Enhancing Virtual Environments Using Sensory-Multiplexing

LCDR Dylan Schmorrow
Office of Naval Research
Arlington, VA
schmord@onr.navy.mil

LT Joseph Cohn
US Naval Research Lab
Washington, DC
cohn@itd.nrl.navy.mil

Roy Stripling, Amy Kruse
Strategic Analysis Inc.
Arlington, VA
rstripling@sainc.com, akruse@sainc.com

ABSTRACT

Virtual Environment (VE) technologies have often been hailed as the ultimate solution for providing comprehensive, affordable and flexible training. Yet, despite the enormous amounts of time and money invested in the development of these devices, the results have, by and large, failed to live up to their expectations. This is likely due to significant mismatches between the virtually presented environment and the anticipated real world one, resulting in a modern day version of Osgood's (1949) *Similarity Paradox.* Recent work indicates that there are at least two factors that limit the 'spectral-range' of current VE training experiences. First, VE systems supply information primarily through visual and non-spatialized audio channels, limiting the quantity and quality of information being conveyed to the trainee. Second, current technologies create an environment in which much of the experience is highly scripted, failing to deliver a user-specific training experience. This suggests that there is much to be gained by recasting Osgood's challenge as an Information Processing problem.

This paper will focus on a "sensory-multiplexing" approach being developed to create adaptive VE training systems that optimize user cognitive and emotional engagement and that naturally direct the user towards appropriate learning strategies. Two lines of investigation are currently being pursued. The first focuses on developing a VE-based training system, using human-centric design principles, to provide Marines with training in Close Quarters Battle (CQB) at both the individual and team level. The second focuses on demonstrating, in the laboratory as well as operationally, that objective measures of attention, arousal, and cognitive workload can be gleaned from the output of non-invasive physiological sensors. When the results from the two efforts are integrated into a single system, the resultant information could be used to adaptively titer the users level of arousal and to direct or re-direct his/her attention as needed.

ABOUT THE AUTHORS

LCDR Dylan Schmorrow is a Medical Service Corps Officer in the US Navy. He is serving at the Defense Advanced Research Projects Agency and is responsible for executing cutting-edge basic science and technology development primarily in the area of human-technology integration. Additionally, he directs and manages science and technology programs at the Office of Naval Research in the area of biomedical and human systems, human performance, and training and education.

LT Joseph Cohn is a designated a Naval Aerospace Experimental Psychologist. Currently, Lieutenant Cohn serves as the Lead, Requirements and Training for Virtual Environments (VE) at the Naval Research Laboratory where he is developing a comprehensive theoretical framework for establishing Training Transfer. As such, he is directing the evaluation of deployable VE training systems for the Naval Aviation and Expeditionary Warfare communities and providing direct training and operational Fleet support to these communities.

Dr. Roy Stripling received his Ph.D. in Neuroscience from the University of Illinois at Urbana-Champaign. His graduate and post-doctoral work investigated molecular, electrophysiological, and behavioral correlates to learning and memory. In 2002, Dr. Stripling became a scientist-contractor at the US Naval Research Laboratory in Washington, DC, where his work seeks to leverage neuroscientific and technological advances to enhance human performance and improve training technologies.

Dr. Amy Kruse currently serves as the Technical Manager for the Improving Warfighter Information Intake Under Stress-Augmented Cognition program at DARPA. In this role she has championed the use of neuroscientific techniques in the operational/applied environment. Prior to her work at DARPA, Dr. Kruse conducted NIH funded post-doctoral research at the Beckman Institute on the University of Illinois Urbana-Champaign campus. Her areas of expertise include learning and memory, neurophysiology and fNIR technologies. Dr. Kruse holds a Ph.D. in Neuroscience from the University of Illinois.

