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ENHANCING SITUATIONAL AWARENESS THROUGH HAPTICS INTERACTION IN
VIRTUAL ENVIRONMENT TRAINING SYSTEMS

by

KELLY SUE KINGDON HALE
B.S. University of Waterloo, 1999
M.S. University of Central Florida, 2001

A dissertation submitted in partial fulfillment of the requirements
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Major Professor: Kay M. Stanney

Had I known more I would never have asked myself questions….Had I known more, I would certainly have been stopped by the biggest of all blocks to improvement: the certainty of being right. But I did not know what was right.

Seyle, 1976, p.16

ABSTRACT

Virtual environment (VE) technology offers a viable training option for developing knowledge, skills and attitudes (KSA) within domains that have limited live training opportunities due to personnel safety and cost (e.g., live fire exercises). However, to ensure these VE training systems provide effective training and transfer, designers of such systems must ensure that training goals and objectives are clearly defined and VEs are designed to support development of KSAs required. Perhaps the greatest benefit of VE training is its ability to provide a multimodal training experience, where trainees can see, hear and feel their surrounding environment, thus engaging them in training scenarios to further their expertise. This work focused on enhancing situation awareness (SA) within a training VE through appropriate use of multimodal cues. The Multimodal Optimization of Situation Awareness (MOSA) model was developed to identify theoretical benefits of various environmental and individual multimodal cues on SA components. Specific focus was on benefits associated with adding cues that activated the haptic system (i.e., kinesthetic/cutaneous sensory systems) or vestibular system in a VE. An empirical study was completed to evaluate the effectiveness of adding two independent spatialized tactile cues to a Military Operations on Urbanized Terrain (MOUT) VE training system, and how head tracking (i.e., addition of rotational vestibular cues) impacted spatial awareness and performance when tactile cues were added during training. Results showed tactile cues enhanced spatial awareness and performance during both repeated training and within a transfer environment, yet there were costs associated with including two cues together during training, as each cue focused attention on a different aspect of the global task. In addition, the results suggest that spatial awareness benefits from a single point indicator (i.e., spatialized tactile cues) may be impacted by

interaction mode, as performance benefits were seen when tactile cues were paired with head tracking. Future research should further examine theoretical benefits outlined in the MOSA model, and further validate that benefits can be realized through appropriate activation of multimodal cues for targeted training objectives during training, near transfer and far transfer (i.e., real world performance).

To my family and friends for their unwavering love and support.

ACKNOWLEDGMENTS

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LIST OF ACRONYMS/ABBREVIATIONS

ANOVA   Analysis Of Variance

CGF   Computer Generated Figure

DOF   Degrees Of Freedom

ELOS   Enemy Line Of Sight

ETSI   European Telecommunications Standards Institute

ERP   Event Related Potentials

HMD   Head Mounted Display

JND   Just – Noticeable Difference

KSA   Knowledge Skills Attitudes

MARS   Mission Awareness Rating Scale

MOSA   Multimodal Optimization of Situational Awareness

MOUT   Military Operations in Urban Terrain

NASA TLX   National Aeronautics and Space Administration Task Load Index

ONR   Office of Naval Research

PQ   Presence Questionnaire

SA   Situational Awareness

SAGAT   Situational Awareness Global Assessment Technique

SART   Situational Awareness Rating Technique

SSQ   Simulator Sickness Questionnaire

VE   Virtual Environment

VIRTE   Virtual Technologies and Environments

CHAPTER ONE: GENERAL INTRODUCTION

A wealth of information is provided via the human haptic and vestibular sensory systems during natural interaction with the world, including awareness of limb position relative to self and amount and direction of forces exerted on the body (i.e., kinesthetics). Various other perceptions are provided via cutaneous sensors in the skin (e.g., temperature, pressure, vibration, chemical), and orientation of the head (i.e., vestibular sense). For most, this information is combined with input from additional sensory systems to create a seamless, integrated, multimodal experience of the world. While haptic and vestibular senses provide a variety of information in the real world, virtual systems have not been able to fully portray haptic interaction due to immature technology; However, this limitation is no longer apparent, as great advances in availability of and research into haptic interfaces have been made in the last 15 years (Biggs & Srinivasan, 2002).

The most common applications in virtual systems have incorporated a single cue into a training environment, such as head tracking to provide angular acceleration vestibular cues of heading to enhance spatial awareness (Bakker, Werkhoven, & Passenier, 1998; Loomis, Beall, Klatzky, Golledge, & Philbeck, 1995; Pausch, Shackelford, & Proffitt, 1993; Stackman, Clark, & Taube, 2002), force feedback systems, passive haptics and/or manipulation of real controls to enhance kinesthetic information and resultant performance (Akamatsu & MacKenzie, 1996; Dennerlein, Martin, & Hasser, 2000; Insko, Meehan, Whitton, & Brooks, Jr., 2001; Murray, Klatzky, & Khosla, 2003), and providing tactile cues to cutaneous sensors to enhance spatial awareness (Chaisson, McGrath, & Rupert, 2002; Lindeman, Sibert, Mendez-Mendez, Patil, & Phifer, 2005; Yang, Jang, & Kim, 2002) and direct visual attention (Tan, Gray, Young, &

Traylor, 2003). While many applications for virtual training systems have been developed, researchers continue to advance the development and use of such training systems to realize personnel and cost savings. As these virtual training systems advance, more will include multimodal technology to provide realistic training scenarios. These efforts could seek the Holy Grail of a perfect duplication of real environments. Koschmann, Myers, Feltovich, and Barrows (1994), however, caution against emphasizing capabilities of technology to minimize the distinction between real and simulated environments; instead, a 'Human-centric' approach is desired, where focus is on how the "human nervous system is designed to interact with / obtain information about the surrounding environment" (Cohn & Patrey, 2001, p. 1892). Thus, the emphasis should be on psychological fidelity (i.e., degree that a simulation mimics the sensory and cognitive processes within a trainee as they might occur in live operations) as opposed to physical fidelity (i.e., degree that a physical simulation resembles the target operational environment) (Caird, 1996); specifically, training systems should be designed to provide necessary sensory cues within the virtual environment that are essential for ensuring targeted training objectives are successfully addressed.

To determine the benefits of adopting multimodal training strategies, it is essential to identify the critical knowledge, skills, and attitudes (KSAs) that are being targeted in training, and relate these to the multimodal human sensory systems that should be stimulated to support this acquisition. Thus, such an examination should not only identify which cues to present but also which sensory system (i.e., which modality) to present them by. Other works have looked at the utility of the visual (Cruz-Neira, Sandin, & DeFanti, 1993, Pausch, et al., 1993, Lantz, Bryson, Zeltzer, Bolas, Chappelle, & Bennett, 1996, Bowman, Datey, Ryu, Farooq, & Vasnaik, 2002) and auditory (Greenwald, 2002; Shilling & Shinn-Cunningham, 2002) sensory systems.

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This work focuses on how best to integrate haptic and vestibular senses into virtual training systems. The goals of the research included in this report are three-fold, to: (1) provide a thorough understanding of the haptic and vestibular systems and associated sensations and perceptions provided by these systems; (2) develop a theoretical framework that outlines how multimodal cues (with specific focus on haptic and vestibular cues) can enhance situation awareness, a complex knowledge component that influences decision making and performance (Endsley, 1995); and (3) validate a portion of the proposed theoretical framework by incorporating tactile and vestibular cues into a complex training environment and evaluating their efficacy to enhance training. The following provides a description of the remaining chapters included in this dissertation.

Chapter 2, entitled 'General Background,' provides definitions of key terms used throughout this dissertation, which stem from a combination of physiology and psychology constructs.

Chapter 3, entitled 'Deriving haptic guidelines from human physiological, psychophysical, and neurological foundations,' provides a review of the multidimensional aspects of human cutaneous and kinesthetic senses. This paper was published in *IEEE Computer Graphics and Applications* (Vol. 24, No. 2, pp. 33-39) in 2004. The objective of this paper was to provide a thorough understanding of the human haptic sensory system (i.e., kinesthetic and cutaneous sensors) and associated sensations and perceptions provided by this system. From there, issues of incorporating haptics interaction into a visual display are discussed. Based on an exhaustive literature review, the chapter offers many haptic design guidelines to aid developers of multimodal interactive systems. Further, an epilogue was added to this chapter to describe the vestibular system and identify associated design guidelines that may aid in development of

multimodal interactive systems. The vestibular system was added as it provides additional interoceptive cues (beyond kinesthetic cues) that may impact situation awareness, as discussed in Chapter 4.

Chapter 4, entitled 'Multimodal sensory information requirements for enhancing situation awareness and training effectiveness,' proposes a theoretical framework, the Multimodal Optimization of Situation Awareness (MOSA) model that outlines how multimodality may be used to optimize perception, comprehension and prediction of object, spatial, and temporal components of awareness. This paper is in press in *Theoretical Issues in Ergonomics Science*. The objective of this paper was to provide a theoretical framework that outlines how multimodal cues (with specific focus on auditory and tactile exteroceptive cues and interoceptive cues) can enhance situation awareness. Specific multimodal design techniques are presented, which map desired training outcomes and supporting sensory requirements to training system design guidelines for optimal trainee SA and human performance.

