Limit-Push – Reduction of Motor Variability in a Virtual, Haptic Environment with Visual Distortions

BY

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B.S., University of Illinois at Chicago, 2012

THESIS

Submitted as partial fulfillment of the requirements
for the degree of Master of Science in Bioengineering
in the Graduate College of the
University of Illinois at Chicago, 2014

Chicago, Illinois

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ACKNOWLEDGEMENTS

It cannot be stressed enough that my ability to write this thesis has been a result of the willingness of my professors and friends to work with me over my years in college. Here I name the people that are most directly related to this thesis project along with my family whose support has been essential throughout my life.

My sincere thanks goes to Dr. Jim Patton for all that he has taught me from classwork in neural engineering and bio-control to the research work presented here and especially for providing an open and welcoming lab atmosphere.

I appreciate the guidance that Dr. John Hetling gave me in neural engineering literature during his introductory class, for his role as an advisor during my undergraduate years, and for helping the BMES board members and I form a group that encourages comradery among students. I thank Dr. Thomas Royston for also supporting our student organization. For the entire committee, I appreciate them giving their time and feedback to help me earn my degree.

For my friends in the robotics lab where I have done my projects, I have great appreciation for their willingness to help me, to hear me out in often long conversations and to listen to my presentations. This includes among others, Dr. Felix Huang, Yaz Majeed, Dr. Farnaz Abdollahi, Moria Fisher, Dr. Emily Mugler, Zach Wright, Joseph Lancaster, Dr. Alejandro Melendez, Peter Cooman and Justin Horowitz. I will always hold dear to me the good times we shared during lab outings. Specifically, this work has been done in collaboration with Amit Shah, and I appreciate his time and helpfulness throughout the process. This work was based on Dr. Ian Sharp’s code and paradigm, and I would like to thank him for his email responsiveness and help.

I would also like to thank Dr. Robert Kenyon, Lance Long and Cristian Luciano at the UIC Electronic Visualization laboratory for their technology advice and recommendations and
the staff members at RIC and the UIC Bioengineering department for their friendliness, patience and responsiveness.

Mentioned here last but certainly are not the least, I would like to thank my family for their support and patience with me during sometimes frustrating times. While I am often self-critical in order to keep myself improving, their pride, excitement, and joy about my work helps remind me of my successes, and I rejoice with them. I am most grateful for having my parents near to my heart and for having my dear sister as a close, loving friend. In life ever changing, they are the constant.

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SUMMARY

As a problem in physical rehabilitation and performance training, there is interest in studying arm movement variability. This study builds on previous motor control work in which subjects performed a projectile catching task with a robotic arm endpoint to control a cursor in a virtual reality environment. In that study it was seen that the distribution of arm movement positions can be influenced by a bounded region. The bounded region was the only space in which subjects would not experience a distortion while they did the task. That is, leaving a pre-defined bounded region caused them to experience a catastrophe where force feedback pushed them further away from the boundary. The subjects’ conception of the boundary, which they otherwise did not see, was evidenced by the reduction in the distance to the edge of the boundary. In this work we have collected a new treatment group using the same setup except that subjects only receive visual feedback in response to leaving the boundary. The visual feedback is a distortion of the cursor away from the boundary rather than a robotic push. We have seen that visual feedback shows promise in manipulating arm movement distribution in the distance to edge and percent outside metrics. These metrics showed a reduction of the subjects’ distance to edge and a shift of their movement distribution inside the boundary compared to a control group that received no distortion. Further work could seek to manipulate the spread of movement distribution perhaps by creating a more appropriate visual distortion.

Constructing and evaluating the use of such virtual environments is important as they have potential to help those with limited arm movement due to stroke or traumatic brain injuries. However, in order for such methods to expand out of the laboratory and be validated clinically, their apparatus must be low cost and portable. In this regard, visual distortions are preferable to force feedback because future experiments can implement them without the use of an expensive robot. In the same effort, we have contracted a new apparatus that provides the same virtual reality environment as the VRROOM system. This system, the LookingGlass, utilizes 3D LCD
SUMMARY (continued)

technology and fewer materials than the old VRROOM system. Future work could implement optical arm movement tracking to conduct motor control experiments such as the one presented here without a robot.
1. **Visual Limit Push Reduces Motor Variability**