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INTRODUCTION

The Challenge

The primary goal of developing any training system is to provide a level of training that translates to enhanced performance on the types of real world tasks being simulated (Lathan et al., 2002). The principal benefit that Virtual Environment (VE) systems have over real world training is that they offer instructors the chance to train situations that would be too hazardous or too costly to actually practice in the real world (Rose, Attree, Brooks, Parslow, Penn & Ambihaipahan, 2000). As compared with Legacy type systems, VEs also afford a smaller footprint and, being essentially software driven, can be more easily reconfigured to support a variety of training tasks (Cohn, Helmick, Meyers & Burns, 2000).

While VE systems offer much potential in the way of supporting training, concrete illustrations of the transfer of complex skills to real-world applications from VE training, or of performance enhancement through exposure to VEs, are few and far between (Cohn et al., 2000). While both spatial (Witmer, Bailey, & Knerr, 1996; Witmer & Sadowski, 1998) and procedural skills (Brooks, Attree, Rose, Clifford, & Leadbetter, 1999) appear to positively transfer between VEs and real world tasks, it is clear from the literature that many of these demonstrations are system specific. In fact, few studies, have characterized the general types of tasks or training activities for which the unique characteristics of VEs can be leveraged to provide significant gains in human performance (Stanney & Zyda, 2002).

Possible explanations for the lack of generalized success include the difficulty identifying and rendering into VE training scenarios those critical real-world experiences and conditions that naturally facilitate the learning process. These shortcomings deny trainees the benefit of the 'full-spectrum experience' of real-world training. In doing so, VE training potentially impairs their students' abilities to fully comprehend and integrate the wealth of information available in real-world tasks. Thus to date, only tasks that can be accurately modeled using 'narrow-spectrum' systems seem to be effective.

The Solution

While this issue can be approached from multiple perspectives, the current effort recasts it primarily as an information processing challenge, whose solution lies in the idea of 'sensory-multiplexing'. From this perspective, three factors limit the 'spectral-range' of current VE training experiences. First, most VE systems supply information through restricted visual (i.e. low resolution, narrow field of view) and non-spatialized audio channels. These sensory-impoverished representations of real-world environments effectively filter the amount and kind of information being conveyed to the trainee. Second, current VE training systems are typically designed to support a single trainee, operating within a scripted scenario populated by computer generated forces and semi-autonomous forces.

Yet, as recent events make clear, success in the real world combat environment requires interactions between members of the same team, members of different teams and even members from teams operating under entirely different rules of engagement. By failing to support truly collaborative, team-training environments, these systems, at best, provide anemic imitations of real-world interactive tasks. Third, the combined impact of these two limitations acts to restrict the cognitive and emotional engagement of the trainee, thus diminishing the impact of the training experience.

These insights into the weaknesses of VE systems also suggest a means of overcoming them – the development of closed-loop, multi-sensory VE training systems that provide rich sensory experiences to the user and enable the real-time assessment of the user's cognitive and emotional responses by the system itself (Conati, 2002). First, such VE systems would be able to achieve 'real-world learning' by providing full-spectrum sensory experiences (achieved with the addition of haptic interfaces and 3-D (spatialized) audio). Such systems would mimic real-world learning by creating robust experiences, where information pertinent to the learning experience is encoded redundantly and realistically. Second, trainee cognitive and emotional states associated with optimal learning effectiveness will be sustained throughout the training experience with the application of new neurophysiologically-based, user-aware adaptive system architectures being developed under such efforts as the DARPA IWIIUS (Improving Warfighter Information Intake Under Stress) program. That is, leveraging technologies from the general field of "augmented cognition." The combined, anticipated result will be augmented VE training systems that enhance learning beyond typical real-world training experiences.

SOLUTION IMPLEMENTATION

Despite its great promise, however, successful implementation of these critical technical advances alone will still not be sufficient to ensure that the augmented VE training systems are able to meet their lofty expectations. A set of guidelines for validating these systems must first be developed, followed by their application to more complex tasks. Once the training applications are validated, enhancements to the virtual technologies supporting them can be considered.

