difference in performance between Balloon blocks and No Effect blocks (Figure 7). Two-way repeated ANOVA measures showed that both day number and block type significantly affected performance, however, practice was a much greater influencing factor. (Table II) Tukey's Honest

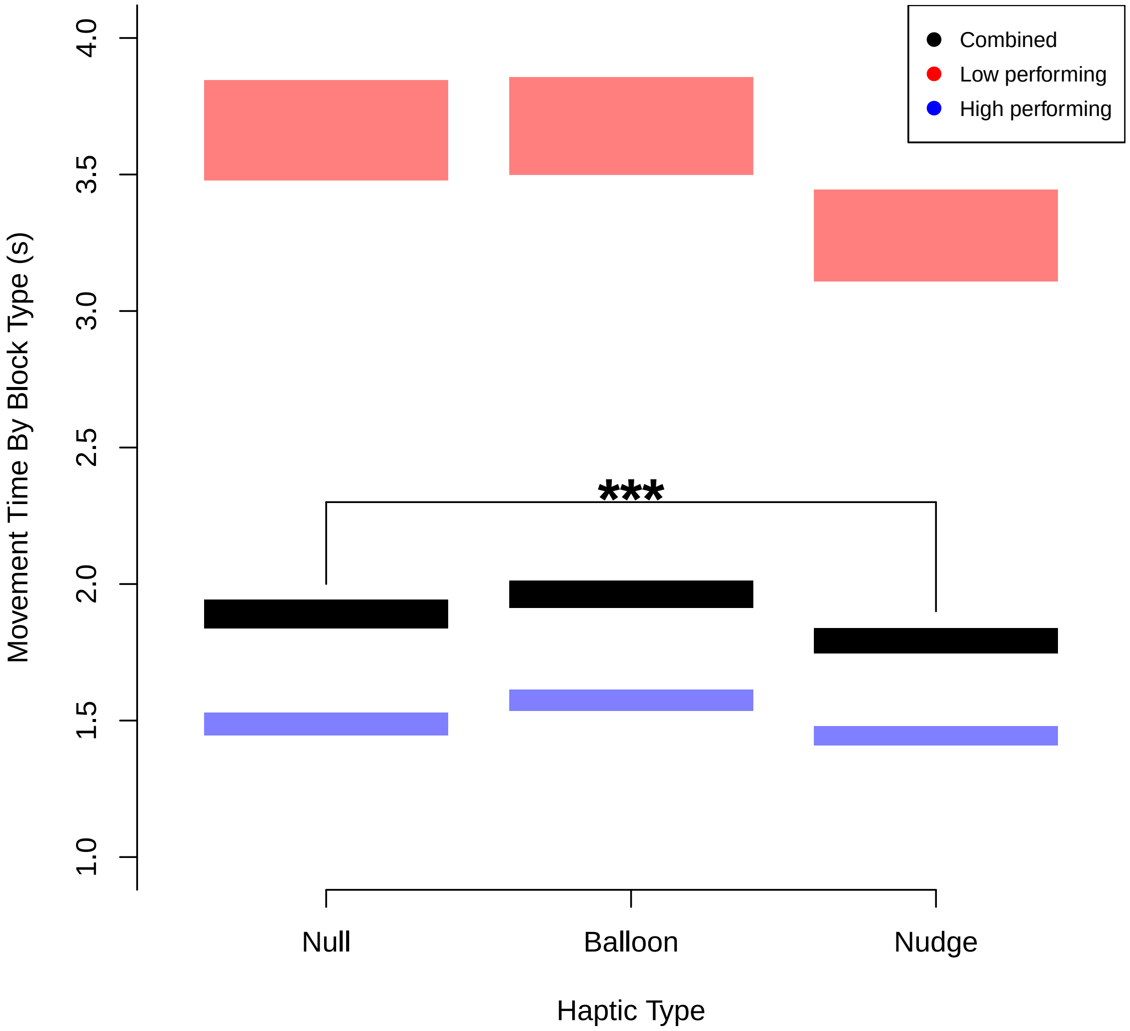


Figure 6. 95% confidence intervals of movement time vs type of haptic effect show strong improvement with nudged blocks for both groups, though distinct difference in response to haptic effects. P-values determined by Tukey's Honest Significant Difference Test performed on a Linear Mixed Effects Model.

