

A Human-in-the-Loop VR Framework Toward Adaptive Public Safety Training

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Abstract

The objective of this paper is to provide an overview of how a Human-in-the-Loop (HITL) VR framework can be developed and implemented for adaptive public safety training. It explains what a Human-in-the-Loop (HITL) framework represents, its principles, and demonstrates how it can be leveraged in an immersive virtual context. The paper examines a multi-phase research experiment where human subjects are immersed in a virtual reality setting designed to induce various emotional states. Adaptive training concepts and industry accepted parameters were incorporated in the course of the development of the virtual reality environments to investigate physiological reactions and changes in behavior associated with claustrophobia related stimuli. Throughout the experiment, physiological data was collected in real time, compared and analyzed against participants' psychological questionnaires which helped to assess their emotional profiles prior to entering the experiment. The experiment outlined in this paper highlights the intersection of systems engineering and adaptive virtual reality development, and demonstrates the potential of Human-in-the-Loop frameworks for public safety training applications.

Keywords

Human-in-the-Loop, virtual reality, adaptive training, public safety, physiological monitoring, immersive learning

1. Introduction

Confined spaces, as a general rule, present a considerable challenge for first responders such as fire fighters, law enforcement officers, and search and rescue teams. VR training environments offer a safe, repeatable platform that also offers objective methods to quantify how specific settings in an environment can influence physiological reactions in humans. Variables such as various dominant visual depths, confinement ratios and boundary visibility characteristics are easily integrated in virtual environments [4, 8, 10]. This study demonstrates a Human-in-the-Loop VR framework designed to research how space variability triggers different reactions in people. At Colorado State University, during a virtual reality custom designed experiment, a temporary state of reduced emotional reactivity was induced in seven participants. The RR measurements for each of the subjects were recorded in real time, using a Polar H10 chest strap. The early data indicate that a relationship exists between a lower intensity of felt emotion and a decrease in physical or psychological responses to confined spaces - this discovery highlights how developers can use virtual reality systems that adjust to the user for emergency response drills and future technological designs that incorporate human feedback. In the context of this experiment, during the research and development effort, the term "adaptive training" refers to adjusting training conditions based on observed participant behavior and changes in their physiological state, with the human researcher remaining part of the decision loop. This paper addresses the following research question: Can continuous physiological monitoring be incorporated into a human supervised VR framework that can serve as the basis for future adaptive training in confined and safety critical environments? The significance of this article lies in the human supervised physiological monitoring architecture that bridges static training with physiological informed adaptive training for challenging environments. The Human-in-the-Loop (HITL) VR proposed framework is a proof of concept that provides supporting evidence for this architecture through continuous RR monitoring across controlled VR conditions, while the spatial characteristics of the environment provide future adaptive implementation.

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1.1. Current Challenges

Most of the VR training today provides value in offering a static, controlled environment, where systems are fixed scenarios that provide little change in response to the trainee's physiological or emotional state. Adaptive VR remains an emerging research area and it has yet to become standard practice in operational training systems [7, 9]. Although most VR training experiences provide a virtual learning environment (VRE), where the users do repeatable tasks in a learning sequence, they provide only limited adaptive follow up scenarios that deal with altered emotional states. In other words, they lack closed loop mechanisms that modify scenarios based on modified emotional states experienced by participants. As a matter of fact, recent reviews identify physiological monitoring as a promising emerging direction with increased potential for use in operational VR systems. Unfortunately, most studies continue to rely primarily on subjective measurement or post-sessions evaluations rather than real-time physiological measurements capable of supporting adaptive training environments [4, 5]. In safety critical training where errors cause physical harm, a system that adapts automatically might suddenly change settings when faulty data from sensors is ingested. An automated program does not understand the situation in which the trainee performs the task. The human-in-the-loop method keeps a human supervisor who evaluates physiological data and looks at how the trainee acts - the same supervisor decides how to change the training task in real time. The current structure is a middle stage between a training task that does not change and a system that adapts automatically using a closed loop, ideally a mixture would exist.