Previous Efforts: Training Framework and Application

Previous efforts, as part of the Office of Naval Research's Virtual Technologies and Environments (VIRTE) program set out to address this challenge in 2 stages. The first stage, Virtual Environment Expeditionary Warfare (VE EW) endeavored to demonstrate the degree to which a Human Centric Simulator Design Model could be developed, validated and utilized to rapidly prototype vehicle based VE training systems. The second stage, Virtual Environment Human Interface Technology (VE HIT) capitalizing on the success with which this model has had thus far, is currently focusing on non-vehicle team based VE training systems, that is, systems that directly interface individual users, rather than through a virtual vehicular intermediary. Each of these stages, while endeavoring to demonstrate real world performance enhancement through exposure to virtual environments, has its own unique evaluative metrics. For VE EW, these metrics included a heavy reliance on Usability Engineering principles to guide system development. For VE HIT, these metrics will shift to more advanced analyses of the minimum ecological validitythat individual user interfaces must have, as well as to the development of a team performance evaluation metrics suite (Gross, Stanney & Cohn, 2004). The intent with this approach is to demonstrate a spiral development cycle not only for the production of actual systems but, also, in the collective understanding of what VE systems are (and are not) capable of accomplishing.

Virtual Environment Expeditionary Warfare (VE EW)

The overarching technical goal for VE EW was to provide a networked, deployable system for training a myriad of concepts relating to a specific type of warfare known as Expeditionary Warfare. Each virtual component of this system is based on real-world operational requirements and each is intended to transition to real world use as shown in Fig. 1. The LCAC (Landing Craft, Air Cushioned) vehicle serves as a highly maneuverable hovercraft platform that can quickly move troops, other vehicles and equipment from ship to shore. The EFV (Expeditionary Fighting Vehicle) acts as a highly defendable troop transport that can move quickly either in the water or on land. The MV-22 (a Tilt-Rotor aircraft) is intended to serve as a platform for, among other things, rapid troop insertion. Finally, the CQB (Close Quarters Battle) component involves training individual Marines to work as part of a fire-team, consisting of four people, to clear a multi-level building of enemy forces. The corresponding VIRTE systems include: a Virtual Environment Landing Craft, Air Cushioned (VELCAC); a Virtual Environment Expeditionary Fighting Vehicle (VE EFV); a Virtual Environment Tilt-Rotor craft (VE MV-22),; and a Virtual Environment Close Quarters Battle (CQB) system.

Figure 1. VE EW focused on providing deployed training solutions to the Expeditionary Warfare community. This community includes air, land and sea elements. *From Far Left to Right Top Row:* Landing Craft Air Cushioned (LCAC); Expeditionary Fighting Vehicle (EFV) The MV-22 (Osprey) is a tilt-rotor craft currently under

development. *From Far Left to Right, Bottom Row:* VELCAC; VE EFV; VE MV-22.

Underlying this technical goal, however, was a theoretically-driven motivation to capture a validated process for rapidly prototyping these systems. The motivation for developing this Human Centric Development Model was to determine how to bound technology solutions with Human Factors principles. The Model that was subsequently developed, illustrated in Figure 2, was validated, piece wise, across the VE EW component systems.

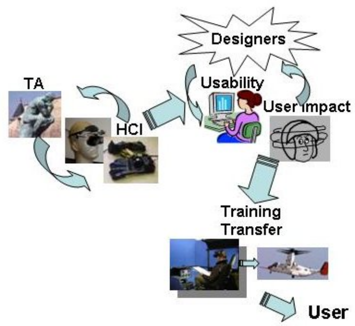

Figure 2. Human Centric Development. Initial analyses include Task Analyses and Human Computer Interface Evaluations, resulting in an initial set of specifications. Once the initial system is designed iterative evaluations, from a Usability and User Impact perspective provide system designers with re-design recommendations. Once stabilized, a final evaluation of performance impact is undertaken, and the system is delivered to the end-user.