Chapter 5, entitled 'Enhancing spatial awareness training and transfer through haptics interaction in a virtual environment' (to be submitted to *Ergonomics*), empirically examines the impact of including two independent tactile cues into a complex virtual training environment, and how the addition of rotational vestibular cues (i.e., head tracking) influences benefits of tactile training cues. The objective of this paper was to validate a portion of the proposed theoretical MOSA framework by incorporating cues into a complex training environment and evaluating their efficacy to enhance training. The experiment consisted of two parts; Part A examined how tactile interactions and head tracking influenced learning across 4 successive training sessions, while Part B examined how these interactions influenced training transfer. Two tactile cues were included in the study, one which mimicked a real-world cue of incoming fire,

and a second that provided a metaphoric distance cue designed to enhance visual distance estimation, which is known to be inaccurate in virtual environments (Witmer & Kline, 1998). Additionally, head tracking was examined, as it enhances interface fidelity (Waller, Hunt, & Knapp, 1998), yet the impact of combining head tracking with tactile cues is unknown. This work uncovers the need for designers of complex virtual training environments to consider the impact of the integrated multimodal experience, and not individual benefits of single cue implementations, as humans fuse all information into a single percept of the environment (Ernst, 2006). The work demonstrates that conflicting cues may negatively impact performance in the training environment as well as training transfer.

Chapter 6 provides a general discussion of lessons learned from the research provided herein. The objective of this chapter is to provide a critical review of empirical results from Chapter 5, including how they support, extend or refute theoretical relationships and hypotheses outlined in Chapters 3 and 4, and present implications for virtual training systems design.

Chapter 7 provides a concise summary of conclusions and offers research ideas for future work in the area of enhancing haptic displays for inclusion in complex, multimodal virtual training environments.

CHAPTER TWO: GENERAL BACKGROUND

This work focuses on determining effective means to incorporate haptic interaction into human-system interaction. Thus, it is fitting to commence with a general overview of the haptic sensory system. As Lawson, Sides, and Hickinbotham (2002, p.159, italics added for emphasis) point out, "The word haptic is applied too ambiguously at present to be meaningful. Haptic usually refers to "active touch", or cutaneous exploration of the world via manual exploration. This usage helps distinguish "active" from "passive" touch and presumably recognizes that *manual exploration is informed by muscle and point receptors as well as cutaneous receptors*. However, the word haptic has come to be applied by the VE community to encompass information derived by manual exploration, locomotion, *and even "passive" cutaneous sensations applied to the torso*."

For the current research, haptics refers to sensations arising from activations of cutaneous sensors (termed tactile perception), or activations of cutaneous and kinesthetic sensors in combination (termed kinesthetic perception), which constitute the sense of touch (Loomis & Lederman, 1986). This functional definition of haptic perception has been used throughout physiological and VE literature to indicate a 'sense of touch' (Barfield, Hendrix, Bjorneseth, Kaczmaek, & Lotens, 1995; Biggs & Srinivasan, 2002; Brewster & Brown, 2004; Lawson, et al., 2002; Lederman & Klatzky, 2002; Loomis & Lederman, 1986; Oakley, McGee, Brewster & Gray, 2000; Reiner, 2004), and incorporates the exteroceptive (i.e., cues originate from outside the body; e.g., tactile perception) and interoceptive (i.e., cues originate from inside the body; e.g., kinesthetic perception) nature of haptics. The following paragraphs provide a brief history of the physiological and psychophysical principles of the two main haptic sensory systems (i.e.,

cutaneous and kinesthetic). Tactual perception is also discussed as it incorporates the idea of active (i.e., self-directed) versus passive (i.e., externally-directed; e.g., limb moved by external force) touch with haptic perception (both tactile and kinesthetic perception) (Loomis & Lederman, 1986). The latter is relevant to the current work in that different cues are provided via active versus passive interaction, and thus the impact on one's situation awareness within a training environment may be differentially influenced by these various interactions.

<center>Physiological and Psychophysical Basis of Cutaneous Sensory System</center>

While touch has been considered one of the five primary senses since the time of Aristotle, studies by Weber in 1826 further divided touch into a sense of location, a sense of weight, and a sense of temperature (Sherrick & Cholewiak, 1986). Because Weber found that these distinctions between various sensations could be recognized by presentation to the human skin, it was concluded that subdivisions of nervous function must exist in the skin. Boring (1942, as cited in Sherrick & Cholewiak, 1986), isolated peak sensitivities to touch, warmth, cold and pain over the body surface. Melzack and Wall (1962) expanded earlier theories posed by Wedell and colleagues in the mid 20th century, emphasizing the importance of patterns of nervous activity (Sherrick & Cholewiak, 1986). The theory states that the quality of experience depends on a collection of numerous separate and more elementary nervous events. Anatomical and physiological studies have since identified individual receptors that support the various cutaneous sensors, including norciceptors (pain), thermoreceptors (temperature) and mechanoreceptors (pressure/vibration) (Lynn, 1975). The current work focuses on contributions of mechanoreceptors, which combine to create tactile perception (Loomis & Lederman, 1986).

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Various studies have been completed on tactile perception, focusing on spatial acuity (Weinstein, 1968; Cholewiak, Collins, & Brill, 2001), localization and direction of attention (Cholewiak, Brill, & Schwab, 2004; Tan, et al., 2003; Lindeman, et al., 2005), and temporal resolution (Verrillo, 1965, 1968) of the tactile sense. In general, these studies have found that acuity for both space and time vary depending on skin activation site (e.g., fingers versus back). In addition, much research has focused on perceptions of patterns of activation (i.e., vibrotactile activation of numerous locations on the skin sequentially and/or simultaneously) (Brewster & Brown, 2004; Geldard, 1957; Gilson, 1968; Gallace, Tan, & Spence, 2005). These studies reveal that humans are able to learn simple as well as complex patterns of tactile stimulation (patterns based on spatial location, vibration, and temporal variation), which may prove effective as another communication channel (beyond visual and auditory). Investigations into sensory substitution for vision have also led to development of various tactile information presentation devices, including the Optacon (Craig & Sherrick, 1982) and the Tactile Vision Substitution System (Bach-y-Rita, 1972).

There is much to be gained from tactile perception (Fowlkes & Washburn, 2004; Geldard, 1957, 1960; Lindeman et al., 2005; Terrence, Brill, & Gilson, 2005), particularly when considering sensory substitution of visual and/or auditory stimuli with tactile stimuli (Geldard, 1957). These studies suggest that activation of tactile sensors can provide declarative knowledge through coded symbols, and can enhance spatial localization and navigation by appropriately directing visual attention to desired points of interest.

The current body of work focuses on tactile perception of tactors placed on the torso. The work seeks to theoretically characterize how exteroceptive tactile cues can enhance situation awareness, including object, spatial, and temporal awareness, and empirically evaluate the

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effectiveness of such cues in enhancing egocentric spatial awareness within a complex, virtual training environment.

<div align="center">Physiological and Psychophysical Basis of Kinesthetic Sensory System</div>

Over the past two centuries, there has been much controversy about the nature and source of sensory inflows to the kinesthetic sensory system (Clark & Horch, 1986). Numerous candidates for sensory information have been proposed, including sensors in the skin, muscles and joints, as well as a sense of innervation, which describes a "sensory experience resulting from some internal monitoring of the impulses originating in the brain and destined for the muscles" (Clark & Horch, 1986, p. 13-2). In the 19th century, the concept of innervation prevailed. Helmholtz (1867, as cited in Clark & Horch, 1986) observed that the visual world jumps not upon actual displacement of the retina, but whether an image shifts in the way we expect from attempts to move our eyes voluntary. Similarly, the observation of phantom limbs (where movement distal to amputation is perceived in the limbs; Henderson & Smyth, 1948) was thought to support the concept of innervation.

The innervation concept lost favor, however, near the end of the 19th century, when discoveries were made that muscles contain sensory receptors. Sherrington (1900, as cited in Clark & Horch, 1986) opposed innervation, and instead promoted a large contribution from the muscle sense with some contribution from joint receptors and little contribution from skin receptors. In the 1950s, research studies concluded (incorrectly) that signals from muscles do not reach conscious levels, and therefore the belief at the time was that the kinesthetic sense depended heavily on joint receptors (Clark & Horch, 1986). Merton (1964, as cited in Clark &

Horch, 1986) argued against a conscious muscle sense, and favored a joint sense combined with innervation, which was later determined to be inaccurate.

Prevailing thought again changed in the late 1960s when Burgess and Clark (1969) found that joint receptors responded only near extreme flexion or extension of the joints, and thus could provide little input to the kinesthetic sense. In addition, joint replacement surgeries replaced joints (and their receptors) with metal and plastic pieces with no measurable loss in kinesthetic sense. Thus, joint receptors are now thought to have a limited impact on the kinesthetic sense (Clark & Horch, 1986).

When studies from the 1950s were replicated, the muscle sense was found to reach consciousness, as humans could sense muscle stretch (Gulfan & Carter, 1967 and McCloskey, Cross, Honner & Potter, 1983, as cited in Clark & Horch, 1986). In addition, demonstrations showed that muscle receptor impulses reach both sensory and motor areas of the cerebral cortex (Clark & Horch, 1986). Current theories support the existence of innervation combined with sensory systems that provide input from peripheral receptors. Muscle receptors are the forefront kinesthetic detectors, with some input from joint receptors and skin receptors (particularly for joint movement; Clark & Horch, 1986).