2. Human-in-the-Loop Architecture

2.1. System Overview

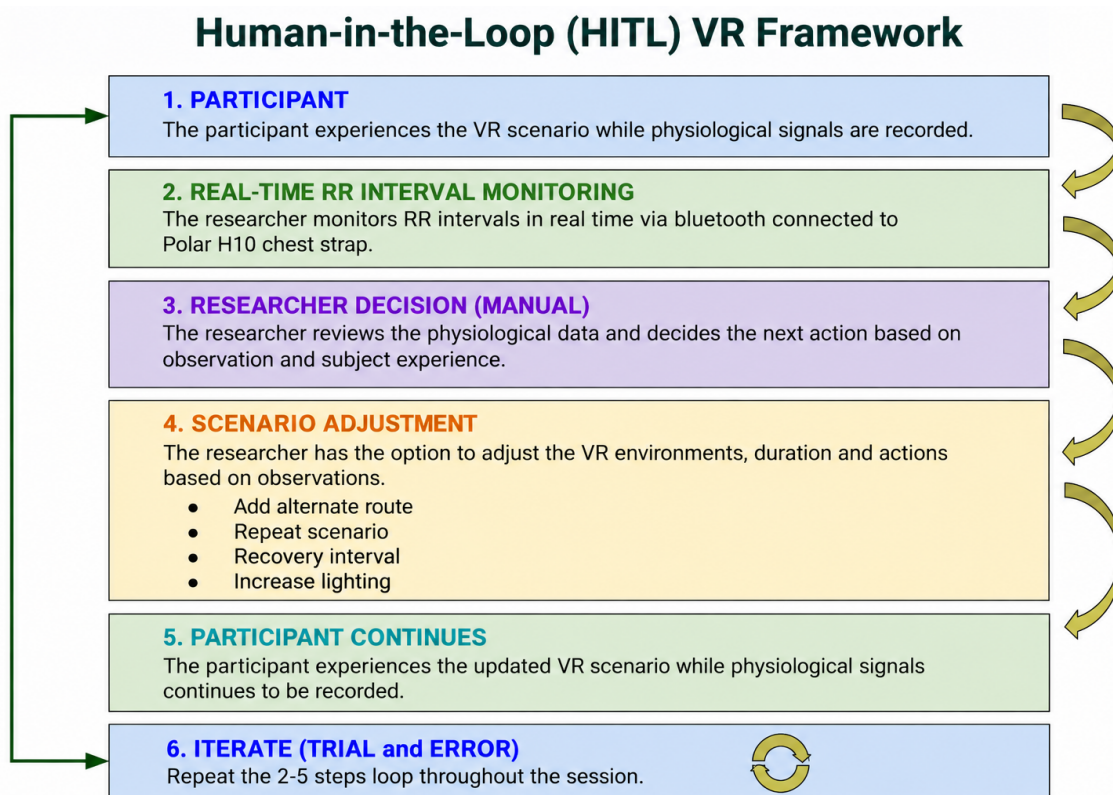


Figure 1: Human-in-the-Loop VR architecture

While the proposed HITL framework supports researcher-supervised scenario adjustments, the

present experiment followed a predefined sequence without real-time physiological feedback-based adaptation. No physiological thresholds or decision rules were used to trigger scenario changes in this experiment. Such criteria will be developed and evaluated in future implementations of the proposed HITL framework. The first phase of the HITL architecture is when the participant interacts with the VR system and progresses through the VR stages. The system is centered around the human, their responses, interactions and emotional responses drive the decisions in the loop. The second phase is called Real-time RR Monitoring, the activity consists of a continuous monitoring of the participant's state which allows early detection of stress, discomfort, or emotional numbness. The researcher decision and manual scenario adjustment represent the third and fourth HITL phases. They are the decision point in the proposed HITL framework, where human oversight ensures that the recordings and data will get processed helping to determine potential adjustments in the VR training sequence. The final phase is where the participant continues to the next appropriate stage based on the participant state and study design - either a brick maze or the elevator enclosures. In a future adaptive implementation, the loop cycle will then repeat, enabling continuous real-time data monitoring until the experiment is terminated by the researcher.

2.2. Virtual Environment Design

After completing the TEPS and CLQ questionnaires, participants were instructed to enter a Meditation virtual space to establish resting physiological measurements. The next step was exposure to the Neverending Tunnel and Dark Room enclosures where the expectation is claustrophobic responses. These environments were selected so they provide a selection of confinement conditions that vary visually as well as spatially. Participants then entered the Emotional Dampening (anhedonia inducing) environment before completing post-induction exposure in the Elevator and Brick Maze environments. The experimental sequence consisted of six environments with approximate exposure durations: Meditation (75 seconds), Neverending Tunnel (74 seconds), Dark Room (62 seconds), Emotional Dampening (109 seconds), Elevator (80 seconds), and Brick Maze (101 seconds). During this time physiological recordings were collected continuously to evaluate changes in responses before and after emotional dampening. Even though the implementation presented in this paper follows a predefined experimental sequence, the proposed HITL framework is designed to support adaptive branching in which physiological measurements determine future virtual environments.



Figure 2: Experimental virtual environments used to compare physiological responses before and after the emotional-dampening condition.

2.3. Assessment and Physiological Monitoring

For each of the volunteers in this experiment anonymous participant profiles were created.