1.1 **Introduction**

Everyday tasks often require arm movement control that is accurate, but consistent attempts could be essential to accuracy. Generally, movement tasks require the central nervous system to integrate sensory input such as vision, proprioception, and touch to create a useful output. For example, a tennis player must reliably match their visual perception of the ball with their experience of racquet swings. A range of racquet locations at the correct times can result in returning a serve, and with practice a player can learn this “sweet spot” that results in good returns. Beyond this range are “high cost” states with catastrophic, failure outcomes in which the player misses the ball or hits it outside the court. Whether it is for performance training or physical rehabilitation, learning occurs only through repetitive practice and experiencing sensory consequences. It may be that the sensory consequences of high cost states are what motivate learning and shape new behavior. If this is true, the prospects of simply distorting feedback may be a viable learning tool. Here we focus on distorting vision in order to modulate movement into an unseen bounded region thereby decreasing variability.

1.1.1 **Error Augmentation**

Visio-motor distortions can favorably modulate human movement tendencies. This has been established in previous work in which a robotic arm pushes a subject further away from their goal according to how much error there is in their position at any time [1]. This *Error Augmentation* (EA) approach postulates that if a person receives unexpected force error feedback, they learn to correct errors more quickly. This can be because exaggeration allows a person to become aware of their error, or because of a typical reaction in the opposite direction of the force. EA was further shown to work with visual distortions in a study where subjects learned to correct for a visual rotation. When the subject deviated from a straight line trajectory,
their cursor was rendered some distance away from the actual robot position according to the magnitude and direction of error. Subjects exposed to this treatment learned to make straighter trajectories faster and with less error compared to a control group [2]. This method was also done in a three dimensional workspace in which subjects learned a complete 180 degree transformation of the workspace with the help of visual EA [3]. It is favorable to continue to explore EA using visual distortions, because theoretically they can be implemented without a robot. This can be done by doing EA with a simple position tracking camera which has a much lower financial cost compared to robotic arms.

While these previous studies shown promise for EA in point to point reaching, the current study investigates how the EA concept can be more broadly applied to the conditioning movement variability. Here, we evaluate a derivative of EA, called limit-push, in a projectile interception task. While the more commonly used point-to-point reaching task calculates error based on a straight line trajectory, our projectile interception task may be more typical of everyday actions because it allows a large number of possible actions that all can successfully complete the task. Consequently a subject’s movement-to-movement variability might be naturally large. Our goals are to use the limit-push approach to reshape variability patterns by encouraging motions within a boundary that is highly constrained along one dimension.

1.1.2 Motor Variability

Variability has been found to be both beneficial and detrimental to human movement depending on its type of occurrence and extent. There is evidence that variability is endogenous as it relates to activity in motor units, the basal ganglia circuits, and the premotor cortex [4]–[6]. Perhaps this means that variability is favorable, and some work has provided evidence that action exploration increasing motor variability facilitates motor learning [7]. Movement variability is also facilitated by the anatomy and physiology of the upper extremity which allows for multiple solutions to accomplish the same goal. Finally, some movement variability has been attributed to
execution noise that can be proportional to the magnitude of effort [8]. While some variability allows for movement flexibility and perhaps is “inherent” to movement, at some levels variability is unwanted and has to be minimized for precision. The compelling question is whether variability can be altered through specialized training.

Given that some amount of variability will always be present, decreasing movement-to-movement variability for a specific task can help improve human performance. This is specifically true for stroke and traumatic brain injury (TBI) patients who exhibit increased motor variability due to incoordination, decreased strength, absent sensation, or combinations thereof [9]–[11]. Decreasing variability is also of interest in microsurgery because of tremor and high signal to noise ratios of the system [12]. In this study we seek ask whether a person’s motor variability can change by exposing them to a catastrophic distortion when they reach outside a pre-determined boundary limit.