Significant Difference Test performed on a linear mixed-effects model showed that only the nudge and no effect blocks were significantly different for both populations. (Figure 6)

		Low Performant		*High Performant*	
	Df	F value	p-value	F value	p-value
Day	1	50.05	<.0001	887.59	<.0001
Type	2	5.68	.0034	18.06	<.0001
Day:Type	2	1.21	.2974	7.35	.0006

TABLE II

TWO-WAY REPEATED MEASURES ANOVA

4.4 Movement Analysis

Finally, we analyzed the effect of haptic nudges on individual movements by combining all of the movements where a nudge had been provided or would have been provided, had it been enabled. We found mixed results and widely differing responses to individual nudges. Patient #10 showed a near immediate response to the nudge as well as an increase in task completion rate. Patient #9, on the other hand, resisted the nudge and was unable to complete the task when a nudge was provided. However, even with a degradation of performance on the specific movements where a nudge had been provided, Patient #9 showed overall improvement on the blocks with nudges compared to those without. Therefore, even though the nudges prevented the patient from completing the immediate movement, they may have stimulated sustained attention that was carried over to subsequent movements. Patient #13 showed some initial

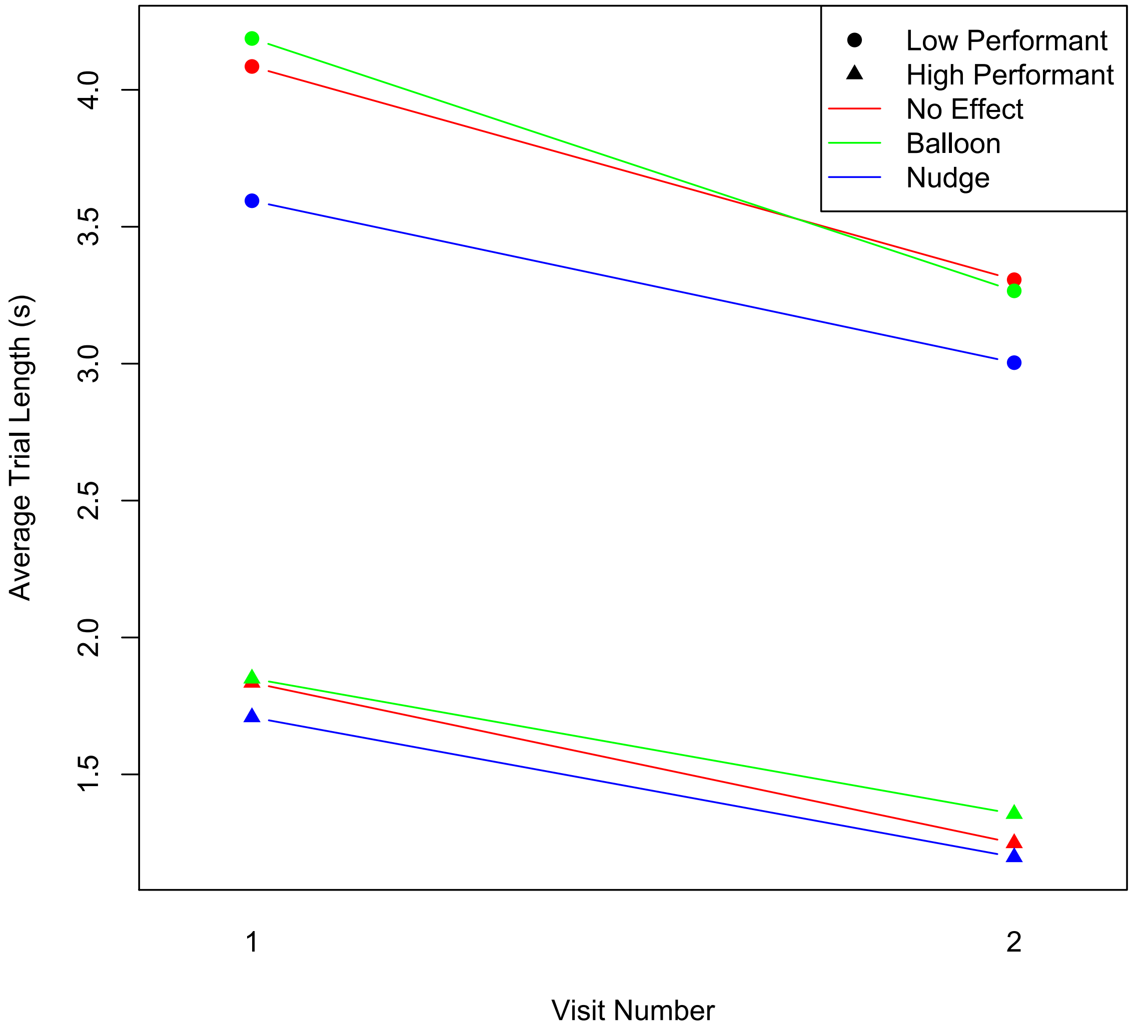
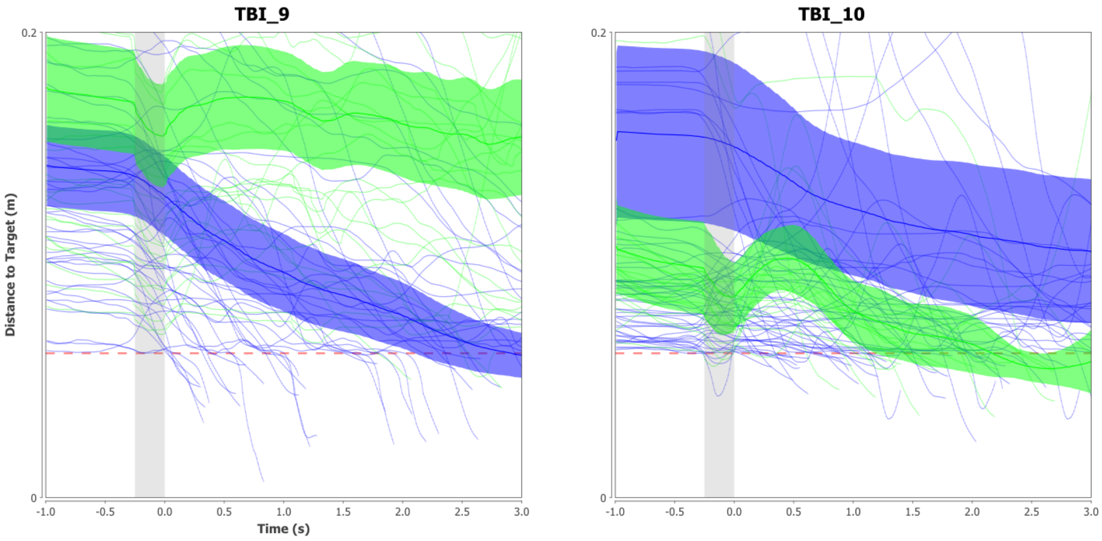