Participants were required to be at least 18 years of age. The experimental protocol was approved by the Colorado State University Institutional Review Board (IRB). The profiles, marked sequentially starting with Subject 1, were established using two questionnaires, one for assessing claustrophobic tendencies called Claustrophobia Questionnaire also known as CLQ [12], and the second for assessing participants' baseline anhedonic tendencies at the time of the experiment via Temporal Experience of Pleasure Scale abbreviated as TEPS [2]. A Polar H10 chest-mounted sensor was used to continuously

record RR intervals throughout the experiment [3]. RR intervals depicted in this paper represent the time between consecutive heartbeats, and provide the needed data used to calculate heart rate and heart rate variability (HRV). For this analysis, mean RR intervals were selected to compare changes in average cardiac cycle duration across the experimental phases. Even though mean RR is not itself a measure of HRV, it provides useful information about changes in heart rate and physiological responses during exposure to different virtual environments [6, 14]. The actual VR environment was developed and implemented on the Roblox platform. During the first sessions the initial headset testing produced cybersickness, panic and discomfort in pilot participants; therefore the proof of concept study was adjusted to use a mixed modality display approach involving both headset based and/or desktop immersion depending on the participant.

2.4. Preliminary Results

During the experiment, the seven participants showed measurable RR variability in each of the phases. Mean RR during the pre-emotional dampening claustrophobic exposures (Neverending Tunnel and Dark Room) was 791.1ms, compared with 943.1ms during the post-dampening exposures (Elevator and Brick Maze) which shows an increase of approximately 19.2%. Mean RR during the Meditation baseline was 859.4ms and increased to 915.3ms during the emotional dampening phase. The increase in mean RR suggests a lower average heart rate following emotional dampening. However, exposure order, habituation, and differences between virtual environments may also explain the observed changes.

Subject	Baseline / Meditation RR (ms)	Tunnel RR (ms)	Dark Room RR (ms)	Anhedonia Induction RR (ms)	Elevator RR (ms)	Maze RR (ms)
S1 (Pilot)	812 (Rest)	760	720	880	930	950
S2 (Pilot)	798 (Rest)	748	716	882	941	962
S3 (Pilot)	824 (Rest)	772	735	901	938	952
S4	805	741	710	895	964	978
S5	817	755	725	889	944	956
S6	792	736	701	781	754	769
S7	1168	1107	1149	1179	1068	1098

Figure 3: Heat-map representation of RR interval behavior across all participants and experimental phases.

3. Adaptive Public Safety Training

Confined Space Rescue: Industrial confined-space rescue operations are some of the most dangerous and life threatening missions in the world. Controlled HITL adaptive VR training environments allow these conditions to be reproduced and adapted safely while providing quantitative measurements of participant response throughout the training session. Protective Suits Operations: HazMat personnel, astronauts, and deep sea divers often work in protective equipment that, without appropriate training, can increase both physical and cognitive workload. Adaptive VR training is the framework that allows not only real-time physiological monitoring and evaluations but also the right environmental adjustments that have the potential to reduce emotional overload and improve decision making under pressure. This framework can easily extend to any training requiring heavy gear, and environments with high intensity, such as astronaut and firefighter training.

4. Lessons Learned and Future Work

The proof-of-concept demonstrated several observations relevant to future development of adaptive VR training systems. Continuous physiological monitoring using a wearable sensor such as Polar

H10 chest strap proved easy to use and provided a feasible way to monitor physiological metrics throughout the experiment without affecting the participant's interaction with the virtual environment. Additional physiological signals, such as EDA, could be considered in future implementations. Future automated adaptation would require reliable physiological thresholds, synchronized sensor data, and validated decision rules to ensure appropriate and safe adjustments to VR environments. Additionally, the suggested spatial integration characteristics provide an objective and flexible option to allow future comparisons between different confined space configurations, easily reproducible in virtual reality platforms. Immersive learning, unlike conventional training, allows participants to experience realistic operational environments that with the aid of Human in the Loop Architecture have the potential to personalize training experiences and greatly improve operational readiness for emergency responders and other public safety professionals.

5. Conclusion

This paper outlined the potential of a Human-in-the-Loop VR framework and how it can be leveraged and utilized for public safety training. The proof of concept research used a predefined experimental sequence to evaluate and adjust components of the proposed adaptive HITL architecture. This HITL system supports the continued need to find novel methods for development of immersive learning for confined space rescue, protective suit operations and other safety critical applications. The preliminary findings demonstrate the feasibility of physiological monitoring within controlled VR environments. While adaptive scenario adjustments remain a proposed capability of the HITL framework, further validation is required to establish their effectiveness in public safety training.

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