1.1.3 Boundary Learning and Limit-push

This boundary learning approach of modulating variability reflects on typical experiences in everyday life in which people have to stay within a specific region to have functional movements as demonstrated by the simple of standing. During standing the human can be modeled as an inverted pendulum. When a person’s center of mass, analogous to the top of the inverted pendulum, moves past a certain boundary during leaning, the person enters a catastrophic region in which they fall. It has been discovered that people create a safe guard in velocity space in order to avoid entering a high risk region in which they would experience a fall [13]. It is possible that a person’s movement variability is too large to be able to stay within the safe region for some tasks. Therefore this work tests whether exposing a subject to a catastrophic visual distortion will reduces their movement variability in a critical dimension while attending to a goal directed task. This limit-push approach has already been shown to be
effective using robotic forces that push the hand further out once the limit is reached [13]. What remains to be seen is whether this will work with simple visual distortions.

In this study, we explicitly test whether people can learn a boundary defined by distortions of vision rather than force. We evaluate the changes in motor patterns in response to training in the presence of a visual distortion that only is present when a person’s exceeds a boundary. This builds on a previous work which showed that people’s movement can be limited to a safe region by using a force distortion that pushed subjects away from the safe region [13]. Similar methods are used here except for the replacement of a force distortion with a visual one. Establishing that a visual distortion is sufficient shows promise that our training environment can be implemented without a robot thereby decreasing cost. If variability can be reshaped in healthy individuals, it may be possible following stroke or traumatic brain injury for whom high variability is detrimental to everyday activity.

1.2 Methods

1.2.1 Subjects and Apparatus

The experiment included 18 neurologically healthy subject volunteers who signed an IRB consent form. Subjects were divided randomly and evenly into a treatment group and a control group. The number of subjects was based on the previous limit-push experiment for which a power analysis showed that nine subjects per group would be sufficient. They sat at the center of the VRROOM (Virtual Reality and Robotic Optical Operations Machine) which provided a 3D, stereoscopic image for a large virtual space superimposed on a robotic workspace (see Chapter 3 for details about the VRROOM system). Interaction with the virtual environment was possible through manipulation of the SensAble Phantom 3.0 robot with a spherical end effector. The virtual space and robot arm limits were large enough such that the subject could fully extend their arm in front of them while grasping the end effector. The end effector was used to control a red cube (5 cm³) that served as a cursor in the virtual space. The virtual space also consisted of
a green sphere (11.5 cm radius) representing the subjects’ workspace and a blue cube projectile (5 cm$^3$). Aside from the projectile, cursor and workspace, the environment was black and the room was pitch-dark to avoid outside distractions. Subjects were told that their task was to intercept the blue projectile with the red cursor while keeping the red cursor inside of the workspace sphere.

At the beginning of each trial the blue virtual cube would launch towards the subject at 0.8 m/s from about one meter away in trajectory chosen randomly from a set of trajectories that always intercepted a semi-transparent green sphere workspace in front of the subject. Subjects were told their task was to intercept the blue projectile while staying within the green workspace sphere. The robot provided a small interception force each time it was successfully blocked by the subject. After interception, the projectile stopped instantly and reset to its home position which was constant throughout the experiment. The virtual environment was rendered with H3D in XML code and manipulated with Python.

Figure 1—Top down (left) and side (right) views of the experimental setup. The boundary (invisible to the subject) is in red. The workspace sphere is in green, and in blue is the projectile and the trajectory lines that it follows upon launch.
1.2.2 Data Processing

Several data processing steps were taken to prepare for analysis. First we applied a low pass Butterworth filter at 16 Hz in order to remove movement frequencies that are far beyond meaningful human movement tendencies. Additionally this filter removed duplicate timestamps that were due to rare occasions of spurious recording that were not resolved before data collection. The data was then down-sampled to 50 Hz to make it more efficient for analysis. Finally any position observations that were beyond what the 95th percentile of what a human could possibly achieve were removed. These occurred due to odd occurrences in data collection such as the subject dropping the robot end effector, for example.

1.2.3 Experiment Phases

The experiment consisted of three phases. In the middle treatment phase a visual distortion was experienced when the subject moved the position of the end effector of the robot outside the invisible boundary. Subjects were told their task was to intercept the blue projectile.

