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Using Vibrotactile Cues for Virtual Contact and Data Display in Tandem

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Abstract

In this paper, we present a treatment of the issues that must be addressed in using vibrotactile cues for multiple purposes within a single simulation system. Similar to the problem of overloading the visual channel in typical graphical user interfaces, care must be taken to keep the added cognitive load devoted to the vibrotactile channel of the user to a minimum. Vibrotactile cues are typically used in virtual reality simulation systems to provide a sense of touch when the user interacts with virtual objects. Other systems use vibrotactile cues to display information to the user, such as directional cues to enhance spatial awareness. Combining these cues in a single, unified system could cause confusion, leading to a drop in performance of the target task. We propose the use of spatial and temporal cue characteristics as a way of disambiguating vibrotactile cues used for different purposes.

1 Introduction

Training simulators have been successfully employed for several decades for use in many fields, such as in flight trainers, driving simulators, and, more recently, rehearsal systems for surgical procedures. In the past fifteen years, simulator technology has improved to the point where we are now becoming able to construct virtual environment systems that support first-person, full-body experiences, such as team-based close-quarters battle (CQB) training. CQB training consists of a complex set of tasks, each made up of several sub-tasks that must be performed in concert. The characteristics of CQB that make it interesting to study (and challenging to implement) are: 1) a need for strong situational awareness to effectively complete the task, 2) the reliance on cues from the visual, audio, haptic, and olfactory senses, 3) our inability to recreate such cues with fidelity equal to the reality being simulated, 4) the need to locomote on foot, 5) the requirement for precision aiming of weapons, and 6) the need for performing multiple tasks at one time, requiring substantial training to master the overall task.

Visual rendering quality has improved so dramatically in the past few years, driven mainly by the game industry, that we can now generate images at interactive frame rates that are (arguably) indistinguishable from their real-world counterparts. Spatialized audio techniques are also sophisticated enough to generate realistic sound dynamics to match the graphics. Creating full-body haptic cues has proven more elusive, with device weight, cumber, and power requirements being the major impediments to their successful deployment. Little work has been done on creating devices and techniques for delivering olfactory cues, though smell could be very important.

From previous work on the use of vibrotactile cues for imparting information when the user contacts virtual objects (Lindeman, Page, Yanagida & Sibert, 2004), and the use of vibrotactile cues as training aids to enhance situational awareness (Lindeman, Sibert, Mendez-Mendez, Patil, & Phifer, 2005), this paper outlines some of the possible approaches to combining these two uses of the same technology with an eye towards providing unambiguous cues, so as to keep cognitive load and mismatches as low as possible. Though we describe our current work in terms of CQB, the issues we address in this paper can be applied to any complex simulation that would benefit from the use of cues utilizing the same sensory channels, but for different purposes.

2 Background

For the past several years, researchers have been exploring the use of inexpensive pager motors as a means for providing vibrotactile (VT) cues to users in real and simulated environments. The end-effecter devices at the point of vibration are called *tactors*, devices that provide some form of tactile stimulation. While most of the work has focused on apparatus design and evaluation, few systems have moved beyond the laboratory and been deployed in an actual simulator in a manner that provides synchronized delivery of visual, auditory, and haptic cues to support task training. We have recently been focusing on the use of VT cues for displaying the result of collision detection algorithms. Independently, we have conducted several empirical studies into the use of VT cues to display other types of information unrelated to collisions with virtual objects.

2.1 Virtual Contact

Virtual contact research addresses the problem of what feedback to provide when the user comes into contact with a purely virtual object within a virtual environment (VE) (Lindeman, Templeman, Sibert & Cutler, 2002). As humans, we interact with our environment using multiple feedback channels, all coordinated to help us make sense of the world around us. The limited multimodal feedback in current VE systems, however, hinders users from fully understanding the nature of contacts between the user and objects in these environments. It has been found that because real-world contact combines feedback spanning multiple channels (*e.g.*, tactile and visual), providing feedback to multiple channels in VEs can improve user performance (Kontarinis & Howe, 1995). Grasping virtual controls, opening virtual doors, and using a probe to explore a volumetric data set can all be made more effective by providing additional, multimodal feedback. In essence, we are addressing the need for supporting effective user actions in environments with reduced sensory feedback, because the only feedback the user receives is that which we provide.