The current body of work uses the term kinesthetic perception to refer to both static and dynamic posture based on muscle and skin receptors (Loomis & Lederman, 1986), and considers proprioception[1] to be an interchangeable term (Biggs & Srinivasan, 2002; Srinivasan & Basdogan, 1997). The kinesthetic system is discussed in further detail in Chapter 3, where its

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[1] Others have referred to the term proprioception as a sense of orientation, which incorporates both kinesthetic and vestibular sense (Klatzky, Loomis Beall, Chance, & Golledge, 1998; Bakker, Werkhoven, & Passenier, 1998).

benefits to spatial and object awareness (Weber, 1995, as cited in Prytherch, 2002) as well as orientation (Bakker, et al., 1998) are highlighted. The goal of the current work is to theoretically characterize how kinesthetic perception can enhance situation awareness, including object, spatial, and temporal awareness, and empirically evaluate the impact of kinesthetic perception in combination with vestibular input (provided via head tracking) on egocentric spatial awareness within a complex, virtual training environment.

<u>Tactual Perception</u>

The above sections deal with the haptic system as two sensory systems in isolation. Conversely, others have noted the importance of the combined percept created by activation of both sensory systems, as well as the cognitive aspects of the haptic system. David Katz (1936, as cited in Krueger, 1982), and later J.J. Gibson (1962; 1966), emphasized that most perceptual experience is of objects and events external to us rather than of the more proximal stages and processes that occur between the distal stimuli and higher brain centers. These works suggest that "the hand should properly be considered the sense organ for touch rather than the mechanoreceptors, and that emphasis ought to be on the active seeking of information by the exploring hand" (Loomis, 1981, p.5). Throughout his research, Gibson used the term active touch, yet did not distinguish this from passive touch in a consistent fashion (Loomis & Lederman, 1984). Most often, Gibson equated passive touch with tactile perception, where sensations are produced by activation of cutaneous sensors in isolation. Active touch refers to purposive exploration of an environment, and includes cutaneous and kinesthetic sensory input, as well as an efferent copy of movement (Gibson, 1966). At other times, Gibson described passive touch as the absence of motor commands to the muscles (i.e., lack of efferent copy, yet activation of both cutaneous and

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kinesthetic sensory systems) (Klatzky & Lederman, 2002). Thus, while Gibson provided an insightful way to describe touch, noting the importance of active exploration, the current body of work is based on more distinct definitions of touch as provided by Loomis and Lederman (1986), who defined five tactual modes:

- Tactile perception (activation of cutaneous receptors)

- Passive kinesthetic perception (activation of kinesthetic receptors)

- Active haptic perception (activation of cutaneous + kinesthetic receptors)

- Active kinesthetic perception (activation of kinesthetic receptors + efferent copy of movement)

- Active haptic perception (active cutaneous + kinesthetic receptors + efferent copy of movement)

Specifically, the current body of work seeks to theoretically characterize how each of these five tactual modes can enhance situation awareness, including object, spatial, and temporal awareness, and empirically evaluate how tactile perception and active haptic perception (in combination with vestibular perception) impact egocentric spatial awareness within a complex, virtual training environment.

<u>Physiological and Psychophysical Basis of Vestibular Sensory System</u>

While the kinesthetic sensory system provides information regarding limb position and orientation relative to the body, the vestibular system provides information regarding orientation of the head relative to acceleration/deceleration of the body, including the impact of gravity. Thus, it is an additional sense that provides knowledge of egocentric position, and can enhance

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sensations perceived by the haptic senses. A detailed description of the vestibular system is provided in Chapter 3.

The initial discovery of the function of the vestibular system was made by Flourens in 1984, and later expanded upon by Breuer, Mach, and Crum Brown in 1875 (Howard, 1986). These researchers proposed movements of the endolymph (fluid inside the sensory organs) induced by acceleration of the head activated the vestibular system. In 1931, Steinhausen established that the critical event that activated the vestibular system was a flow of the endolymph round the cavity of the canal and a subsequent deflection of the cupula, a gelatinous structure within the semicircular canals (Howard, 1986). Electrophysiological recordings of vestibular afferents were first made by Lowenstein and Sand in 1940 and Adrian in 1943 (Howard, 1986).

Information from the vestibular system is integrated with information from both kinesthetic sensors and the visual system to create a sense of body posture and movement. Output from the vestibular system is used to (1) control eye muscles so eyes remain fixed at the same point, (2) control reflex mechanisms for maintaining upright posture, and (3) provide conscious awareness of position and acceleration of the body after relaying signals via the thalamus to the cortex. The third area is of interest to the current research in that activation of vestibular senses via active head rotation provides additional sensory cues that combine with kinesthetic sensory cues and an efferent copy of movement to provide a more accurate indication of orientation. The importance of the vestibular system becomes obvious from studies of those with loss of vestibular function. For example, humans who have bilateral loss of vestibular function lose static balance when eyes close and have trouble walking along a narrow beam (Howard, 1986).

The current body of work focuses on angular acceleration cues provided by the semicircular canals. The work seeks to theoretically characterize how such cues can enhance spatial awareness, including object, spatial, and temporal awareness and empirically evaluate how vestibular input (in combination with haptic perception) provided via head tracking enhances egocentric spatial awareness within a complex, virtual training environment.

The following chapter now will summarize physiological and psychological sensory thresholds for cutaneous, kinesthetic, and vestibular receptors, and provide design guidelines for incorporating these sensory cues into a multimodal interactive system.

CHAPTER THREE: DERIVING HAPTIC GUIDELINES FROM HUMAN PHYSIOLOGICAL, PSYCHOPHYSICAL, AND NEUROLOGICAL FOUNDATIONS[2]

Unique from other senses, the human haptic system supports two-way communications between humans and interactive systems, enabling bidirectional interaction between users and their surroundings. More specifically, haptic interaction offers an independent sensory channel that the brain can process to further enhance a user's experience in a multimodal environment. Such interaction can speed reaction time and reduce hand-eye coordination errors for computer-related tasks.

Many interactive systems use visual and, to a lesser extent, audio cues to present users with information about their surroundings and interactions with objects. Haptic feedback can enhance interactive systems' realism through more natural interaction with objects and the environment. Rupert (1997) for example, used tactile actuators to provide cues for resolving spatial disorientation in aviation environments when visual cues are absent or misleading. Tan, Lim, and Traylor (2000) designed a haptic car navigation guidance system by leveraging sensory saltation, a spatiotemporal illusion of movement across a person's back. Determining how to best design haptic interfaces is essential for further advancement of such novel haptic devices. An examination of haptic sensory systems and associated cognitive and motor processes should help direct the design of haptic interaction devices.

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[2] Adapted from Hale, K.S., & Stanney, K.M. (2004). Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundation. *IEEE Computer Graphics and Applications*, 24(2), 33-39.

This article surveys the haptics literature and identifies conditions under which haptic interaction displays can enhance human perception and performance. Tables present the guiding principles and issues associated with haptic interaction devices as well as haptics design guidelines for multimodal interactive systems.

Haptics in Interactive Displays

Haptic interaction relates to all aspects of touch and body movement and the application of these senses to computer interaction. This involves not only sensation and perception, but also motor and cognitive aspects of active movement (that is, self-initiated movement) for which detailed motor plans are created, stored in memory, and compared to receptor feedback from the muscles, joints, and skin.

When should haptics be used? In general, haptic displays effectively alert people to critical tasks, provide a spatial frame of reference within an individual's personal space, and support hand–eye coordination tasks. Tactile cues, such as those conveyed via vibrations or varying pressures, are effective as simple alerts. Kinesthetic devices are advantageous when tasks involve hand–eye coordination (for example, object manipulation), in which haptic sensing and feedback are key to performance (Mulgund, Stokes, Turieo, & Dervine, 2002 ; Biggs & Srinivasan, 2002).

Although scientists have demonstrated the behavioral benefits of haptic interaction, ensuring effective design of such systems requires a greater understanding of how best to convey haptic information. Physiological and psychophysical knowledge can help us develop such an understanding.

Haptic System Physiology and Psychophysics

Because of the vast number of perceptions that can be activated through the haptic system (vibration versus limb movement, for example), designers must consider which haptic stimulation (tactile, kinesthetic, or some combination) best suits a given task.

Tactile Mechanoreceptors

Table 1 lists the characteristics of tactile mechanoreceptors. Designers can use this list to select appropriate haptic sensors to support human system interaction.

Four distinct receptors exist in glabrous, or hairless, skin (such as that on the palms, fingertips, and soles of the feet), and each is sensitive to distinct physical parameters. Their sensitivity depends on their size (large receptors have poor spatial resolution), density (many receptors in a given area results in high spatial acuity), frequency range (receptors don't perceive signals outside their range), and nerve fiber branching (higher branching leads to spatial and temporal summation of signals). In addition, the type of stimulation (skin motion or sustained pressure) affects the degree to which individual mechanoreceptors are activated.

Hairy skin, which covers most of the body, has three active mechanoreceptors. As Table 1 shows, receptors in hairy skin have low spatial resolution, indicating that they don't effectively perceive detailed texture or 2D form (that is, the specific geometric structure of a surface or object) information in these areas.