The experiment consisted of three phases of 200 trials each. Subjects received a rest period of 15 seconds every 25 trials. During each trial the position of the robot was recorded at a frequency of 100 Hz. Subjects from the treatment group experienced a visual distortion when they moved outside of the invisible boundary during the middle 200 trials, which is the treatment phase. The control group received no distortion. The boundary was defined by a right rectangular prism of infinite height along the inferior-superior axis, narrow (3.75 cm) depth along the anterior-posterior axis and large (25 cm) lateral width with respect to the subject. This boundary intersected with the workspace sphere. The distortion displaced the subjects’ cursor in vector with predetermined magnitude of 0.3 m. The direction of the vector was the same as the vector direction between the center of the workspace and their current position. Hence the relationship between the robot position and cursor position was simply,
\[ P_c = \begin{cases} 
    P_r & \text{inside the box} \\
    P_r + 0.3U & \text{outside the box} 
\end{cases} \] 

(1)

Where \( P_c \) is the position of the cursor, \( P_r \) is the endpoint of the robot held by the subject and \( U \) is the unit vector (direction) between the center of the workspace and \( P_r \) (Fig. 1).

![Diagram](image)

**Figure 2** – Left: transformation of an example cursor position shift from the robot position based on equation 1. Right: Vector field displaying the direction of the cursor shift at a set of possible robot positions around the workspace. The subject would be seated at the bottom of the figure facing upward.

### 1.2.4 Metrics and Analysis

Several metrics were used to give different views of the subject’s movement tendencies relative to the boundary region. While common variability metrics such as standard deviation or range might characterize the spread of data, often these are not specific enough to identify how the variability changes relative to the boundaries we have created in our training scheme. Instead, we employed *distance to edge* (DTE) to measure how the subjects moved with respect to the boundary edges. We focused on the most limiting direction, along the anterior-posterior axis. DTE was calculated as the difference between the robot position and the nearest boundary edge. The boundary edge is zero DTE. Movement outside of the boundary was assigned negative DTE while movement inside the boundary was assigned positive DTE. Minimum
values of DTE were taken for each trial. If the subject left the boundary during the trial, then their furthest position away from the boundary would be their minimum DTE. The rest of that trials data must lie between the minDTE value and the boundary edge. While outside of the boundary, increases in DTE imply getting closer to the boundary edge. When the subject stayed inside of the boundary for the entire trial, their minimum DTE was their closest distance to the boundary edge. All other DTE values for that trial must be between the minDTE value and the middle of the boundary. While inside of the boundary, increases in DTE imply getting further from the boundary edge, further into the safe region. MinDTE is essentially a measure of extent of failure in which failure is venture too far out of or getting too close to leaving the boundary. Conversely, DTE gives a measure of how well the subject could stay within or get close to the “safe” boundary region.

Time to edge (TTE) was calculated to assess the subjects’ modulation of velocity in response to a conception of the boundary edge. TTE was found for each timestamp within a trial with subjects’ instantaneous velocity and the displacement magnitude between their position and the nearest boundary line (Time=Distance/Velocity). It was marked as zero if the subject was outside of the boundary. An average TTE of all the timestamps from each trial was taken.

The metric percent outside (PO) was found to assess how often the subject left the boundary region. PO was calculated as the number of timestamps with positions outside of the boundary over the total number of timestamps for each trial.

Several analytical steps were taken to extract subject behavior across the experiment. Given a metric value for each trial, we fit these values to an exponential equation

$$M = P_1 + P_2 e^{-P_3 t}$$

where $M$ is the fitted metric value, $P_1$, $P_2$, and $P_3$ are the parameters of the fit, and $t$ is the trial number (1-200) within the phase. The parameter values that defined the non-linear fit were
obtained using a combination of Levenberg-Marquart nonlinear optimization and simulated annealing to assure the most global minimum solution.

The endpoints of these linear fits at the beginning and end of each phases were used as evaluation points. Specifically, the changes from the beginning to the end of training, from the end of baseline to the end of training, from the end of baseline to the beginning of washout, and from the beginning of baseline to the end of washout, were of interest.

1.3 Results

Subjects that received the visual limit-push treatment demonstrated training effects that both shifted and reduced movement variability. Distinct changes in the subjects’ movement tendencies for the average time to edge (aTTE), minimum distance to edge (minDTE), and average percent outside (PO) metrics were found when the visual distortion was applied. These changes can be observed in the position distributions for each phase (Fig. 3). No distinct changes were found in the subjects’ standard deviation or range of position. In the baseline phase, the subjects quickly became accustomed to using the robotic arm within the first few trials while the remaining trials had no large changes in movement tendencies. In the training phase, subjects changed their movement tendencies exponentially within the first ten trials, and there was a significant shift by the end of the phase (Fig. 4). In the post-training phase, subjects retained their new movement tendencies for less than ten trials and then quickly washed out.
back to their baseline values. These trends were found in the treatment group only, and were compared to the control group to account for learning the environment over the course of the experiment. All changes found to be significant had a p-value less than 0.05.