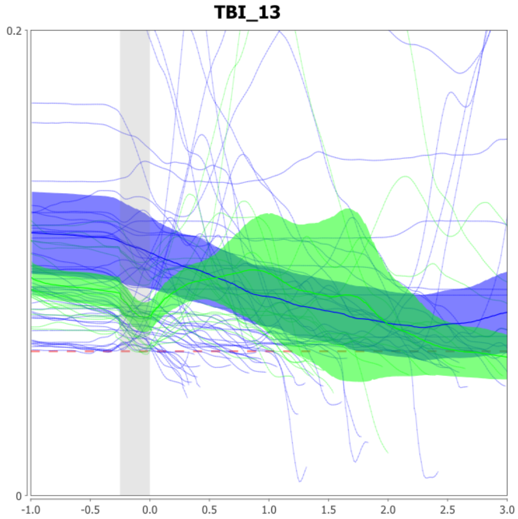
Figure 7. Interaction plot of average trial length vs visit number, split across block type and high/low functioning patients.

resistance causing movement degradation; however, this was quickly corrected, resulting in slightly better performance on the task at hand. (Figure 8)



(a) Patient #9

(b) Patient #10



(c) Patient #13

Figure 8. Distance to target vs time. Movements with attention loss as evidenced by decrease in movement speed. Movement times are normalized to (green) haptic nudge or (blue) where haptic nudge would have been provided. Shaded overlay is 95% confidence interval of position vs time. Gray marker identifies time span of nudge.

5. DISCUSSION

This study was a preliminary foray into the rehabilitation of attention in severe TBI using haptic robots in a virtual environment. Previous studies, from our group and external groups, have shown the viability of robotics in rehabilitation (22; 23; 24; 25), the ability of a minimal virtual environment to differentiate between TBI and healthy individuals (31), and the ability to direct visual attention with sensory information (19; 20). No previous studies, however, have used virtual environments for the rehabilitation of attention in inpatient severe TBI. We showed that the severe TBI population was tolerant of a VR-based therapy, that the population's performance of the provided task improves through time, and that haptic nudges improve overall performance but differentially influence immediate movements. The most surprising results were that not only does the population improve within tasks and retain improvements on following days (savings), but actually improve overnight between days.

Our analysis of nearly twenty-thousand movements identified two distinct subgroups of the population, those who received either less than ten nudges, amounting to less than .5% of all trials, or more than twenty nudges, at 3-20% of all trials. These two groups had significantly differing performance results as well as different responses to haptic feedback.

