Physiologically Driven Rehabilitation Using Virtual Reality

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Abstract. Creating a platform that allows the fusion of real-time physiological measurements and virtual reality (VR) simulation will greatly improve present human-computer interaction, adaptive displays, military training, and anxiety therapy. The Virtual Reality Medical Center (VRMC) has developed a physiologically-driven rehabilitation platform that correctly assesses user anxiety levels based on multiple real time physiological measures, determines the optimal level of physiological arousal for each individual user, and automates the virtual simulation to the proper intensity for each user. Additionally, VRMC collaborates with UCF to develop novel, state-of-the-art sensors to be integrated within the platform that are capable of measuring electrocardiogram, (EEG), skin conductance, gait, and pupillometry. In Phase I VRMC developed a capability to monitor, fuse, and evaluate physiological measures (heart rate, skin conductance, skin temperature, and respiration) in real time to assess user anxiety levels. The physiological data collected will be used to assess user anxiety levels in real time as neutral, low, or high with 90% accuracy and to determine the optimal level of physiological arousal for each individual user.

Keywords: physiological measurement, stroke, traumatic brain injury, cerebrovascular accident, rehabilitation, cognitive rehabilitation, simulation, mixed reality.

1 Introduction

Modern human-computer interaction (HCI) development has recently been focusing on creating user-centered applications that adapt to the mental, or cognitive, state of the user. These systems commonly measure EEG [2, 15, Wilson & Russel, 2004), pupillometry [16], and cardiac function (Liddle et al., 2005) to evaluate user mental load in real time, and adapt the displays accordingly. If cognitive functioning is low, the display adapts to engage the user; if the user is overwhelmed, the display lessens its demands or stimuli to allow the user to focus. Some systems train users to control their physiology, e.g., brainwaves as measured on EEG, to control displays, such as driving simulators for those who have acquired brain injury (Lew et al., 2005) or communication devices for people who are completely paralyzed [1]. These human-in-the-loop systems are extremely valuable in training and rehabilitation of these populations.

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There are many challenges, though, in creating such a system. First, the system needs a battery of strategies to recognize user mental status; that is, developing techniques (e.g., data fusion) to determine what the physiological input from the user means – is the user bored, overwhelmed, or distracted? Once the system can recognize the mental state of the user, developers must train the system to decide how the input will determine the output, and how the output will relate to the user. Next, developers must ensure the accuracy of the input recognition and output decisions the system is making, as data fusion and processing in real-time places increased demands on the software. Finally, once the system accurately assesses the input from the user, it must learn to correctly adapt its display based on the input to create a successful human-in-the-loop system.

Mixed Reality (MR) is a simulation technology that blends virtual reality with physical reality into a seamless landscape. The advantage of MR is that it creates an altered or augmented reality without losing the benefits of the physical setting - touch, smell, hearing, taste, and visual contact with other humans. The MRRS will enable Cerebrovascular (CVA) patients to receive physical and cognitive rehabilitation both in the therapist's office and at home. CVA patients include those impaired from a stroke or traumatic brain injury (TBI). The Virtual Reality Medical Center (VRMC) has developed the MRRS to provide an interactive, engaging rehabilitation tool for these patients.

Approximately 700,000 Americans are affected by stroke annually, costing an estimated $62 billion in 2008. A recent RAND survey found that 19.5% (over 320,000) of service members may have experienced at least a mild TBI while deployed. Multiple re-deployments, unprecedented in this all-volunteer U.S. military, may compound the risk for physical and psychological injuries, potentially resulting in more severe and chronic mental health problems. In 2008, the annual level of suicides among soldiers was the highest it has been since the Pentagon began tracking the rate 28 years ago. Expanded development of the MRRS adds the ability to perform cognitive assessment for CVA and stress injuries, including Post Traumatic Stress Disorder (PTSD), by capturing and analyzing the patient's reactions and performance while in a controlled environment. The ability to detect mental health issues with the MRRS before and after deployments could save lives.