Minimum DTE per Trial -- Treatment Subject

Figure 4 – The minimum Distance to Edge (minDTE) in each of the 600 trials is plotted along with an exponential fit of each phase (200 trials each). This exemplary subject shows a distinct exponential increase in the DTE metric in the training phase. Later in the post-training phase there is an exponential change back towards a minDTE closer to baseline values. The rest of the treatment and control subjects’ metric vs. trial plots are found in Appendix A.

The training phase had a distinct effect on movement for all subjects. There was a significant increase in minDTE by an average of 7.7 cm from the beginning to the end of training for the treatment group. This change was significantly different from the control group which had no significant change (Fig. 5). During this phase, the treatment group also had a significant increase in TTE by 1.86 seconds which was significantly different than no change in the control group (Fig. 6). The subjects significantly decreased the average percent of the movement positions that landed outside of the boundary by 58.2% compared to no significant change in control.

Comparing the beginning of baseline to the end of training showed significant changes for the treatment group compared to no change in the control group. In this comparison subjects increased their minDTE by 6.12 cm, increased their TTE by 1.94 seconds and decreased their PO by 70.1 %.
The beginning of the post-training phase also had a significant difference with the end of baseline compared to no change in the control group. The effect of the training retained values at a 4.8 cm increase for minDTE, a 1.54 second increase for TTE and a 29.4% decrease in average positions outside the boundary. Finally, subjects in the treatment group returned to baseline values by the end of training as there was no significant difference compared to the end of training.
Figure 5 – TOP: The minDTE values at the beginning and end of each phase are plotted in thin lines for each subject in the treatment group (blue) and control group (green). The mean minDTE values are plotted as white diamonds in the center of bars representing confidence wings. The visual distortion is on for the points that are highlighted in yellow. Zero and maximum possible DTE lines are plotted in red. Δ1 is the change within the treatment phase. Δ2 is the change between the end of treatment and end of pre-treatment. Δ3 is the pre to early post-treatment change. Δ4 is the pre to late post-treatment change. BOTTOM: Mean changes for each of the changes identified in the top figure for each group. Asterisks represent a significant difference (p<0.05) between groups based on an unpaired t-test.

Figure 6—Changes 1-4 as seen in Figure 4 for two additional metrics. TOP: Change in the average time to edge per trial averaged across all subjects to compare between groups. BOTTOM: Change in the average percent movement outside of boundary per trial averaged across all subjects to compare between groups. These are differences of the averages seen in Appendix B.

1.4 Discussion

The purpose of this experiment was to determine whether a visual distortion could modulate human movement variability to an unseen boundary region. Based on the chosen metrics, results show that subjects reached consistent baseline levels, adapted during the training phase, and retained what they learned for several trials without distortion before their after effects washed out in the rest of the post-training phase. Importantly, these changes were
significant compared to a control group without any distortion. They are an indication that the subject reduced their trial-to-trial variability.

The minimum distance to edge metric (minDTE) helped identify how subjects’ movements changed with respect to the boundary. All of the subject’s evaluation point values for this metric were found to be outside of the boundary edge where they were defined as negative values. Considering this, the metric, as a minimum, identified the furthest the subject would move from the boundary edge when they were outside of the boundary. It was found that subjects, on average, learned to stay closer to the boundary edge by the end of the training phase compared to both the beginning of the training phase and the end of the baseline phase. This shows that the subjects learned roughly where the boundary was. Additionally, they retained the boundary region as a guide for where to move for several trials at the beginning of the post-training phase.

Complementary to minDTE informing movement outside of the boundary, results of a decline in the percentage of movement outside (PO) of the boundary region elucidate that subjects tended to move inside the boundary in reaction to the visual distortion. It is important to note that due to its small depth, staying inside of the boundary was very difficult. However, these metrics show that subjects must have adopted a strategy of avoiding a distorted cursor and staying inside of the small safe region while trying to catch the projectile.