Typical approaches to providing haptic feedback use force-reflecting devices, such as the PHANToM, or exoskeletons. These devices can provide very effective feedback, but their use in full-body applications is limited by their expense and cumber. Yano, Ogi & Hirose (1998) developed a suit-type vibrotactile display with 12 tactors attached to the forehead (1), the palms (2), elbows (2), knees (2), thighs (2), abdomen (1), and back (one on the left side and one on the right). They examined the effectiveness of using this vibrotactile display for tasks that required the user to walk around a virtual corridor visually presented in a CAVE-like display. They showed that presentation of tactile cues was effective for imparting collision stimuli to the user's body when colliding with walls.

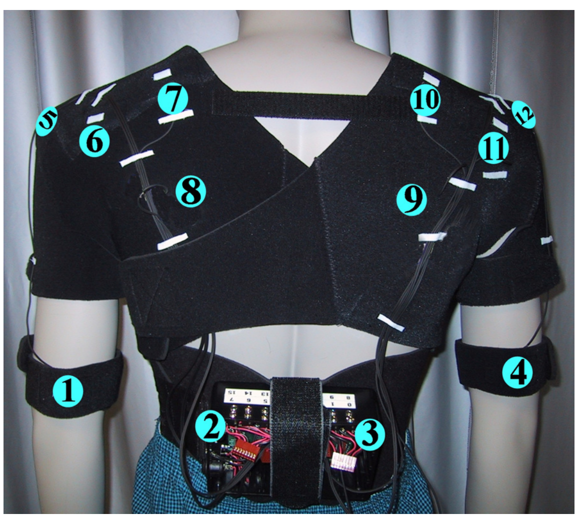

Figure 1: TactaVest (back) with Tactor Locations Marked (locations on the front of the vest are roughly equal to locations 2, 3, 8 & 9, but on the front)

Figure 2: TactaVest integrated in an immersive virtual reality system

Some previous work on body-worn designs uses a regularly-spaced layout pattern for placing the tactors (Rupert, 2000; Tan, Lu & Pentland, 1997; Gemprele, Ota & Siewiorek, 2001; Erp & Veen, 2003; Jones, Nakamura & Lockyer, 2004; Yang, Jang & Kim, 2002), reflecting the fact that their target application is information display, as opposed to virtual contact. Similar to Yano *et al.* (1998), we choose to mount the tactors on our TactaVest at locations on the body with a high probability of contacting virtual objects (Figure 1). In addition, our application environment has users wearing a military tactical protective vest (a modern version of a flak jacket) during the simulation, so care was taken to choose locations that would not be adversely affected by this and other gear worn during a typical session (Figure 2). The 16 tactors we are currently using are positioned on the elbows (numbers 1 & 4 in Figure 1), on the end of the shoulders (5 & 12), across the shoulder-blades (6, 7, 10 & 11), along either side of the spine (2, 3, 8 & 9), and the front-side of the torso (not shown). Multiple tactors can be triggered together, and at varying vibration levels, to accommodate different contact scenarios.

2.2 Information Display

Several interesting approaches have been proposed for displaying information to users via the haptic channel. Tan *et al.* (1997) combined input from pressure sensors mounted on the seat of an office chair with output in the form of tactors embedded in the back of the seat to create an input device with haptic feedback. They integrated this system into a driving simulator, used a classification system of the pressure sensors to determine when the driver intended to change lanes, and then gave attentional cues to the driver with vibrotactile pulses about danger based on dynamic traffic patterns. Rupert (2000) developed a system using a vest with tactors sewn into it to allow pilots to better judge the down-vector when performing aerial maneuvers that alter the pilot's vestibular system, causing possibly-fatal errors in judgment. He found that feedback to the torso could be effective in improving a pilot’s spatial awareness. Veen & Erp (2000) studied the impact of G-forces on both the mechanical workings of vibrotactile devices, and on reaction times to vibrotactile stimuli displayed on either the right or left side of the torso. They showed that after initial familiarization with the environment, subjects had fairly stable response times and accuracy levels, even up to 6G of force. There was also no apparent difference in performance with and without a pressure suit.