Table 1: Haptic tactile skin mechanoreceptor characteristics*

Haptic Features	Mechanoreceptors				
	Pacinian Corpuscles	**Ruffini Endings**	**Mesissner Corpuscles**	**Merkel Disks**	**Hair Follicie**
Skin Type	Glabrous and hairy	Glabrous and hairy	Glabrous	Glabrous	Hairy
Stimulation Objective (physical parameters to be sensed)	Vibration, acceleration, roughness	Skin stretch, lateral force, motion direction, static force	Velocity flutter, slip, grip control	Skin curvature, pressure form, texture, edges	Touch
Stimulation Type	Skin motion	Skin motion and sustained skin deformation	Skin motion	Skin motion and sustained skin deformation	Hair motion
Spatial Resolution	Very poor (2 cm)	Poor (1 cm)	Fair (3 - 5mm)	Good (0.5 mm)	
Stimulation Frequency Range (Hz)	100 - 1,000	0.4 - 100	2 – 40	0.4 - 10	
Interstimulus Interval	← Five ms to perceive separate stimuli; 20 ms to perceive stimuli order →				

Glabrous skin, particularly in the hands, is most effective for detailed tactile information. Hairy skin effectively detects vibration and static force, however, and can be used to present spatial tactile cues at various skin locations. Thus, actuators in a haptic device for texture or 2D form perception must activate the skin on the palms, fingertips, or soles of the feet; actuators for conveying vibratory information can be placed anywhere on the body.

Although distinct mechanoreceptors exist, tactile perception results from combined inputs of all receptors in a given skin area, as all skin sensors are simultaneously stimulated. Psychophysical experimental designs (such as step, impulse, and periodic functions) are one way to evaluate multireceptor perception and global tactile perceptual limitations. Researchers can use such psychophysical studies to derive tactile interaction design guidelines, such as those listed in the "Psychophysical Tactile Interaction Design Guidelines" summary in table 2.

Perceptual thresholds for touch depend on location, stimulus type, and timing. Because mechanoreceptor density varies across the skin, tactile thresholds for single and two-point discriminations vary based on the skin area activated. Actuator design must therefore consider these thresholds to ensure that human mechanoreceptors receive the tactile stimulus.

Sherrick and Cholewiak (1986) discuss actuator placement for various sensations, including single-point localization and two-point discrimination. The most sensitive actuator sites for a device conveying single-point localization are the nose and mouth, followed by the fingerpad. The least sensitive place for such an actuator is the back. The most sensitive actuator site for two-point discrimination, however, is the fingerpad, followed by the nose or mouth. Pressure limits also show different levels of sensitivity dependent on body loci and gender. These limits are flexible, however, as both pressure and vibrotactile stimuli show adaptation— that is, a rise in absolute threshold from normal generally follows presentation of finite suprathreshold stimuli.

Table 2: Psychophysical Tactile Interaction Design Guidelines

• Haptic input must consider sensitivity to stimuli across various skin locations (for example, the two-point threshold grows smaller from palm to fingertips, where spatial resolution is about 2.5 mm on the index fingertip).[*]
• To ensure that receptors perceive individual cutaneous signals, stimuli must be at least 5.5 ms apart.[*]
• To successfully activate an individual's pressure sensors, the force exerted must be greater than 0.06 to 0.2 Newtons per cm^2.[*]
• Pressure limits depend on body loci and gender. Just-noticeable values range from 5 milligrams on a woman's face to 355 mg on a man's big toe.[*]
• Vibration from a single probe must exceed 28 decibel (relative to a 1-microsecond peak) for 0.4 to 3-Hz frequencies for humans to perceive.[**]
• For a user to feel a hard surface after initial contact, the haptic system must maintain active pressure.
• Maintaining the sensation of textured surfaces requires relative motion between the surface and the skin.

*C.E. Sherrick and R.W. Cholewiak. (1986). Cutaneous Sensitivity, *Handbook of Perception and Human Performance v.1: Sensory Processes and Perception*, K. Boff, L. Kaufman, and J. Thomas (Eds.), John Wiley & Sons.
**S.J. Biggs and M.A. Srinivasan, (2002). Haptic Interfaces. In *Handbook of Virtual Environments: Design, Implementation, and Applications*, K.M. Stanney (Ed.), Lawrence Erlbaum, pp. 93-115.
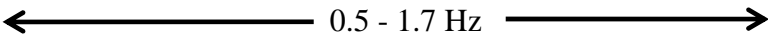
Stimulus surface characteristics also influence the sensation of touch: as the stimulus changes, so does the tactile sensation. A haptic display for simulating tactile sensations must include several properties. For example, the haptic device must maintain active pressure for the user to feel a hard surface after initial contact. For soft surfaces, the haptic device must maintain a slight positive reaction against the skin after initial contact, without active pressure or relative motion. To accurately display texture, there must be some relative motion between the haptic surface and the skin.

Kinesthetic Receptors

Designers can also use Table 3, which lists kinesthetic receptor characteristics, to select appropriate haptic sensors for human system interaction. Humans' kinesthetic sense makes them aware of how fast and in which direction their limbs are moving, and whether the movement is voluntarily or externally imposed. This sense also makes them aware of a limb's static position when movement stops.

Kinesthetic sense is associated with four receptor types found in muscles, tendons, and joints. Receptors found in or near joints (Golgi and Ruffini endings) are most active at extreme joint positions (full flexion or extension) and are thus considered protective receptors. Ruffini endings have shown some activation during both static position and dynamic motion. Receptors in the tendons (Golgi tendon organs) sense active positioning (for example, self-initiated movement to place arm in a given position) and static limb position. Muscle spindles provide information about supported limb weight—that is, the subjective weight of an object in a person's hand—and are thought to provide the conscious awareness of body movement. Although the feedback loop for individual sensors is slow (between 0.5 and 1.7 Hz), humans can produce much faster complex movements. Scientists believe this occurs because the motor and cognitive haptic systems, which direct active movement, create a memory motor trace of the predicted movement. This allows for faster execution of complex movements (in the absence of slower, receptor feedback) and provides a comparison trace for receptor feedback when such a trace is available.

Table 3: Haptic kinesthetic receptor characteristics [*]

| Haptic Features | Kinesthetic Receptors | | | |
	Golgi Endings	Ruffini Endings	Golgi Tendon organs	Muscle Spindles
Location	Joint ligaments	Joint capsules	Tendons	Muscles
Stimulation Objective (physical parameters to be sensed)	Joint movement at end range of motion Extreme flexion/ extension	Joint movement, particularly at end range of motion Static and dynamic	Active position sense Link to limb position Force	Active movement of muscles Conscious experience of body movement and position Weight supported by limb
Stimulation Type	Joint tension at extreme positions	Capsule stretch	Muscle tension and force	Muscle stretch/rate of change Vibration
Feedback Loop Range	← 0.5 - 1.7 Hz →			

*Sources: L. Radman, Simulation of Responses in Proprioceptive Afferents During Human Manipulation, http://www.kogvet.psy.umu.se/kvguiden/exjobb/exjobb_lars%20radman.pdf; and F. Clark and K. Horch. (1986). Kinesthesia. *Handbook of Perception and Human Performance v.1: Sensory Processes and Perception*, K. Boff, L. Kaufman, and J. Thomas (Eds.), John Wiley & Sons.

Sensory information from the kinesthetic receptors combines with available information from the motor and cognitive systems to produce perceived limb position and movement. A person's ability to detect limb movement depends on the joint moving, the movement's velocity, and the contractile state of the muscles controlling the joint. The kinesthetic sense bandwidth ranges from 20 to 30 Hz, with proximal joint rotations being more sensitive (for example, the

just-noticeable difference, or JND, for the shoulder is 0.8 degrees) than those of distal joints (for example, the JND for a finger joint is 2.5 degrees; for a wrist or elbow, it's 2 degrees) (Tan, Srinivasan, Eberman, & Cheng, 1994). These JND values vary slightly depending on movement direction (flexion/extension) and speed. A person often perceives that a movement has occurred before sensing its direction. Thus, a passive kinesthetic stimulus must contain enough movement to indicate direction.

Partial virtual force levels can result in adequate task performance. O'Malley and Goldfarb (2002a, b) showed that endpoint forces above 4 Newtons or surface stiffness above 400 Newtons per meter do not significantly enhance performance on size identification tasks (that is, examining a human's ability to classify similarly shaped objects, presented one at a time, by size alone). Although higher stiffness values enhanced perceived surface hardness, no performance gains above 400 N/m were evident. Thus, fairly low levels of end-point force and surface stiffness can promote significant haptic information transfer.

Kinesthetic displays can offer a spatial frame of reference, allow gesture interaction, and provide force feedback from virtual objects. The kinesthetic sense provides information from the moving parts of the body and develops an egocentric frame of reference within the environment by continuously updating relative positions and rhythmic motions of body segments. The kinesthetic sense therefore calibrates the spatial motor frame of reference. Adding locomotion (likely a haptic interpolation of rhythmic motor patterns produced during walking) to a system can enhance the egocentric perspective by activating kinesthetic sensors in the lower limbs. Because they monitor positional data, kinesthetic displays can provide effective gesture interaction. Gestures are a natural, flexible input mode that can aid control and navigation. Devices providing force feedback add realism to virtual systems by more closely matching real-

world interaction. A summary of preliminary kinesthetic design guidelines based on psychophysical research is displayed in Table 4.