Aside from position based metrics, average time to edge (TTE) for each trial also showed distinct changes due to the training phase. Importantly, this metric only had non-zero values inside of the boundary and therefore its trend delineates subjects’ behavior in that region. Over the training phase, TTE shows that subjects learned to move more slowly while inside of the boundary. Both the end of training movements and the several non-distorted trials following them were also slower compared to baseline values. Additionally, TTE considered all three
dimensions of movement and therefore gives a more general interpretation of movement tendencies in a 3D workspace.

This paradigms visual distortion made it impossible for subjects to stay inside of the workspace as they were instructed without also staying inside of the unseen boundary. This implied that the distortion was “bad” with respect to the given instructions and therefore motivated the subjects to find the safe bounded region inside of the workspace. Based on this, the experiment “clued-in” the subjects to where the boundary might be. However, subjects had no idea of the shape or size of the boundary. Hence, the changes in the metrics above show that subjects, to some extent, conceptualized the boundary based on trial and error through in the first five to ten trials of the training phase.

There are several limitations on the meaning of the results in this study. The reduction of variability was limited to the metrics described above. Changes in other measures of variability, such as standard deviation or range, were not seen. Another limitation is in maintaining new movement tendencies beyond the distorted phase. Subjects quickly de-adapt in the post training phase. This may be because healthy subjects preferred their typical movement tendencies over the ones imposed by the boundary. However, results may be different if a similar paradigm was implemented in stroke or TBI patients who might have typical movement tendencies that are detrimental to performing the catching task. Finally, this study does not investigate how much retention limit-push can induce compared to an assistive robotic manipulation. Such limitations can be investigated in further study.

This work adds some support that visual limit-push could help in training human movement control. Importantly, such distortions’ effects washout quickly, and this is typical in such paradigms. It would be beneficial for future work to investigate methods similar to the ones used here in training stroke or traumatic brain injury patients. What is encouraging is that this
study motivates the exploration of the use of robotic and virtual reality systems to rehabilitate, improve or discover the characteristics of human arm movement.
2. LookingGlass System Design for Practical Clinical Use

2.1 Background

Research on human motor control is done in order to find methods of facilitating rehabilitation after brain injuries and strokes that limit the patient’s range and accuracy of arm motion. Although physical therapy techniques currently allow for a subject to gain back some of their arm movement capability, there is evidence that virtual reality (VR) haptic environments where subjects can perform repetitive, but engaging tasks are a useful tool for therapy [14], [15]. This usefulness lies in the flexibility of a virtual environment in rendering augmented realities that can induce the patient to re-learn healthy motor ability.

An essential part of producing such environments is to be able to render them to match the full extent of human arm motion and to facilitate their usability in the therapy setting. Having 3D environments allows for visual and haptic feedback in the user’s full, three-dimensional workspace. Additionally, having a large workspace allows for using the full extent of the user’s arm, and also wide enough for using both arms (bimanual). This is important since there evidence that a subject’s healthy arm can be used to train the paretic arm [16]. Finally, a large workspace allows for the system to be used by both the patient and the therapist simultaneously in order for the therapist to lead the patient in the exercises. Both 3D and large workspaces allow the user to practice in an environment that mimics daily living. With such a virtual reality setup, rehabilitation can include task specific motions that allow for training movements that are useful to day to day living.

However, the richness of the environment is not the only requirement for a rehabilitation VR system; a system must also be accessible to the patient. Research has shown that early massed practice, movement exercises of the affected limb that are done repetitively and within a few weeks of injury, is most effective in recovering arm function [17]. To be readily available to
the patient, such VR haptic systems must be compatible with the clinical environment and affordable.

Recent advances in TV technology have made available low cost LCD 3D displays. The LookingGlass system presented here has been built around this technology with the design specifications that include a large 3D workspace, portability, multi-use, and low cost compared to previous research tools that are limited to laboratory use. This new design shows promise that virtual reality environments for arm control rehabilitation can be taken to the clinic to increase accessibility to patients. Continued development could allow this system to move to clinical trials and aiding in rehabilitation.