There are a number of parameters that can be used to vary the characteristics of a vibrotactile stimulus (Lindeman *et al.*, 2002). For a single tactor, these include *frequency*, *amplitude*, *temporal delay*, and *pulse patterns*. For groups of tactors, both regularly-spaced (Rupert, 2000; Lindeman *et al.*, 2005) and non-regularly-spaced layouts (Yano *et al.*, 1998; Lindeman *et al.*, 2004), *tactile movement patterns*, *body location*, and *interpolation method* can be identified. MacLean & Enriquez (2003) introduced the notion of haptic icons (*hapticons*) and performed empirical analysis of the design space of these vibration characteristics. Using a haptic knob held by the thumb and index finger, they found that frequency and *stimulus shape* (*i.e.*, sinusoid, square, sawtooth) were the most orthogonal properties. Frequencies in the range of 3-25 Hz provided the best distinguishability, and a sinusoidal waveform was found to be easily distinguishable from waveforms with discontinuities, such as square or sawtooth waveforms, at least at low frequencies. Brewster & Brown (2004) explored the notion of tactile icons (*tactons*), structured, abstract messages that can be used to communicate information non-visually. Similar to previous work, they outlined the possible parameters for distinguishing tactons, adding *rhythm* to those previously listed. They define more-complex tactons consisting of compositions of simple stimuli, as well as hierarchical structures that vary different signal parameters of a common tacton to differentiate, for example, an underflow error from an overflow error; both are errors, so they share a common portion of the tacton, but have a unique portion as well. They outline some interesting possible approaches for off-loading the visual channel, such as using motion around an array of tactors around the waist to display a "progress bar" for such tasks as downloading files.

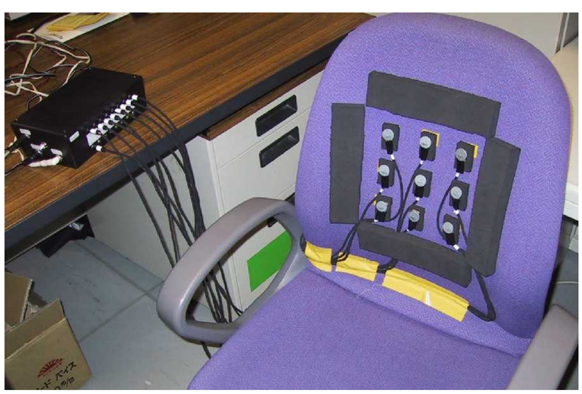

Figure 3: Office chair with 3 x 3 array of tactors

One of the properties that makes effective use of VT cues so challenging is the fact that different body locations have different densities and types of skin mechanoreceptors; the makeup of the stimulus location dictates the frequency range that will be most noticeable to users. In an attempt to better tease out some of the thresholds of discrimination on the back, we conducted several studies using a desktop computer and a 3 x 3 array of tactors mounted on an office chair (Figure 3) (Lindeman & Yanagida, 2003). In a location discrimination task, tactor location, defined as the row and column of the stimulus, was the experimental manipulation. Each of the 21 subjects performed 36 trials during one session, with each of the nine array locations appearing four times in a pseudo-randomized order (756 data points total). The only cue given during each trial was a one-second 91Hz VT stimulus output at the start of the trial; no visual indication of the stimulus tactor was given. The subjects then indicated the location of the stimulus by selecting the corresponding button on the desktop display (Figure 4).

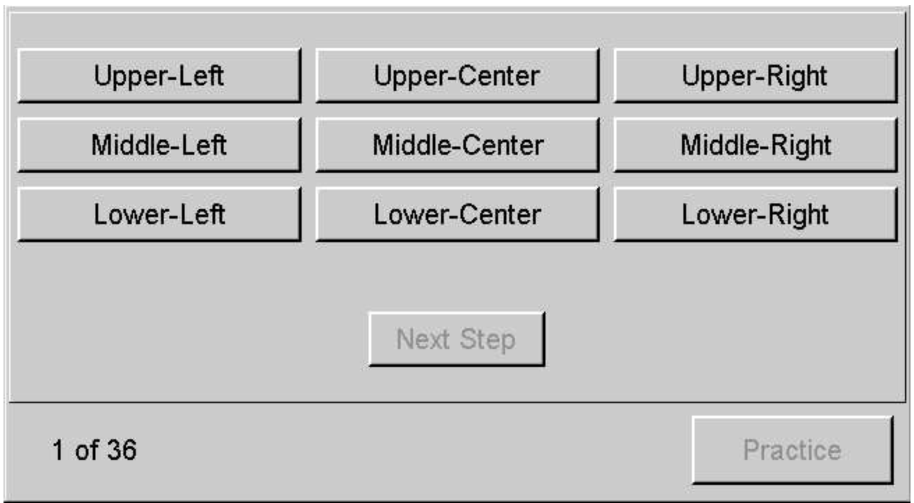

Figure 4: Array of buttons corresponding to tactor locations

The overall success rate for selecting the correct location was 84%. A closer dissection of the errors committed by subjects gives an even more in-depth look at the perceptual picture. A total of 119 errors were committed over the 756 trials. Of these, 103 were misjudgments where the actual and perceived stimuli were in the same column, 15 where they were in the same row, and one error was diagonal in nature. If we generate a rank-order list of all error pairs of actual and perceived stimuli locations (a total of 23 pairs), and then take only those that represent more than 5% of the total errors, Table 1 results.