Two-way ANOVA analysis showed that both haptic effect and ordering had significant effects on performance; however, ordering was a much greater contributing factor, thereby identifying practice time as the primary effector of performance. Within single days, there was significant improvement every other block, regardless of haptic effect. For a population not known to even be able to retain visuomotor memory, these results on their own were surprising. Furthermore, performance significantly improved between the last block of the first day and the first block the second day. Not only did the population retain performance increases between successive days, but actually gained further improvement overnight.

The retention of performance has been shown to exist in healthy patients and has been identified in previous studies as 'savings'. Some studies have further demonstrated that visuomotor memory to a field of motion can be improved, even over the time course of days, as long as the subject is not exposed to a different field with a conflicting motor map (34; 35). However, this has not been previously shown to exist, or not exist, in the case of the severe TBI population.

As all of our tasks involve an identical field of motion, it is possible that all patients would show significant improvement between days. However, because those patients who performed porrly overall only showed retention, but no improvement, another set of questions are presented: Are some groups of severe TBI unable to retain long-term visuomotor memory? How would performance across multiple days be affected if we provide a conflicting field at the end of each visit in order to diminish long-term motor memory? These questions can not be answered by the current study, but could be by a slightly modified version.

Furthermore, results also showed that those who performed well stopped improving on the second day, indicating a "floor effect". This suggests that this group would be prime subjects for progression to more complex tasks targeting higher orders of attention. Some patients also complained that the task had become too easy on the second day. These findings are in line with clinically proven attention therapy in that as attentional processes improve, more demanding tasks are necessary. (13) Results show minimal variance at the point where patients stopped improving, allowing for the identification of a threshold that could be used such that once passed, the patient would be provided with a more challenging task: for example, a task where two different colored targets are shown, while the patient is instructed to reach towards one color.

Significant difference tests showed that balloon effects caused minor degradation of performance, while haptic nudges resulted in significant performance improvements. Furthermore, our results show that even in cases where a patient resisted a haptic nudge and was unable to complete the immediate movement, he still performed better during the block where nudges were provided. The application of nudges therefore, although preventing immediate completion, may have captured and promoted sustained attention to subsequent tasks. As our study has shown that haptic nudges do improve performance on immediate blocks of tasks, it thereby presents a following question, leading to the long-term goals of this work: Can haptic nudges improve the efficiency of rehabilitation?

All of the nudges we provided were applied in the direction of the target and for a fixed length of 250ms. Because the activation of attention requires only sensory feedback and does not necessarily have to be directional, further questions are introduced: How would different nudges affect performance? If we provide nudges that act as simply vibrations with no lasting transposition of the cursor, would performance still be improved? If nudges were in the opposite direction of the target, or in random directions, how would the identified performance gains be affected?

As we recorded exact three-dimensional hand position and head orientation at each measurement, there are many more measures that could have been analyzed in this study but were left out. We focused primarily on task completion times and two-dimensional distance from cursor to target. While the data is available, we have not yet explored three-dimensional movement error, movement onset time after presentation of target, or number of within-movement stops and speed peaks, all of which may provide additional insight and information.

Lastly, only two of our eighteen patients requested to withdraw from the study, and one of those had refused all forms of therapy. We expected a higher dropout rate from the population, and our clinicians have reported that these results are promising from a strictly tolerability standpoint. Overall, this study has corroborated previous results that VRROOM-based therapy is well-tolerated by the TBI population.

This study directly leads towards an extended clinical intervention into the use of haptic robots to improve attention in severe TBI. We are beginning a study analyzing the performance of a VR and haptic-based therapy for attention in severe TBI over a thirty-day period. The forthcoming study will use the foundation laid by these results as well as address some of the discovered problems, such as the need for complex tasks.

One of the primary benefits of virtual (and augmented) reality is its ability to dynamically create, modify, and extend different sensory environments. It furthermore provides cost and space-saving benefits. This study has shown that virtual environments are tolerated by a population known to be fairly intolerant of therapy and that haptic feedback can be used to beneficially alter movements and attention. It thereby lays evidence that VR would be tolerated by many different populations, and that virtual environments and haptic robots may be used in different forms of cognitive rehabilitation.

6. CONCLUSION

Our results showed that severe TBI patients, who are normally resistant to therapy, were tolerant to our virtual environments. It showed that patients that patients' performance improved over the first day, as well as overnight between the first and second days. However, they leveled off over the second day, seemingly requiring more challenging tasks. Both block number and haptic effect were significant contributing factors to performance. Haptic nudges applied when movement stopped significantly improved performance across blocks even in cases when nudges were applied in less than one percent of the trials, giving evidence that nudges were able to improve attention to subsequent movements.

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