2.2 Design

2.2.1 LCD and Mirror System

An important distinction between different integrated virtual reality systems is how the robotic workspace and the visual workspace are related. In a general example with a computer mouse as a “robot” and an LCD screen presenting visual feedback as a cursor, the (robotic) workspace of the mouse is decoupled from the screen workspace. However, in order to have an immersive, engaging environment the visual and haptic workspaces have to be integrated. Doing so is challenging since it requires the displayed image to be on the robot itself. A solution called Personal Augmented Reality Immersive System (PARIS), developed by the Electronic Visualization Laboratory (EVL) at UIC, is to use a projector and three mirrors to create a “virtual” image in the space seen through a semi-silvered mirror that rises out in front of the user (Fig. 7). The position of the resulting image is “inside” of the mirror that is closest to the user and that the user looks through. Placing a
robot under the mirror allows for haptic integration such that the robotic endpoint and the cursor are coupled, one to one. This overlay, along with 3D stereoscopic displays, creates a more immersive environment.

The new system design, the LookingGlass, was inspired by PARIS, and it uses a 3D LCD screen instead of a projector (Fig. 8). The LCD screen is mounted on an extruded aluminum frame made of base parts from 80/20 Inc. The frame consists of two main posts which reach the ground and are held up by two shorter legs. The legs are coupled with a beam that traverses them perpendicularly. The two legs are attached to the two main posts on a pivot joint this allows the angle between the legs and the posts to be modulated. This modulation changes the height of the entire system. Wheels at the bottom of the posts and legs allow the system to be easily transported.

The posts and legs hold up an LCD screen and a mirror which can be adjusted into many configurations. The LCD screen is hung from a stanchion that spans the distance between the two main posts. The mirror is framed with minimal 80/20 extrusions which are themselves attached to the main posts with stanchions. Slides and joints between the main posts and the TV stanchion and the mirror frame allow for several degrees of freedom. The mirror can slide transversely between the two main posts, slide along the main posts into higher and lower positions, and pivot. The TV can also slide along the main posts taking on different heights and pivot changing its angle with respect to the ground.

Figure 8 – The LookingGlass in a setup similar to PARIS.
These degrees of freedom allow for the system to be placed into several configurations. In the PARIS setup, the LCD screen faces the ground in order for its image to be reflected off of the mirror mounted below it. The mirror is placed at an angle with the ground such that it faces the user. Spinning the TV 180 degrees such that it is facing up, lowering it along the two main posts, and spinning or sliding the mirror down and out of the way allows the system to be used like the Immersadesk technology which was also developed by the EVL (Fig. 10). Placing the LCD screen perpendicular to the ground allows typical TV viewing. The TV and LCD screen can be placed at heights that are suitable for either sitting or standing. Finally, both the TV and the mirror can be slid down into a compact setting for easy transport.
2.2.2 Block and Tackle System

A block and tackle rope setup was implemented in order to simplify the task of raising and lowering the system by changing the angle between the legs and the two main posts. Pulling the rope moves the two legs and the two posts together and decreases the angle in the joint between the legs and the posts. The rope wraps around the base of the system such that it is out of the way from the user. The block and tackle provides a mechanical advantage such that it pulls both legs simultaneously and reduces the overall weight required to increase the height. Rubber bands at each side of the system couple the post and leg at each side. These also assist with raising the system. They also provide some tension against gravity when lowering the system.

2.3 Cost of Implementation

The system significantly reduced the cost of rendering a virtual space similar to that rendered by the PARIS system. The LCD screen at about $2500 is much less expensive than the cinematographic projector yet it still provides high 1080p resolution. Additionally, the LookingGlass system uses one mirror instead of three and is constructed of less extruded aluminum than PARIS. The estimated cost of PARIS is about $70,000, while the LookingGlass system costs $4500 at maximum. This lower cost makes it more feasible for multiple LookingGlass systems to be built and tested in clinical studies.

2.4 Future Work

Although the design is more efficient than the PARIS system, the LookingGlass can still be further redesigned with less parts. Working with the built system has elucidated that the attachment between the legs and the posts can be fixed. Height changes previously done by changing the post/leg angle can be done by simply sliding the screen and the mirror along the posts. This type of height change also simplifies the overall process, because it does not require
pivoting the screen and mirror as was required by a post/leg angle change. The number of parts used to create the joints between the mirror/TV and the main posts can also be reduced.