2 Review of Literature

Much research has been done examining the role physiology has in "peak performance" from athletic to military training. Researchers have determined that most individuals are unaware of the effect their thoughts have on their physiology, and in turn, the effects their physiology has on their performance or execution of a task [3, 5, 10, 17].

The Yerkes-Dodson curve, illustrated in Figure 1, shows the inverted U-curve of anxiety's relationship with performance. Physiologically, there is an optimal level of anxiety/arousal that influences individual's performance efficiency. As anxiety increases, performance efficiency improves and reaches an optimal point. As shown by the curve, if a person becomes over-anxious or complacent, his or her performance efficiency will suffer. Low anxiety does not allow someone to become invested in

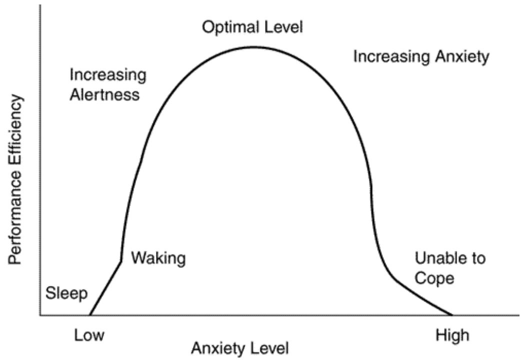

Fig. 1. Yerkes-Dodson curve showing the relationship between anxiety (arousal) and performance

executing an activity, while high anxiety leaves a person unable to cope in a stressful situation. Neither extreme is conducive to optimal efficiency in executing a task.

A CVA patient experiencing phobic stimuli may be at the high-anxiety end of the curve. These individuals are left unable to cope or execute tasks when faced with stimuli, and may even experience panic attacks or physical discomfort. These types of reactions are completely debilitating when trying to perform activities of daily living. It is necessary for patients experiencing this discomfort to understand the role physiology has in their reaction to stimuli and how to manage their physiology when faced with a provoking situation. Typical physiological reactions of people experiencing anxiety include:

- *Increased heart rate (HR).* Heart rate has been considered a particularly strong measure of anxiety [8, Nesse et al., 1985].
- *Decreased skin resistance (SR).* In 1907, Carl Jung discovered that skin resistance (SR, which decreases as sweat gland activity increases) was a means to objectify emotional tones previously thought to be invisible. Skin resistance, unlike electromyography (EMG) and skin temperature, tends to reflect mental events more quickly and with more resolution than other physiological measures [9]. Baseline levels of SR vary widely by individual so percentage change from baseline is normally measured rather than absolute value [13].
- *Drop in skin temperature.* Circulation slows in the extremities during stress, causing skin temperature to drop. Although change in skin temperature is less sensitive than and temporally lags changes in heart rate, its response curves are similar [6, 11].
- *Poor respiration.* Phobics typically show increased breaths-per-minute and less respiratory sinus arrhythmia (RSA) than non-phobics during exposure to phobic stimuli [14], and patients with anxiety disorders exhibit decreased RSA in general [4, 8].

While these physiological changes are often measured during anxiety or phobia therapy, whoever is monitoring the physiology must interpret the significance of each measure in relation to the patient, as well as in relation to the separate physiological signals. This can lead to discrepancies in treatment. While physiological monitoring and biofeedback greatly improve therapy outcomes, these techniques could be greatly improved upon by technological advancements, specifically data fusion and signal processing to interpret anxiety levels in patients. Having a network that evaluates patients' anxiety levels allows therapists to focus on individualizing treatment by teaching patients how their physiology is affecting their everyday living, as well as techniques to cope and manage physiology to improve their cognition and lessen their anxiety.

3 Method/Approach

In an effort to improve cognitive deficits and diminish abnormal behaviors caused by brain trauma, VRMC, partnered with the Media Convergence Lab (MCL) at the University of Central Florida (UCF) Institute for Simulation and Training (IST), to create a haptics-enhanced true 3D stereo mixed reality system especially designed to stimulate and improve cognitive functions in warfighters that suffer from Traumatic Brain Injury (TBI) and CVA patients.