Virtual Environment Human Interface Technology

The efforts undertaken by VE EW focused primarily on developing and validating principles for rapidly prototyping vehicle simulations. From both a research and science and technology perspective, these efforts mark the first step towards developing a comprehensive understanding of how to quantify and exploit VE technology to support training. In order to gain deeper insights into the range of training applications for which VE may be suited, one must consider expanding the design space to include non-vehicle based simulations, in which the user directly interfaces with the environment and, through this environment, with other users who are similarly interfaced. From this enhanced perspective, it becomes clear that the principles developed in VE EW form only a single piece of the larger picture. Additional efforts, moving away from a purely Usability Engineering based approach, and focusing on the ecological validity of user interfaces as well as on techniques for quantifying team-based training, are required.

The development of vehicle based simulations requires a certain level of Usability/ Human Computer Interaction assessment. Typically, the primary focus of these efforts is determining the level of fidelity – or ecological validity- that the simulated interfaces must share with their real world analogues. Thus, when developing cockpit interfaces, such as those designed for VE EW's VELCAC system, a primary question was which instruments needed to be reproduced in such a manner that the way in which the user interacts with them is preserved, and which ones could be reproduced using a more minimalist approach.

Solutions to these interface challenges are typically derived through design specifications developed from the Task Analyses, which can then be implemented in the overall system and evaluated in terms of performance measures. For VELCAC, the Task Analysis made clear the fact that primary flight controls were required to have high correspondence with their real world counterparts –essentially, perfect ecological validity-, while other instruments (knobs, switches and dials) could have less correspondence, using visual representations which could be activated through keyboard and mouse clicks. Note that, since the training goals and objectives were defined through the task analyses, this solution essentially still maintains a high level of ecological validity, within the specific training context.

The switch in emphasis from vehicle based systems to non-vehicle based ones introduces a level of complexity to the simple relationship laid out in Figure 2. Unlike the vehicle simulation, where an artificial interface was being developed that mapped onto a well-defined real world correlate, in this case, the challenge is actually defining what elements of the real world itself must be supported during normal interactions in order to make behaving in the Virtual world smooth. These specifications can not simply be determined by 'sampling' the real world. Instead, the general context within which the behaviors that are being trained may occur must be identified, and the stimuli propogated by them –as well as the stimuli that are necessary for certain behaviors- must be re-created in the VE. Thus, unlike the vehicle based experience, the reliance for system specifications for VE HIT depends more on an understanding of the perceptual and cognitive components of a human behaving in the real world.

Current Work: Sensory Multiplexing

In a sense, the approaches discussed thus far, which focus on developing training systems, can be decomposed into two types of solutions:

- Solutions guided by Information Technology
- Solutions guided by properties of the Human Nervous System

VE EW focused mainly on developing solutions guided by information technology, the challenge being how to quickly map mature technologies onto identified training requirements in a logical fashion. VE HIT took this approach and expanded it to include a larger training space, with more users behaving within a single type of 'platform', here, the MOUT (Mobile Operations in Urban Terrain) environment. VE HIT also began melding this larger Information Technology approach with solutions guided by more neurologically-based guidelines – sometimes considered as sensory integration or sensory multiplexing. Thus, the range of solutions is expanded to include:

- Solutions guided by Information Technology
    - – Expand the training space
        - Within platform
- Solutions guided by properties of the Human Nervous System
    - – Sensory Multiplexing
        - Vision
        - Spatial orientation
        - Kinesthetic
        - Audition
        - Haptic

Yet, on closer inspection, it would seem that these two solutions could be expanded even further, to include cross platform training, such as characterizes Expeditionary Warfare, or even training teams of teams that operate across platform environments. Of particular interest, VE offers a unique opportunity to integrate training augmentation tools, further enhancing the quality of the overall experience, and likely leading to enhanced real world performance.

Solutions guided by Information Technology
- – Expand the training space
    - Within platform
    - Cross platform
    - Multi-spectrum
- – Augment the training
    - Real-time detection of performance
    - Real-time detection of user state
- Solutions guided by properties of the Human Nervous System
    - – Sensory Multiplexing
        - Vision
        - Spatial orientation
        - Kinesthetic
        - Audition
        - Haptic

Figure 3 illustrates this progressive evolution of VIRTE, from simple VE training system, to ensemble collective training system.