Table 1: Identification errors

Rank	Stimulus Location	Perceived Location	# of Errors	% of Total Errors
1	Upper-Center	Middle-Center	20	16.8
2	Upper-Left	Middle-Left	14	11.8
3	Lower-Center	Middle-Center	13	10.9
4	Middle-Left	Lower-Left	12	10.1
5	Upper-Right	Middle-Right	11	9.2
6	Lower-Left	Middle-Left	9	7.6
7	Middle-Right	Lower-Right	8	6.7

A more-graphical representation of this data gives still more insight into the nature of the errors (Figure 5). We can see from this figure that a large number of misjudgments were made in the vertical direction. Furthermore, subjects tended to misjudge stimuli as being lower on the torso than they actually were.

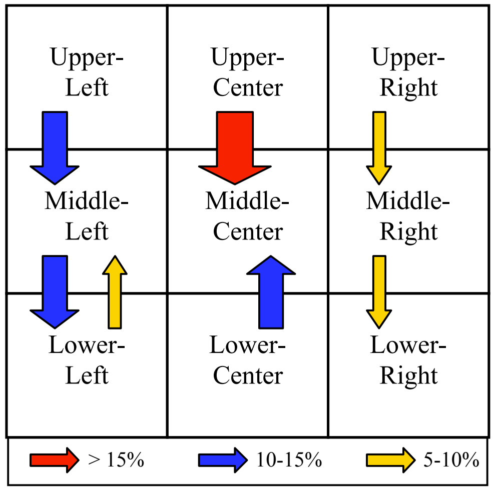

Figure 5: Characteristics of errors. Arrows originate at stimulus location, and terminate at perceived location. Arrow-thickness and color show error frequency.

These observations suggest that people have a greater ability to determine absolute location in the horizontal direction on the torso than in the vertical direction. This is supported by results reported by Erp & Werkhoven (1999). The dual-pathway hypothesis (which states that stimuli that follow different neural pathways, or that terminate in different hemispheres of the brain, are easier to discern than those that take the same pathway, or that terminate in the same location) seems to be supported by our findings. In another study using the same setup, we found that visual prompting was superior to VT priming in a visual search task, and that combined visual/VT priming caused no significant degradation in performance to the visual-only treatment (Lindeman, Yanagida, Sibert & Lavine, 2003). Furthermore, we found that in the absence of visual cues, VT cues allowed subjects to perform significantly better compared to a random search.

Yanagida, Kakita, Lindeman, Kume & Tetsutani (2004) explored the use of a similar low-resolution (3 x 3) tactor array on the back for a letter-reading task. Ten subjects were presented with 100 trials of strokes making up characters from a known set, and were asked to identify the character they felt. The accuracy rate was 87.6%, 86.7%, and 86.0% for numeric, alphabetic, and alphanumeric sets, respectively, with an overall accuracy rate of 87%. These results were similar to some previous work on tactile Japanese character recognition reported which used a 10 x 10 array, 95% accuracy (Saida, Shimizu & Wake, 1978) or a 7 x 9 array, 80-95% (Shimizu, 1982), and far better than work on English letters which used a 20 x 20 array, 51% (Loomis, 1974). All of this work reported far better results when a tracing approach was used as opposed to static display, suggesting the power of motion-cues for the haptic channel.

3 Providing the Vibrotactile Cues

Delivering VT cues for virtual contact and information display requires addressing several problems. Any successful system must employ hardware to generate the control signals, deploy end-effecter devices (tactors) at or near the location the cues will be delivered, and provide software interfaces for application programmers to define *what* the cues are and *when* they should delivered. Finally, deciding the makeup of a given cue requires careful evaluation of the task being performed.