TBI is the most common combat-related injury. It often results in disturbances of attention, memory, and executive function; moderate to severe cases can cause seizures. Sixty percent of troops who survive external injuries from bomb blasts, the leading cause of death in Operation Iraqi Freedom, could also have brain injury. While there are potential drug-based candidates for neuroprotection of brain injuries, comprehensive-holistic neuropsychological rehabilitation that attempts to address multiple cognitive deficits seems to be effective for the remediation of attention deficits and memory impairments after TBI; however, such intensive daily treatment within hospitals would no doubt be costly and has only been shown to be effective in mild memory impairments. Finding alternative, cost-effective ways to rehabilitate soldiers would help save the military and government a significant amount of resources.

Recent advances in communication and visualization technologies are resulting in the ability for a mobile user to effectively "browse" a physical environment and obtain site-specific information or access representations of real-time data about their immediate location. Our research has focused on combining mobile multimedia, virtual reality, and wearable computing technologies, to create systems that provide MR experiences. MR is a type of virtual reality that combines real and computer generated images to create an augmented reality. The existing system also provides multisensory feedback, including auditory and tactile feedback.

The MRRS incorporates scenarios, under the direction of the therapists, that stress the importance of activities of daily life (ADLs) and seek to improve patients' independence by retraining them in routine activities necessary for daily living. The human factors study examined the ergonomics of the system setup and the validity of mixed reality. The MRRS was evaluated by test participants. All participants were able to complete the 9 minutes 41 seconds scenario. Every participant was outfitted with biofeedback equipment to measure physiological effects of the experience. Fourteen healthy participants (six males and eight females) were enrolled in this study. Participants were recruited at the University of Central Florida. Participant ages ranged from 18 years of age to 63 years of age. They varied in their experience and familiarity with video games and mixed reality.

Participant physiological measurements were monitored by the J&J Engineering's I-330-C2-system. This system measured the participant's heart rate, skin conductance, skin temperature, respiratory effort, and breaths per minute. Participants also filled out self-report questionnaires that included: Parent's Modified Simulator Sickness Questionnaire consisting of 38 questions, the seven item Presence Questionnaire, the State-Trait Anxiety Inventory, the Tellegen Absorption Scale, and the Dissociative Experiences Scale.

Additionally, participants provided subjective feedback in a structured interview. This included verbal rankings on a Likert scale of 0 to 10 for level of enjoyment, level of comfort, and ease of use, where 0 was none at all and 10 was most enjoyable, comfortable, and/or easy to use. Participants also ranked their accuracy in completing the tasks assigned and overall performance on a 0-100% scale, in which 100% resembled the highest accuracy and/or most proficient performance. Each participant would also provide subjective feedback regarding the functionality and physicality of the system. With negative feedback, the participant provided possible ways to improve the system.

Participants were first required to provide a signed informed consent form following a discussion of the possible risks with the consent administrator. Participants were asked to complete a set of two pre-questionnaires. Next the participants were familiarized with the MRRS setup. At this time, their role in the scenario and the three tasks they would be responsible for were explained. Spatial audio tests and scanner instruction tests were also performed. Following these instructions, all participants were then fitted with the head-mounted display (HMD). Participants then completed a few of the assigned in-game tasks to familiarize themselves with the equipment. Then the participants were asked to relax, close their eyes and concentrate on their breathing for five minutes while a physiological baseline was established. Finally the participants completed the three tasks assigned to them in the supply depot scenario.

Following the scenario, participants were interviewed by a research assistant. Participants answered questions that dealt with comfort, ease of use, performance, accuracy, and replay value. Three self-evaluated questionnaires were collected at the end of the session.

4 Results

Physiological measures were collected from all 14 participants that participated in this study. Table 1 below depicts the average physiological measure of heart rate, skin conductance, respiratory effort, breaths per minute, and temperature from the baseline and the scenario. The results show increases over baseline readings in heart rate, skin conductance, and breaths per minute after participants had executed the scenario.