Table 4: Psychophysical Kinesthetic Interaction Design Guidelines

• To ensure more accurate limb position, use active rather than passive movement.
• Avoid minute, precise joint rotations, particularly at distal segments.
• Minimize fatigue by avoiding static positions at or near the end range of motion.
• Surface stiffness of 400 Newtons per meter should effectively promote haptic information transfer.
• End-point forces of 3 to 4 Newtons should effectively promote haptic information transfer.
• Add kinesthetic information to enhance objects' spatial location.
• Gestures should be intuitive and simple.
• Minimize fatigue by avoiding frequent, awkward, or precise gestures.
• Avoid precise motion gestures, as making accurate or repeatable gestures with no tactile feedback is difficult.

Multimodal Interaction (Haptics and Vision)

Because most interactive systems use some form of visual display, a multimodal system designer must consider how to combine haptics interaction with visual displays. Including haptic interaction with a visual display has improved individual task performance in object interaction, way finding, and collaborative environments. In a spatial task, kinesthetic information about target location showed no appreciable decay after 10 seconds; visual location information,

however, shows rapid memory decay in the same time period (Chapman, Heath, Westwood, & Roy, 2001). Thus, adding haptic location information (through active position pointing, for example) can enhance target location memory.

Object identification and manipulation—that is, 2D and 3D form perception—and spatial awareness tasks, particularly those requiring the user to move in the environment, might be the most advantageous environments for combining vision and haptics. Haptics can enhance visual displays by increasing the system's naturalness to better match real-world interaction. Continuously updating relative positions and rhythmic motions of body segments creates an egocentric frame of reference, which can calibrate a spatial motor frame of reference; such calibrated spatial information is thus likely better scaled than visual-only spatial knowledge. By adding physical force to virtual objects, we have enhanced knowledge concerning the locations of stationary virtual objects and the direction and speed of moving virtual objects within arm's reach (such as a doorway that has been pushed open). By mimicking real-world interaction, a multimodal interface lets users apply their natural interaction schemas, likely reducing training times and increasing interaction efficiency and accuracy.

Because vision and haptics provide fundamentally different types of information, combining these percepts has additional benefits. An individual viewing an object can identify a number of attributes instantaneously (size, form, topography, color, and so on). Using the haptic sense alone, an individual gathers information progressively as he or she explores an object's physical aspects (texture, weight, solidity, temperature, and so on) and surroundings.

Combining these modalities, however, brings additional design challenges. Behavioral studies have found that vision frequently dominates an integrated visual/haptic percept, such as when judging size, shape, or position. By understanding the conditions under which vision

dominates haptics, designers could exploit this sensory dominance, incorporating meaningful active haptic interactions for virtual objects. Table 5 summarizes the theorized benefits of combining various haptic devices with visual displays.

Table 5: Theorized benefits of adding haptic devices to visual displays

Benefit	Display Devices				
	Visual Display (VD)	VD + Tactile Interface	VD + Positional Actuator	VD + Probe-Based (Force Feedback) System	VD + Exoskeleton System
Tactile perception Texture perception (hard/soft, smooth/rough, and so on)		More accurate judgment of softness and roughness than visual alone		Possible to judge with same accuracy as when using fingertip	If tactile actuators are present in fingertips, possible to judge texture
2D form perception (spatial acuity, pattern recognition, curvature perception, and so on)	Relative depth in field of view (FOV)	Tactile can be ignored when irrelevant Cross-modal cueing effects useful		Not useful	If tactile actuators are present in fingertips, possible to judge 2D form perception
Kinesthetic perception Spatial awareness/ position (for example, objects in environments, limb with respect to trunk, body with respect to environment)	Relative depth of object in FOV Visual proprioception within FOV		Allow egocentric frame of reference within personal space Gestures used to navigate environment Kinesthetic target location has less decay than visual target location	Force feedback enhances distance judgments within personal space (arm's reach)	Force feedback enhances distance judgments within personal space (arm's reach)
3D form perception (length discrimination, weight, and shape identification, for example)	Identification and discrimination depend on viewing angle No indication of weight			Deform-ability through force feedback aid discrimination and identification Adding force to virtual scene increases presence	Adding force to virtual object increases presence Improved weight discrimination of objects Improved object interaction

Cross-modal Effects

We can analyze the benefits of cross-modal interaction neurologically. The increasing availability and advancement of technology (for example, positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and electroencephalograms (EEG) to assess brain activity in real time helps us evaluate the brain's reaction to multimodal interaction displays. Many studies have examined brain activity during multimodal tasks involving haptics and vision. We leverage these studies to hypothesize design guidelines to further improve human–system interaction when multiple modalities are incorporated into system design. For example, when visual attention is endogenously directed via tactile stimuli to one side, reaction time is faster on the cued side, suggesting cross-modal links between spatial attention in vision and touch.

Gray and Tan (2002) found strong dynamic links between vision and touch using dynamic tactile information (five tactors placed on the forearm, vibrating in sequence) to accurately reorient visual attention. They also found the reverse—that is, visual dynamic information accurately reoriented tactile attention. These cross-modal cueing effects follow an external spatial frame-of-reference (posture-independent) model rather than a hemispheric (anatomical) model. Thus, cueing effects depend on where the stimulated hand rests (for example, crossed versus uncrossed hands) as opposed to anatomical left/right associations. These findings suggest that we can effectively incorporate multimodal stimuli (visual and haptic) into cueing strategies to provide spatial cues within an environment.

Cross-modal priming has shown effect sizes similar to within-modality priming (James, Humphrey, Gati, Servos, Menon, & Goodale, 2002). Priming studies differ from cueing studies

in that they present users with stimuli in one modality and ask them to identify the same stimuli in another modality. Cueing studies use one stimulus (in any modality) to prompt users to attend to future stimuli presented in that location (on the left side of body, for example). Having compared visual-visual priming (identify visual stimulus after being presented with the stimulus visually) with tactile-visual priming (identify visual stimulus after being presented with the stimulus tactually), James, et al. (2002, p. 1712) suggested that "no extra computational step is required to prime visual processing of object shape using a representation based on previous haptic input than is required to prime visual processing of shape using a representation based on previous visual input" . Thus, for example, if the visual system is overloaded, haptic devices can provide information concerning object identification without significantly increasing cognitive load. Although switching from a tactile to visual stimulus doesn't seem to increase cognitive load, the reverse (switching from visual to tactile) may negatively affect cognitive processing.

Kawashima, Watanabe, Kato, Nakamura, Hatano, et al. (2002) found that activation patterns during visual-tactile and tactile-visual cross-modal discrimination (based on cylinder diameter) differed, possibly indicating that the human brain mechanisms underlying this process involve two different pathways depending on the temporal order of stimulus presentation. In addition, cross-modal information transfer was less accurate during visual-tactile than during tactilevisual stimulus, indicating that switching from a visual-tactile stimulus might require a greater cognitive load than switching from a tactile-visual stimulus.

It's possible to decouple tactile stimuli from other modalities during spatial attention tasks—but only when the tactile signals are considered irrelevant. For example, Eimer and Driver (2000) asked study participants to detect visual-tactile or visual targets while ignoring irrelevant modality information. They found crossmodal links for spatial attention in event-

related brain potentials, as tactile stimuli produced systematic modulations of these Event Related Potentials (ERPs). Unlike the cross-modal influences on visual ERPs, no significant attentional modulations occurred for somatosensory ERPs when touch was entirely response irrelevant. This result pattern supports the idea that vision and touch become linked when touch is potentially response-relevant while distribution of spatial attention within vision might not affect tactile processing when tactile stimuli are ignored. Thus, if they can monitor brain activity in real time, designers might be able to identify when users erroneously perceive additional stimuli (such as tactile stimuli) as irrelevant, as somatosensory ERPs would show no modulation. After making such a determination, designers can increase the tactile stimuli to enhance reception of the signal, and thus draw attention to task-relevant tactile information.

Table 6 provides a summary of guidelines for combining visual and haptic stimuli.

Table 6: Multimodal Interaction Design Guidelines

- Because vision frequently dominates the integrated visual/haptic percept, use caution when combining vision and haptics for tasks involving size, shape, or position judgment.

- Adding haptic location information (through active position pointing, for example) to a visual display enhances target placement memory.

- Minimize confusion and control instabilities in the multimodal system by avoiding time lags between visual and haptic loops.

- Use dynamic tactile information (for example, five tactors placed on the forearm vibrating sequentially) to accurately reorient visual attention or vice versa.

- Make sure that cross-modal cueing effects used within multimodal displays follow an external spatial frame-of-reference (posture-independent) model rather than a hemispheric (anatomical) model.

- If the visual system is overloaded, you can provide object identification information haptically without adding significant cognitive load.

- If touch is potentially response-relevant, vision and touch stimuli can become cognitively linked, which may hinder the effectiveness of conveying additional information tactually.

- If touch can be entirely ignored, visual spatial attention tasks won't affect tactile processing, allowing it to convey additional information (such as a tactile warning).

Future Research: Cross-modal Transition

Although much research has focused on the behavioral and neurological effects of combining vision and haptics, many questions remain. For example,

- When should we combine these modalities?

- When should we transition between modalities?

- How do we effectively transition within and/or between modalities to ensure efficient and accurate information transfer?

In addition, no one has effectively examined task complexity, particularly for highly complex tasks.

Alone, haptics are rarely effective as a single-interaction modality, although they must sometimes be used in isolation (in dark or smoke-filled environments, for example). Thus, in most situations, simply transposing visual display data into haptic data would be inefficient. Instead, integration schemas should focus on redundancy—that is, adding haptics to visuals when it would most enhance performance.