3.1 Hardware

The various techniques for delivering VT cues each provide support for controlling different parameters of the signal. Voice-coil-type (VC-type) and piezoelectric-type (PE-type) tactors allow frequency and amplitude to be controlled precisely and independently. These two approaches also have shorter minimum attack and decay times when triggering the signal than pager-motor-type (PM-type) tactors. This type of tactor consists of an eccentric mass attached to the shaft of a DC motor. A change in supply voltage leads to a change in frequency and amplitude of the vibration. However, since frequency and amplitude are mechanically coupled, there is no way to control them independently. Finally, PM-type tactors typically cost a fraction of VC- and PE-type tactors, US$ 1-2 vs. US$ 20-40.

Control circuitry for generating the stimulus depends on the tactor technology being employed. Because of the modest power requirements and simplicity of the control circuitry, we employ PM-type tactors in our work. The major drawbacks of this type of tactor are their sensitivity to how they are mounted, as well as to dynamic changes in load. Because of these factors, it is difficult to know the *exact* frequency that is being delivered to the user. For a more-detailed treatment of this problem, see (Cohen *et al.*, 2005). We use the TactaBoard (Lindeman *et al.*, 2004) as our control circuit.

3.2 Software

Controlling the cues at the software level should be made as straightforward as possible. Most haptic devices offload the low-level signal control from the host computer to a dedicated processing unit, either a control box or a dedicated computer, and provide a programming interface for higher-level control. The classic tension between control and automation, commonly found in computer graphic systems, applies here as well. For low-level (*e.g.*, physiological/psychophysical) studies, access to individual signal characteristics is desired. However, application programmers should probably be shielded from signal details, and instead work at a conceptual level (MacLean & Enriquez, 2003; Brewster & Brown, 2004). As an example, an application programmer should be able to trigger a contact cue by supplying the body location and velocity of a given contact, and have a cue be generated that incorporates this information. Pragmatically, the *output* from a collision detection algorithm should be used as *input* to VT cue generation. Similarly, if the goal is to present direction and distance information of a teammate, a cue generation function should accept these parameters and generate an appropriate cue.

3.3 Task Dependencies

Cues designed for conveying contact information in a simulated world would ideally include as many as possible of the cues we receive from contact in the real world. As with displays for every sensory channel, however, the state of current technology precludes recreating reality with comparable fidelity. The trick, then, is to tease out those aspects of the cues that will give the most benefit for the task at hand. As mentioned, this is not unique to the sense of touch. Desktop-computer-based flight simulators have been shown to be effective for training some aspects of flying, such as instrument flying. The overall fidelity of these consumer-grade systems is significantly lower compared to high-end, motion-platform-based flight simulators, but are nonetheless effective for the task being trained. When designing cues, it is important to select the proper mix of cues, instead of the brute force "more is better" approach. In the CQB example, one could argue that the cue for being exposed to possible hostile soldiers should be unpleasant, so that subjects develop an aversion to being exposed.

3.4 Cue Design

We can classify cue types based on their conceptual mapping. The notion of virtual contact is the mapping of a real-world event (*i.e.*, coming into contact with physical objects) to computer-generated stimuli. Thus, this mapping can be classified as *concrete*. On the other hand, information display is, by definition, the mapping of abstract concepts to learnable, relatively arbitrary, stimuli. We can call this an *abstract* mapping.

3.4.1 Virtual Contact Cues

Virtual contact cues must not only take into account the user colliding with objects in the environment, such as doors and other users, but also the effect of things colliding with the user. In the CQB example, one obvious cue that should be included is the user getting hit by weapons fire. Arguably, in an effective simulation, being shot should feel like being shot, or should at least possess some characteristics that make the user understand the consequences of his or her actions. Virtual contact cues should be delivered on the body as close to the point(s) of contact as possible, and should incorporate other information that can be used to judge the nature of the contact, such as contact velocity being mapped to the amplitude of the cue.

3.4.2 Information Display Cues

Cues for information display are more difficult to describe because of the wide array of information that could be displayed. In general, whenever possible, cue designers should take advantage of any natural mappings that present themselves. As an example, we have experimented with the use of eight tactors arrayed around the waist at the cardinal directions, called the TactaBelt, and cues that denote exposure to uncleared areas of an environment (Lindeman *et al.*, 2005). We took advantage of the relationship between the direction of exposure and the tactor location, allowing the user to deal with the exposure appropriately, such as by rotating towards the vibration. In this study, we only presented direction information (*i.e.*, turned the tactors ON and OFF) without any distance information. Future studies are looking at classifying *exposure severity*, and mapping vibration intensity to this. For example, exposure while standing in a doorway (a "fatal funnel") would be classified as high exposure, and as such would deliver a stronger vibration than exposure to one corner of a room that had not been secured. Similarly, cues being used to guide a user along a path could vary in intensity by how quickly the user should move in the given direction.