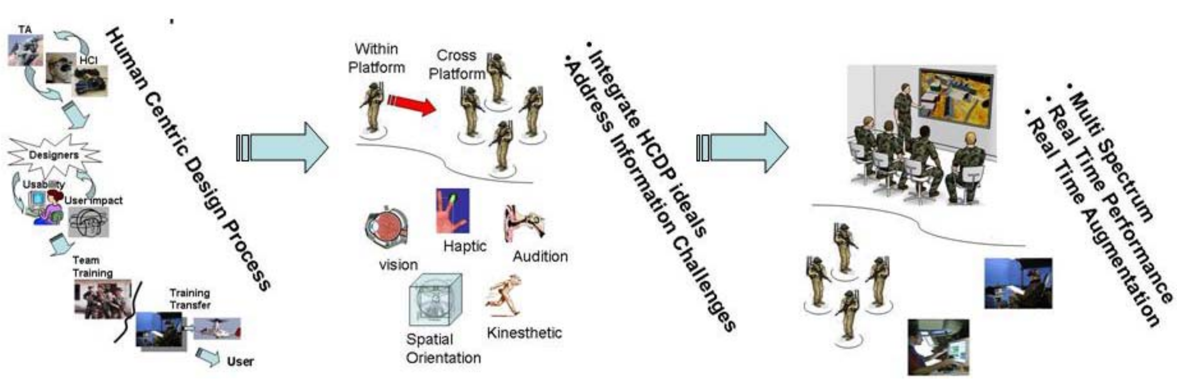

Figure 3. Early in the VIRTE program the focus was on evaluating systems primarily through a Usability Engineering approach, combined with a simple Performance-based assessment (*far left).* Subsequent efforts focus on expanding this approach to include a more team based and multi-sensory approach (*middle)* and, ultimately a more all-inclusive application *(far right)*.

MAKING IT WORK

The first step in developing this system was to identify a community with defined training requirements that could be supported through the use of training with a VE system. This enabled the development of a specific set of training goals and objectives that could be met by the system being developed, Currently VIRTE has identified the Marine Corps Infantry Officer Course (IOC) as both the recipient and the subject matter expert (SME) for VEHIT development. Collaboration with IOC staff will allow the identification of insertion points within the twenty six week training program where advanced VE systems can be used to enhance their training. This collaboration will also enable VIRTE to address issues in the difference between individual training and team training. In support of this effort, the VIRTE program is establishing a 'Warfighter Human System Integration and Operational Neuroscience' (WHSION) laboratory at the U.S. Naval Research Laboratory to test and evaluate a suite of networked VE training 'pods' capable of running up to 4 subjects onsite. This lab will network with additional subjects being run simultaneously at other labs. The WHSION laboratory will also serve as the testbed for developing and, ultimately integrating haptic and spatialized audio interfaces within the VE-based training environment.

To meet the need for delivering 'full-spectrum' sensorial experiences, the WHSION lab is pursuing a series of exeperimnets aimed at identifying human-based parameters to bound the development of these new technologies. These experiments will also quantify the benefit to adding these systems to performance in a VE as well as to the ability of the training experience to improve real-world performance. Importantly, the tasks against which these verification and validation efforts will be assessed will be based on MOUT-like activities, enabling a highly realistic level of evaluation.

The first task will be to maintain full awareness of the position and actions (rounding a corner, entering a room, etc.) of the team leader (played either by a computer generated avatar or by a second human user), while also securing the team's rear from potential assault. The task will be carried out both in our VE systems as well as in a real-world location. Spatial audio cues play a natural role in this skill in the real-world, and new haptic vests are currently being procured for silent communication between dismounted Marines. Thus, through this training scenario, we will evaluate both the value of adding these sensory channels to VE training and test a potential use for the haptic vest in enhancing CQB team situational awareness.