When incorporating haptic interaction with visual displays, integration should be smooth and seamless, ensuring that haptic cues help the user complete the task rather than distract the user or detract from performance. Sensory redundancy design guidelines will invariably be task-dependent (that is, depend on the task's nature, duration, and complexity), and therefore future studies must determine when multimodal (haptic and visual) displays outperform unimodal, visual displays.

<div align="center">

Epilogue

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An epilogue has been added to this paper because the ensuing conceptual model – the Multimodal Optimization of Situation Awareness (MOSA) model (see Chapter 4) – extended the original scope of the work to also include vestibular stimulation. The vestibular system provides interoceptive sensations related to orientation and acceleration of the head, as it provides an indication of rotational and translational movements and position of the head.

The vestibular apparatus, consisting of the otolith organs and the semicircular canals, are located within the bony labyrinth of each inner ear (Stoffregen, Draper, Kennedy & Compton, 2002). The otolith organs include the utricle and saccule. Each of these organs contains a macule

surrounded by gelatinous fluid. When linear acceleration occurs, shearing forces are created on hair cells of the macule activate associated neurons. These organs are activated by static head position (i.e., head tilt; impact of gravity) as well as dynamic linear forces (Howard, 1986). The utricle is strongly influenced by horizontal linear accelerations, while the saccule is strongly influenced by vertical linear accelerations (Stroffregen, et al., 2002). Accuracy of head tilt is within $2^0 - 4^0$ for tile angles up to 40^0, and minimum perceived accelerations are 5-15 cm/s^2 for the utricle and 10-12 cm/s^2 for the saccule (Baloh & Honrubia, 2001).

In addition to the otolith organs, there are three semicircular canals (anterior, posterior, horizontal) that detect angular acceleration/deceleration during rotation of the head along three perpendicular axes (Howard, 1986). Each canal has one direction of maximum sensitivity, but most often multiple canals are activated during head movement. Within each canal are cilia (hairs) closely ensheathed by a gelatinous mass, the cupula. Displacement of the cupula, which takes approximately 5-7 seconds from acceleration/deceleration onset, creates shearing forces on the cilia that alter resting potential of the cells (Howard, 1986). Thresholds for angular acceleration detection range from 0.1 to 0.5 ^{0}/sec^2; responses diminish with constant angular rotation (Baloh & Honrubia, 2001).

Table 7 outlines components of the vestibular apparatus that contribute to sensations of head movement.

Table 7: Vestibular Apparatus*

Sensor Features	Vestibular Apparatus		
	Otolith Organs		Semicircular Canals
	Utricle	Saccule	
Location	Bony labyrinth of each inner ear		
Stimulation Objective (physical parameters to be sensed)	Horizontal linear acceleration of the head and effects of gravity	Vertical linear acceleration of the head and effects of gravity	Angular acceleration of the head
Stimulation Type	Shear force of macula hair cells	Shear force of macula hair cells	Displacement of cupula causes shearing of cilia (hair cells)
Threshold	5-15 cm/sec^2 linear acceleration	15-12 cm/sec^2 linear acceleration	0.1-0.5 ^{0}/sec^2 angular acceleration

*Sources: Baloh, R.W., & Honrubia, V. (2001). *Clinical Neurophysiology of the Vestibular System*. New York: Oxford University Press; Howard, J.P. (1986). The vestibular system. In *Handbook of Perception and Human Performance,* Boff, Kaufman & Thomas (Eds.), New York: John Wiley and Sons, pp.11-1 – 11-30.

Information from the vestibular system is integrated with information from both kinesthetic sensors and the visual system to create a sense of body posture and movement. Output from the vestibular system is used to (1) control eye muscles so eyes remain fixed at the same point, (2) control reflex mechanisms for maintaining upright posture, and (3) provide conscious awareness of position and acceleration of the body after relaying signals via the thalamus to the cortex. The third area is of interest to the current research.

The addition of vestibular cues to kinesthetic and visual cues provides a stronger indication of direction of travel or heading through activation of hippocampal neurons, which are

thought to continually monitor vestibular cues to aid in maintaining orientation (Stackman, et. al., 2002). Studies have found that directional responses were significantly poorer when optic flow (i.e., visual input) alone specifies the outbound path (as compared to when a physical turn was allowed [vestibular input]; Loomis, et. al., 1995; Klatzky, Loomis, Beall, Chance, & Golledge, 1998). Similarly, Bakker et al. (1998) found that pure vestibular input (e.g., when participants are seated and whole body rotates with no visual feedback) produced significantly better heading judgments than pure visual input (optic flow alone) when orienting oneself to angles greater than 90^0. This enhanced orientation may not carry over to more complex environments such as the one studied by Ruddle and Peruch (2004), however, where they found no significant difference in efficiency of exploration or route knowledge between participants using a desktop display (i.e., no head tracking) and those using an HMD (i.e., head tracking). Thus, while head tracking may be effective at maintaining orientation (relative heading) in simple environments, it may be ineffective at calibrating the spatial surround. A summary of preliminary vestibular design guidelines based on psychophysical research is displayed in Table 8.

Table 8: Psychophysical Vestibular Interaction Design Guidelines

• Incorporate activation of vestibular cues to enhance indication of head position and overall body posture and orientation.
• To activate semicircular canals, angular acceleration/deceleration must exceed 0.1-0.5 $^0/s^2$.
• To activate the utricle, horizontal linear acceleration should be greater than 5-15 cm/s^2.
• To activate the saccule, vertical linear acceleration should be greater than 10-12 cm/s^2.

CHAPTER FOUR: MULTIMODAL SENSORY INFORMATION REQUIREMENTS FOR ENHANCING SITUATION AWARENESS AND TRAINING EFFECTIVENESS[3]

Introduction

Multimodal virtual training systems, where trainees can see, hear and feel the surrounding environment and interact in a natural, realistic setting, offer unprecedented exposure to training tasks. Here, trainees may be exposed to complex training environments in which their processing and cognitive abilities can be effectively engaged to optimize human performance and situation awareness (SA), while promoting efficient training transfer to real world tasks. The current challenge is determining how best to design such multimodal systems; specifically how to leverage each modality to enhance training effectiveness. To date, many visual displays (e.g. desktop displays, projection screens, head-mounted displays [HMD]) have undergone in depth study examining implications on human performance (Bowman, et al. 2002; Cruz-Neira, et al. 1993; Lantz, et al. 1996; Pausch, et al. 1993). In general, these studies indicate that visual displays are well suited for conveying information representing real world physical objects, spatial relations, and dynamic information that changes over time or requires persistent attention (European Telecommunications Standards Institute [ETSI] 2002, Watzman 2003). Less focus has been devoted to auditory and haptic displays and the benefits these technologies can add to virtual training environments due to the immature nature of the associated technology; however, this is no longer a limitation today. Thus, to fully exploit the training value of VEs it is essential

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[3] Adapted from Hale, K., Stanney, K., Milham, L., Bell, M.A. & Jones, D. (in press). Multimodal sensory information requirements for enhancing situation awareness and training effectiveness. *Theoretical Issues in Ergonomics Science (TIES): Special Issue: Optimizing Virtual Training Systems.*

to look beyond their visual display capabilities alone, particularly when training tasks that require more fully engaging sensory processing.

Ideally, all sensory cues present in the real environment would be presented in a training environment in some form to maximize SA, performance and training transfer; however, tradeoffs based on technology and implementation costs of sensory cues often must be made. Yet, currently developers have limited guidance to support making such tradeoffs in a systematic manner. The objective of this paper is to develop a framework that outlines how multimodal sensory cues may be used to enhance SA, from which designers can select appropriate cues to include in their training environments based on their specific training needs and objectives. Specifically, the framework identifies SA components that may be targeted during training, and relates these to the multimodal human sensory systems that should be stimulated to support this acquisition. This study focuses, in particular, on how exteroceptive (i.e., originating outside the body) auditory and tactile sensory cues and interoceptive (i.e., originating within the body) cues may be used to enhance a trainee's situation awareness, as exteroceptive visual sensory cues have been dealt with in detail elsewhere (ETSI, 2002, May & Badcock 2002, Watzman, 2003).