All participants filled out a Simulator Sickness Questionnaire following the usability testing. This questionnaire presents users with several symptoms, such as Headache and Nausea, which may result from interacting in a virtual environment. Participants ranked the symptoms on a scale of 0 to 3, indicating if symptoms were

Table 1. Average Physiological Measures

Situation	Physiological Measures				
	HR	SC	BPM	RESP	TEMP
Baseline	82.03086	7.843363	10.44903	541.589	85.55564
Scenario	92.36581	15.71259	15.36546	407.133	81.25739

(0) absent, (1) slight, (2) moderate, or (3) severe. The overall average score for simulator sickness during exploration of the virtual environment was 0.283. Difficulty focusing and blurred vision were the two most experienced symptoms. Two out of the 14 participants did not feel any symptoms at all.

According to user feedback, the MRRS achieved an average enjoyment rating of 7.14. Participants gave the level of comfort an average 7.00 rating, while the ease of use generated an 8.82 rating. Based on correlations calculated using a Pearson correlation coefficient, the variables level of comfort and level of enjoyment is positively correlated. Figure 2 depicts the level of enjoyment versus the level of comfort.

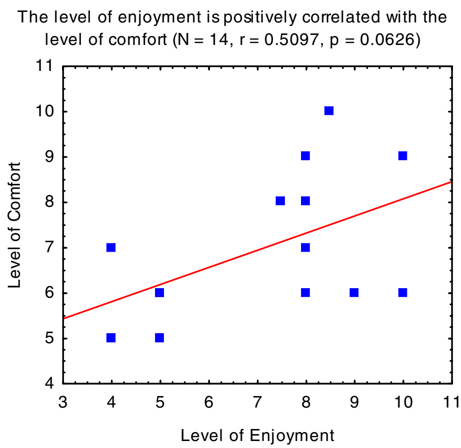

Fig. 2. Level of Enjoyment Versus the Level of Comfort

In addition to the Simulator Sickness Questionnaire, participants were asked to complete the Presence Questionnaire. Presence was scored on a scale of 1-7. The overall average score for the Presence Questionnaire was 5.35. When correlated with the ease of use, presence is found to be positively correlated with the system's ease of use. Figure 3 depicts the ease of use versus the presence score.

Participants considered their accuracy and overall performance to be 74.07% and 70.77%, respectively. The perceived overall performance rating was positively correlated to the level of comfort. Figure 4 depicts the level of comfort versus overall performance rating.

Subjective user feedback revealed that 11 out of the 14 participants encountered difficulties reading any type of text through the head-mount device (HMD). Five out of the 14 participants mentioned the latency in the HMD. Participants felt that there