The WHSION lab will also perform a second experiment to evaluate the merits of 'full-spectrum' VE training systems as well as to determine its utility for a specific aspect of CQB training. Beginning in mid-September, tests will be conducted to determine the merits of using spatial audio and haptic cues as feedback indicating the research participant's potential exposure to enemy forces. In the real world, as warfighters pass by windows, doorways, or round corners they expose themselves to potential enemy combatants. Full awareness of this exposure is a skill that must be learned until it is an automatic behavior. Some non-intuitive aspects of this skill include not allowing the warfighter's weapon to prematurely reveal their location. The merit of these sensory cues in the training of this skill will be measured by evaluating the research participant's performance when these training aids are removed.

A series of additional studies are planned to test the potential for leveraging closed-loop, "augmented cognition" technologies in our prototype VE training systems. The first and simplest experiments will focus on identifying objective physiological measures of attention, arousal, and/or engagement from subjects working in a MOUT/CQB virtual environment. The data derived from these efforts will be used to establish parameters for optimal engagement (by comparing these objective measures to relevant performance scores). These parameters will then be applied to the next three 'closed-loop' studies. The first of which will demonstrate the ability to use these validated neurophysiological measures to manipulate action or events in the VE and to thereby control the cognitive and emotional states of the VE users. In this study, a minimum of two subjects will be run in our VE 'pods' simultaneously. Each subject will take the role as leader of their own CQB team (the remainder of the team will be played by computer generated avatars). Secondary tasks (such as route redirections, message handling, etc.) will be passed to the subject that the system deems to be most capable based on the cognitive/emotional state derived from their neurophysiological measures. Assessment of cognitive/emotional state will be based on evaluations made by trained neural-network processors. Success will be measured by the collective effectiveness (combined performance score) of the two subjects.

The second of these three studies will directly test our concept of maximizing training effectiveness by holding subjects at their optimal cognitive/emotional state for learning. It is both a general belief and an empirical observation that training environments which are more emotionally and cognitively engaging are more effective. This observation plays to the strength of VE training systems which provide an interactive, immersive experience for the student. However, until recently the means to measure, in real-time, the students cognitive/emotional engagement were not available. Consequently, there was no way to modify the training environment in response to the subjects current state so as to raise, lower, or sustain their level of engagement. By leveraging "augmented cognition" technologies as well as the results of the previously described experiment, we will demonstrate and evaluate the capability of such systems to achieve this goal. Skills trained in this study will be those described for the first and second experiments above (maintaining situational awareness of the team leader and minimizing own-self exposure). Thus this study will also leverage knowledge gained from these experiments as well.

The final and scientifically most ambitious experiment will be to determine if there are neurophysiologically-based measures of team cohesion. The hypothesis to be tested here is that optimal team performance arises when team members are perceiving and interpreting external cues and experiences in a like manner. In such cases, the elicited perceptual and cognitive states should drive the individual team members into matched rhythms of neurophysiological activity as compared to team members that are not perceiving and conceptualizing the ongoing events in a like manner. Once identified, such measures would find several useful applications, including: serving as a metric for real-world team performance, use as a means of selecting compatible team members, and use in augmented VE team-training systems, where real-time, closed-loop manipulation of the VE scenario would be used to more rapidly bring team members to a state of optimal cohesion.

Collectively, these ambitious experiments will close the gap in our ability to provide 'real-world training' in a virtual environment. The planned experiments focus on the dismounted soldier training systems which is itself the focus of the ONR VIRTE program's VEHIT efforts, however, the findings of these experiments will substantially enhance future efforts. As currently envisioned, future VIRTE efforts (dubbed "Multi-platform Operational Team Training Immersive Virtual Environments," or MOT^2IVE) will seek to create fully immersive combined training virtual environments These systems will likely take advantage of VE training systems located around the country and will thus require networked technologies. Our VEHIT team-training efforts will support this need and provide the necessary experience for leveraging rapid solutions. MOT^2IVE also addresses the reality of real-world military operations, which rely on the complex interactions of multiple combat platforms. This final phase of VIRTE seeks to accomplish this by demonstrating the potential for VE systems to accelerate training and enhance the cross-platform, collective performance of our fighting forces. The experiments to be performed by the WHSION lab will advance this cause as well by providing tools for maximizing training effectiveness and by developing direct measures and training tools for enhancing team training and performance.

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