Multimodal Optimization of Situation Awareness (MOSA) Model

Situation awareness (SA) is commonly referred to as 'getting the big picture' or knowing what is going on in an environment and being able to foresee future events that may occur (Dennehy & Deighton 1997). Using an information-processing model approach (Uhlarik & Comerford 2002), Endsley (1995) defines SA as the perception of elements in an environment within a volume of space and time, comprehension of their meaning, and prediction of future events. Thus, level 1 SA (i.e. Perception) involves stimulus detection, and is where sensory processing, world

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modeling, and value judgment all interact and are influenced by one's view of a given situation and relevant primitive elements that have been perceived (e.g. incoming information) versus one's expectations/biases (Albus 1997). Level 2 SA (i.e. Comprehension) is the process of combining, interpreting, and storing perceived information, and determining the relevance of this information to one's overall goal (e.g. does it fit the current mental model?). Level 3 SA (i.e. Prediction) involves complex strategic decisions including accurately projecting how a situation is likely to develop in the future, provided it is not acted upon by any outside force and predicting or evaluating how an outside force may act upon a situation to affect one's projections of future state. Based on current state, a user must decide on a course of action, which will influence changes in the environment. The course of action may involve self-initiated interactivity with the system or maintenance of the current system state as a memory trace for future comparison (Endsley, 1998), as well as determining how a current course of action will impede one's ability to function (e.g. the implications of *not* mitigating a threat). These interactions between SA and changes in the environment are summarized in Figure 1. Based on the current environment status, *perception* of environmental changes (both exteroceptive and interoceptive) leads to *comprehension* (i.e. consolidation of incoming multimodal cues into an understanding of the situation). From this understanding, one *predicts* future states, and decides on a course of action (e.g. to act on the environment or observe changes within the environment).
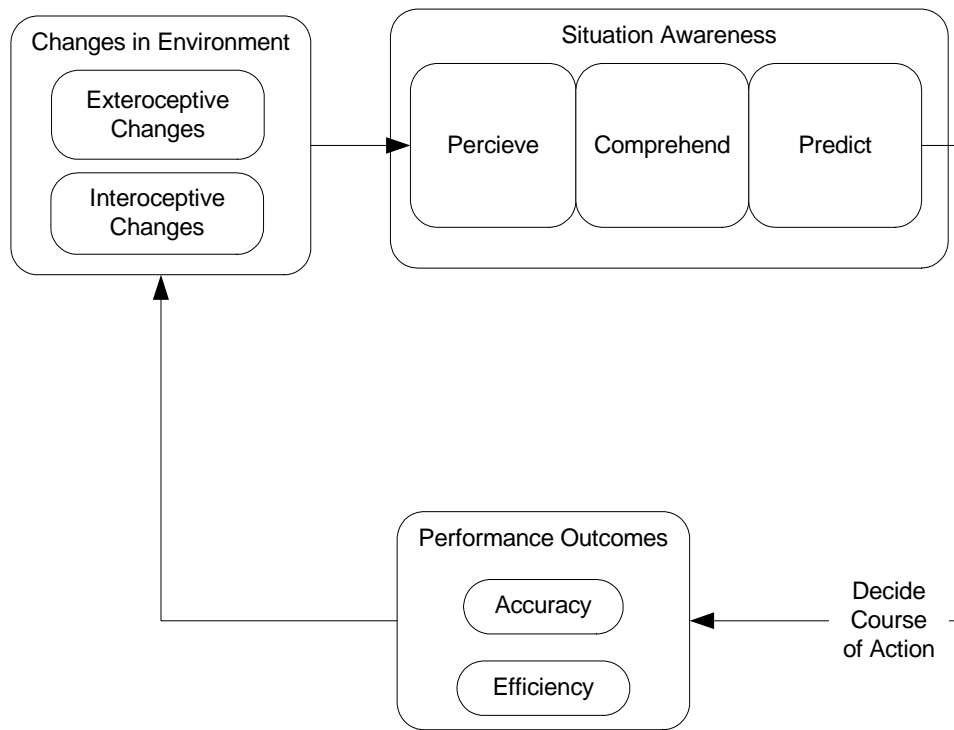
Figure 1: Situation Awareness Development Cycle (adapted from Endsley, 1998)

While Figure 1 incorporates individual capacities for perception, comprehension, and prediction of one's surrounding, specific environmental awareness components required for adequate awareness are not characterized in this model. Figure 2 introduces the Multimodal Optimization of Situation Awareness (MOSA) model, which integrates these additional components into the traditional SA model, thereby providing a more prescriptive characterization of the SA construct from which design guidelines can be drawn regarding the benefits of incorporating different sensory cues into a training system (i.e. based on filling in gaps where a training system is not effectively supporting SA components).
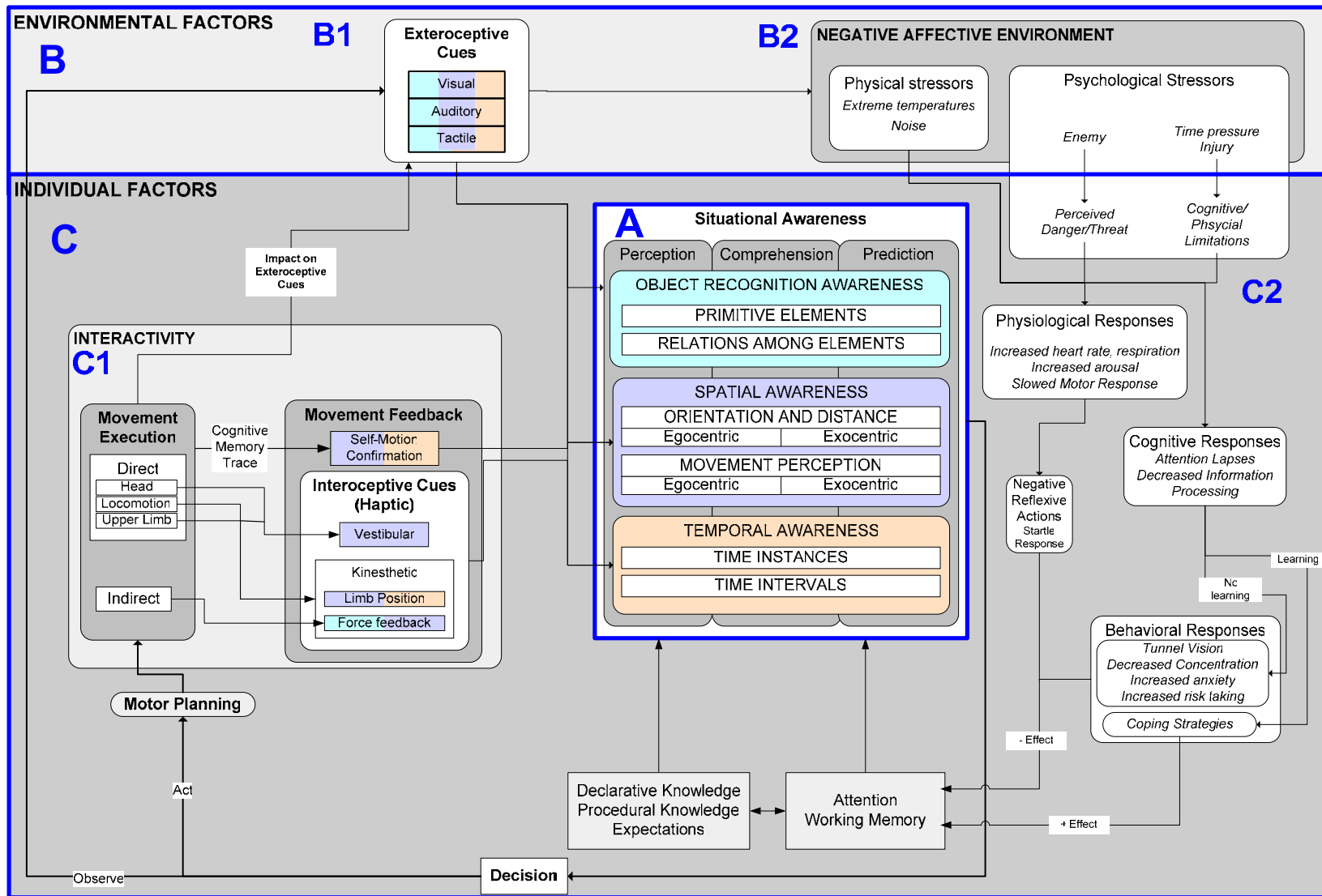
Figure 2: Multimodal Optimization of Situation Awareness (MOSA) Model

The MOSA model is broken up into three main sections. Section A includes the traditional perception, comprehension, prediction SA model, which has been further differentiated into three components (see section 'A,' Figure 2) including object recognition awareness (Sewards & Sewards, 2002), which characterizes *who* or *what* is in the environment based on primitive elements (Biederman, 1987; 1995), spatial awareness, which incorporates spatial location and movement of objects/entities and self (Montello, 2002), and temporal awareness, which identifies elements related to time instances and intervals (Allen, 1983). Section B characterizes environmental factors that influence SA development. These environmental factors include exteroceptive cues that can be presented using visual, auditory or tactile displays (or a combination of these displays; Figure 2, section B1), which, if perceived, may enhance SA by providing bits of information that may be integrated into an overall perception of the current situation. In addition, exteroceptive cues can also provide affective cues, such as negative stressors (Figure 2, section B2) that can impact SA development. Section C identifies individual factors that influence SA development, and include cognitive factors (e.g. attention, working memory, declarative knowledge, procedural knowledge, expectations; Endsley 1995) and interoceptive cues, which result from motion planning and interactivity (movement execution and movement feedback) between human and system, as well as movement execution, which creates interoceptive feedback (e.g. vestibular and kinesthetic cues) that may provide bits of information for development of SA, dependent on the type of interactivity. In addition, movement execution can directly impact multimodal exteroceptive cues (e.g. moving a joystick updates a visual display). Thus, movement execution creates a number of interoceptive cues that can be combined with resultant multimodal exteroceptive cues to provide

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object recognition, spatial, and temporal awareness of entities in the environment, thereby enhancing awareness of one's surround.

The MOSA model theorizes that optimal SA is achieved when each component of awareness (i.e. objection recognition, spatial, and temporal) is accurately perceived, comprehended, and used to formulate predictions (expectations) of future events without undo influences from negative stressors. The question remaining, then, is how can training systems optimize each of these components while mitigating the effects of stressors? This requires a thorough understanding of both environmental and individual factors that influence awareness components critical for developing SA based on training goals/objectives, as well as usability design knowledge to ensure required information is presented in the right form at the right time. A sample scenario based on military operations in urban terrain (MOUT) that outlines how the MOSA model can be utilized in training system design will be used throughout this paper.