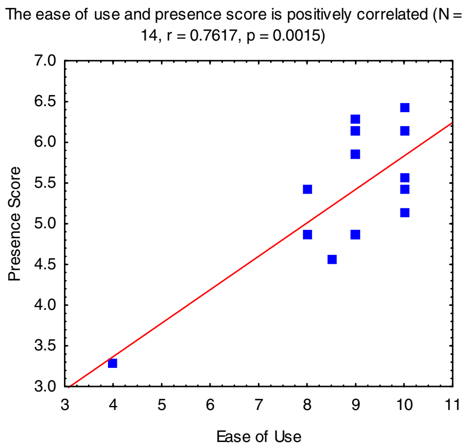

Fig. 3. Ease of Use Versus the Presence Score

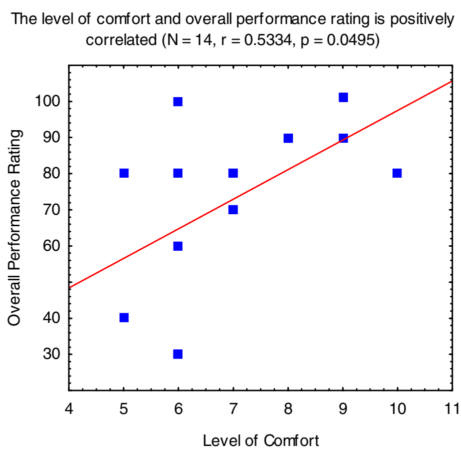

Fig. 4. Level of Comfort versus Overall Performance Rating

was a lag in the display when moving the head. Ten out of the 14 participants felt the audio was realistic and presented no flaws. Among the 4 participants that claimed the audio was flawed or stated that it was too loud, which covered the sound of the trucks parking in the loading docks. Thus, this prevented them from accomplishing one of their tasks.

The results provide evidence that this MRRS presents a user friendly interface, immersive virtual interaction, and an enjoyable experience. The participants gave themselves high ratings in accuracy and overall performance, indicating that they were engaged and participating fully in the scenario. The correlation between the ease of use and presence score indicates that the user's level of immersion can ultimately be improved by making the virtual environment more user friendly. This would include making the controls easier to function and the virtual environment easier to navigate. Also, tasks must avoid complication by remaining simple without several steps.

The presence scores suggest that the MRRS commands an immersive experience. Based on subjective user feedback, the scenario provided the participants with enough activities to keep them busy. Many felt the amount of tasks were sufficient despite the constant audio and visual distractions. The scenario displayed higher physiological readings in categories of heart rate, skin conductance and breaths per minute. Generally, an increase in heart rate, skin conductance, and breaths per minute indicates more activity and arousal. Temperature can be used as a physiological indicator of distress and anxiety, as temperature decreases through stress induced vasoconstriction and increases through vasodilation caused by relaxation. Thus, a higher average temperature in the baseline suggests a reduced level of discomfort and anxiety.

5 Discussion

The use of novel, miniaturized, portable sensors and electrodes improves patient acceptance and also broadens the field of possible applications of physiologically-driven MRRS. In addition, the new sensors may lead to completely unobtrusive methods for physiological data collection, depending on the way MRRS is implemented. The collection and measurement of multiple emotional conditions will help standardize and enhance rehabilitation in general. Improved sensor recognition of emotions and behavior from speech, EEG, facial expression, and other natural reactions will also provide the patient with more accurate audio, visual and haptic feedback.

The MRRS has many capabilities and great potential. The current state of the system could easily be augmented to accommodate various levels of cognitive functioning. For example, a scenario involving making cereal could have various levels of complexity. The easiest level may have all the ingredients open or ready for the user to prepare cereal. An intermediate level may require some prior preparation, such as opening the milk carton or cereal box. To further challenge the patient, he or she may have to find and retrieve one or more of the necessary components from around the virtual kitchen: a bowl from cabinets, a spoon from the drawer, milk from the refrigerator, and cereal box from the pantry. Other scenarios of task training will have similar levels of difficulty.

6 Conclusions and Recommendations

There are many reasons why MR applications may be effective for rehabilitation. First, MR, like VR, is an interactive, experiential medium. In the same way that children and teenagers intuitively grasp computers, MR users become directly engaged with the effects of the mixed reality experience. In addition, MR creates a safe setting where patients can explore and act without feeling threatened [7]. Patients can make mistakes without fear of dangerous, real, or humiliating consequences. Moreover, unlike human trainers, computers are infinitely patient and consistent. In cognitive rehabilitation, MR can be manipulated in ways that the real world cannot. For example, MR can convey rules and abstract concepts without the use of language or symbols for patients with little or no grasp of language.

MR creates a safe, controlled environment for repetitive practice, which is crucial in learning tasks, while providing immediate, real-time feedback about performance. Because of its interactive nature, MR can increase compliance by making the experience fun. While these technologies will have immediate benefit for CVA patients, their development will also serve to catalyze improvement and change within clinical rehabilitation at large. MR may indeed help create a more enjoyable and effective method of rehabilitating patients with brain injuries than the current paradigm.

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