Another major issue in information display has to do with the size of the vocabulary (uniquely distinguishable units) that can be used to convey the information. Temporal and spatial characteristics may be used to effectively disambiguate vocabulary elements. For example, a one-second pulse to the shoulders could be used to display a cue to make the wearer look up, and the same pulse delivered at waist level could cue the wearer to look down. In terms of timing, a fast-paced pulse could alert a cell-phone wearer to an important call, whereas a slower pulse could be used to indicate a call with low-priority. As a more general example of this use in cell phones, we can envision an approach similar to the way ringtones are used to differentiate between callers. We could allow the user to define and assign "shaketones" to classes of calls. For example, business-related calls could use a different pulse pattern than personal calls.

3.4.3 Combining the Cues

Over the years we have been working on VT cueing, several ways of differentiating VT cues used for different purposes have emerged. Borrowing the notion of *functional areas* from desktop UI design, we can designate different regions of the body to be for information display, while others would be used for virtual contact. Because our implementation has a low-cost per tactor, and requires minimal processing on the host side, scaling up to a large number of tactors (> 32) seems tractable.

Another approach is to use different devices for information display than for virtual contact. For example, PM-type tactors with low-frequency vibration could be used for information display, and PM-type tactors with high-frequency vibration could be used for virtual contact. Along the same lines, different end-effecter devices, such as solenoids, could be used for virtual contact, and PM-type tactors for information display. The use of different pulse-patterns is also an option.

We plan to investigate the effectiveness of these approaches by comparing, for example, 1) an immersed user with haptic virtual contact and haptic information display, 2) an immersed user with haptic virtual contact and information display from another modality (*e.g.*, sound or visual), and 3) an immersed user with haptic virtual contact and no information display.

4 Future Work

The advent and pervasiveness of graphical user interfaces has led to interaction techniques that aim to simplify the presentation and manipulation of abstract information. The desktop metaphor is a construct that tries to ease the burden on users by providing a mental framework for organizing information. With this "improvement" in interaction with information has also come an added cognitive burden when there is too much information for the visual channel to process. Common ways of disambiguating information are to use temporal and/or spatial characteristics (*e.g.*, closing one window before opening another vs. placing multiple windows side by side). Can we apply similar techniques to the haptic channel? How well can users keep the cues separate? How does it affect performance? These are some of the questions we plan to address in the future.

Amemiya, Yamashita, Hirota & Hirose (2004) used tactors on the fingertips to communicate with deaf-blind individuals using Finger-Braille. In this form of communication, taps on the back of the fingers correspond (roughly) to keys on a Braille typewriter. In the real-world use of this technique, one person places their fingers on top of the deaf-blind person's fingers and taps out words. They also used a similar system to guide deaf-blind individuals along a route through a city. Their system uses a Linux-based wristwatch to control the vibrations, and short-range communication to allow a guide to lead without a tether. Since their information display is based on an existing form of communication, there was both a natural mapping of the cues, as well as a well-defined vocabulary. The guidance cues and the Finger-Braille cues both used the same body location, and a mental mode-switch was used to differentiate the cues.

Using the current version of our CQB simulator as a starting point, with the TactaVest used to display virtual contact cues, we plan to add our TactaBelt to supply the user with directional exposure cues. We have identified two different approaches for introducing these two cues. On the one hand, we could start subjects out with both the virtual contact and exposure systems active. After training them on how to distinguish between cues, we would let them work on learning or improving their CQB skills. Once they have achieved some proficiency in the CQB task, we can begin to remove the exposure cues, so that they do not become dependent on a cue that will not be present in the real environment, when they are actually clearing a building in combat. In this way, we hope to minimize the difference between the real and training environments, hopefully improving transfer affects.

Another approach is to allow subjects to train with only the virtual contact system active. Once they become proficient in the CQB task, activating the exposure system would provide a way to evaluate their performance using an advanced cue. Similar to audio cues, VT cues do not require attention by the user, as opposed to visual cues that can be missed if the person is looking in the wrong direction. Anecdotal evidence from users of our system has shown that a VT stimulus can be a very powerful cue. We see great promise for soldiers in training to "minimize the buzz" that accompanies unwanted exposure. Measuring their performance with and without virtual contact cues will bear out the utility of our approach.

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