An advantageous addition to the system would be optical head and arm tracking. We attempted to do such tracking by mounting a Kinect off of and behind the mirror. However, the mirror frame was an obstruction that disabled the Kinect software from properly keeping track of the user’s limb position. Overall, with some fine tuning and a dedicated robot or optical tracking, the LookingGlass system would have what is necessary to be a working experimental tool that can be moved into the clinic.
WORKS CITED


APPENDICES

A. Individual Subject Metric Values

Figure 11 – The nine treatment group subjects’ metrics. Each point is the metric value at a single trial. From left to right: minimum distance to edge per trial, average time to edge per trial, percent outside the boundary per trial. The yellow box highlights the trials in which there was a visual distortion. Exponential fits were done on each of the three phases individually for each subject.
Figure 12 --- The nine control group subjects' metrics. Each point is the metric value at a single trial. From left to right: minimum distance to edge per trial, average time to edge per trial, percent outside the boundary per trial. Exponential fits were done on each of the three phases individually for each subject.
B. Average Subject Metric Trends

Figure 13 – Wings Plots of Changes for the Time to Edge and Percent Outside metrics. Each dot is an exponential fit endpoint as seen in figures 11 and 12. Each bar shows the 95% confidence interval of the subjects’ metric values at the given evaluation point.
C. IRB Approval Letter

UNIVERSITY OF ILLINOIS
AT CHICAGO

Office for the Protection of Research Subjects (OPRS)
Office of the Vice Chancellor for Research (MC 672)
203 Administrative Office Building
1737 West Polk Street
Chicago, Illinois 60612-7227

Approval Notice
Initial Review (Response to Modifications)

July 17, 2014

Eyad Hajissa
Bioengineering
5191 Scott Circle
Lisle, IL 60532
Phone: (630) 749-8128

RE: Protocol # 2014-0209
“Upper Limb Dexterity Training within a Manifold”

Dear Eyad Hajissa:

Your Initial Review (Response to Modifications) was reviewed and approved by the Expedited review process on July 17, 2014. You may now begin your research.

Please note the following information about your approved research protocol:

**Protocol Approval Period:** July 17, 2014 - July 17, 2015
**Approved Subject Enrollment #:** 9 (0 at UIC)
**Performance Sites:** Rehabilitation Institute of Chicago
**Sponsor:** None

**Research Protocol:**
- a) Upper limb dexterity training within a manifold; Version 2.1, 5/8/14

**Recruitment Material:**
- a) Recruitment activities will be conducted through the Rehabilitation Institute of Chicago, in accordance with the Northwestern University IRB approval. No subjects will be recruited for participation at UIC.

**Informed Consent:**
- a) Informed Consent will be obtained at the Rehabilitation Institute of Chicago, in accordance with the Northwestern University IRB approval. No subjects will be enrolled for participation at UIC.
**Additional Determinations for Research Involving Minors:**
These determinations have not been made for this study since it has not been approved for enrollment of minors.

Your research meets the criteria for expedited review as defined in 45 CFR 46.110(b)(1) under the following specific category:

(4) Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving X-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.)

**Please note the Review History of this submission:**

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Please remember to:

→ Use your research protocol number (#2014-0209) on any documents or correspondence with the IRB concerning your research protocol.

→ Review and comply with all requirements on the enclosure, "UIC Investigator Responsibilities, Protection of Human Research Subjects" ([http://tigger.uic.edu/depts/ovcr/research/protocolreview/irb/policies/0924.pdf](http://tigger.uic.edu/depts/ovcr/research/protocolreview/irb/policies/0924.pdf))

Please note that the UIC IRB has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact OPRS at (312) 996-1711 or me at (312) 413-3202. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.

Sincerely,
Teresa D. Johnston, B.S., C.I.P.
Assistant Director
Office for the Protection of Research

Subjects

Enclosure:

1. **UIC Investigator Responsibilities, Protection of Human Research Subjects**

cc: Thomas Royston, Bioengineering, M/C 063
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NAME: Eyad Hajissa

EDUCATION: B.S., Bioengineering, University of Illinois at Chicago 2008-2012
M.S., Bioengineering, University of Illinois at Chicago 2012-2014

CONFERENCE: Poster presentation at the 2014 Midwest Biomedical Engineering Career Conference (MBECC) of the Biomedical Engineering Society (BMES)

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