MOSA Model (Section A): SA Awareness Components

Optimal SA of a situation requires awareness of who/what entities are in an environment (i.e. object recognition) and where (i.e. spatial) they are across time (i.e. temporal; where they were; where they are; where they will be relative to self and/or each other) (see Figure 2: section A). Object recognition awareness involves the recognition and categorization of entities (e.g. combatant/non-combatant; Phillips, McCloskey, McDermott, Wiggins, Battaglia, et al*., 2001) according to standard rules based on primitive elements (i.e. geons for visual scenes, phonemes for speech perception; Biederman, 1987). For example, MOUT trainees need to associate incoming percepts with previous knowledge stores (e.g. perceive person in an environment), comprehend the value or meaning of the percepts (e.g. hostile vs. non-hostile), and predict how

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these percepts may impact self goals (e.g. is entity likely to evoke injury to self?) during virtual training.

The second component required for SA, spatial awareness, incorporates where entities are in the environment, including both static and dynamic distance and orientation information (Montello, 2002). Static information includes distance/orientation of entities in an environment relative to self (egocentric) and relative to a global space (exocentric). Within a dynamic scenario (i.e. movement through space) entities and self are constantly updating spatial position. For example, each incoming percept (e.g. location of enemy) must be compared to previous location information to elicit an accurate understanding of entity movement (e.g. speed, direction of travel) to ensure appropriate predictions of movement are made (e.g. identifying highest threat).

The third component required for SA is that associated with time. Endsley (1995, p.36) notes the importance of time within SA development by stating SA is "the perception of the elements in the environment within a volume *of time* and space". Awareness of time consists of instants (i.e. time points) and associated time intervals (i.e. periods), and is often strictly relative (e.g. A before B; Allen, 1983). In other words, event recall generally does not rely on exact minutes/hours but on the order of events as they occurred. Such individual memory of events that have happened (e.g. number of enemies neutralized) is referred to as episodic memory, and can be used to develop knowledge-based inferences and enhance SA development.

Table 9 summarizes training implications for object recognition, spatial, and temporal awareness components for SA development.

Table 9: Awareness Components for SA Development

	Object Recognition Awareness	Spatial Awareness	Temporal Awareness
Perception	Perceive who/what is in environment	Perceive where entities are in environment	Perceive when actions occur
Comprehension	Categorize entities	Compare where entities are relative to where they were over time	
Prediction	Prioritize actions based on entity classification	Location of where entities will be at a future time	
Training Implications	- Awareness components can be represented in numerous ways via multimodal presentation (see Figure 2) - Maximum SA is achieved when all three components are accurately perceived, comprehended, and used to formulate predictions (expectations) of future events - Designers of training systems should determine how best to present cues dependent on training environment, objectives and goals		

Given that optimal perception, comprehension, and prediction of object recognition, spatial, and temporal awareness within an environment are required for SA development, designers must determine how best to present world knowledge to optimize associated cognitive processes and ensure all essential information required to optimize SA is presented to trainees in a readily perceived and easily understood format. Thus, in the MOSA Model additional components (i.e. environment and individual factors) have been added to the traditional SA model (see Figure 2, sections B and C).

MOSA Model (Section B): Environmental Factors

Section B of Figure 2 represents means in which environmental factors (i.e. those multi-sensory stimuli outside the body that drive perception, comprehension, and prediction) can be leveraged to enhance SA development. Specifically, to enhance SA designers must consider how environmental multimodal exteroceptive cues can be presented and updated within a training system, in order to provide a continuous flow of stimuli for trainees to perceive, understand, and create future state predictions upon (Figure 2: section B1). Exteroceptive cues that cannot be represented via ecologically valid 'real world' cues (e.g. walking through an environment), could be considered for representation via metaphoric cues[4] (e.g., an auditory metronome to represent one's traversal pace). Each multimodal exteroceptive cue presented to trainees should be precisely targeted to provide a specific sensory stimulus present in the real world that impacts one or more awareness components (i.e., Figure 2 shows how visual, auditory, and tactile exteroceptive cues can support all three levels of awareness [object recognition, spatial, and temporal]). If a cue does not support such awareness, its representation likely cannot be justified unless budget is of no concern. For example, enemies must be identified in a MOUT training environment. This representation could be supported via a visual representation, auditory sounds associated with enemies (e.g. gunfire and/or footsteps), or haptic cues such as incoming gunfire. If the transfer environment requires identification of enemies based on the type of gunfire heard outside of the visual field of view (i.e. a training objective), then auditory cues would likely best

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[4]It is important to note that metaphoric exteroceptive cues may be seen as training crutches, however, if implemented using a training wheels paradigm (Carroll & Carrithers, 1984), metaphoric cues may be used to effectively enhance performance for novices, and then faded over the course of several training scenarios to ensure cues do not lead to negative transfer of skill.

be chosen for incorporation into the MOUT training environment. If, however, the training objective was to develop correct room-clearing procedures, then visual cues could be used to represent enemies throughout the building.

The following review focuses on specific auditory and tactile exteroceptive cues that may be incorporated into a VE to enhance situation awareness (visual display elements to enhance SA have been dealt with in detail elsewhere; ETSI, 2002; May & Badcock, 2002).

MOSA Model (Section B1): Auditory Exteroceptive Cues

The MOSA model characterizes how auditory exteroceptive cues can influence SA development, particularly through non-spatialized and spatialized sound sources (see Figure 2, Section B1).

Non-spatialized Auditory Cues: There is vast research (Gilkey & Anderson, 1997) on using sound sources as attentional cues (i.e. alarms), which indicate that auditory signals are well suited to facilitating perception (level 1 SA). Specifically, auditory cues have been used to alert operators about various events that require attention, resulting in higher detection of events, a precursor to SA development (Welch & Warren, 1986). Non-spatialized auditory cues can also be used to present object facts regarding a surrounding environment using familiar sounds (e.g. doors closing, footsteps), thereby enhancing object recognition awareness, particularly when entities are outside one's field of view.

Auditory cues have also been used to enhance temporal awareness via explicit temporal pacing (Zelaznik, Spencer, & Ivry, 2002), thereby supporting temporal awareness acquisition. A metronome (i.e. auditory signal at constant time intervals) may be used to provide pace information (e.g. tone every 5 seconds). Similarly, an auditory signal *pattern* may be used to

elicit temporal awareness (e.g. faster sequence indicates 'speed up', slower sequence indicates 'slow down').

Spatialized Auditory Cues: The benefits of spatialized signal presentation have been demonstrated in a number of simple environments (Kramer, Walker, Bonebright, Cook, Flowers, et al., 1997). Current research into auditory cues suggests there are a number of benefits with regards to spatial awareness (i.e. localization, visual search performance, and navigation) and movement perception (i.e. aurally 'tracking' a moving object from one area to another), as spatialized auditory signals provide natural cues regarding where one is in an environment (Loomis, Golledge, Klatzky, Speigle, & Tietz, 1994), or where an object is, particularly when an object is outside an individual's field of view (Nelson, Bolia, & Tripp, 2001). Research on moving auditory signals suggests that spatialized sound cues can be used to create the perception that objects are moving from one location to another (Caelli & Porter, 1980). Such dynamic spatial cues can assist individuals who must monitor where moving targets, team members, or objects are located (Perrott, Cisneros, McKinley & D'Angelo, 1996).

In summary, exteroceptive auditory cues can effectively:

- Present facts of one's surrounding environment using familiar sounds (e.g. doors closing, footsteps), thereby enhancing object recognition awareness, particularly when objects are outside one's field of view;

- Present rhythmic information, thereby enhancing temporal (i.e. time interval and period) awareness;

- Direct attention and aid in localization of objects, thereby enhancing spatial awareness;

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- Create the perception that objects are moving from one location to another, thereby enhancing spatial (i.e. movement perception) and temporal (i.e. episodic memory) awareness.

MOSA Model (Section B1): Tactile Exteroceptive Cues

The MOSA model characterizes how tactile exteroceptive cues (i.e. stimuli placed in contact with the skin that activate cutaneous receptors including mechanoreceptors and thermoreceptors) can influence SA development, particularly through static and apparent motion cues (see Figure 2, Section B1). While thermoreceptors might well be leveraged to enhance SA, due to the current state of associated technologies, tactile mechanoreceptors (i.e. vibration, roughness, hardness, skin stretch and pressure) are the focus of this report.

Static Tactile Cues: Static exteroceptive tactile cues (e.g. static vibration) are presented to mechanoreceptors in the skin, and can be used to provide components of object recognition awareness (Geldard, 1957), egocentric spatial awareness via object contact or localization cues (Fowlkes & Washburn, 2004), and temporal awareness (ETSI, 2002) as shown in Figure 2, section B1. Object recognition information may be provided through exteroceptive tactile cues, such as by implementing coded vibrations (i.e. distinct tactile signatures that have meaning). Geldard (1957) found that after 12 hours of practice, three participants were able to recognize singly presented tactile representations (45 representations that different in location, vibration and duration) 90% of the time. In a MOUT exercise, active tactors may indicate contact with a wall, thereby enhancing visual perceptions by adding tactile cues concerning a physical property of an object (in this case, solidity of a wall). The amount of object recognition awareness that can

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be provided via exteroceptive tactile cues is limited by the number of coded vibrations one can effectively remember (Miller, 1956; Cowan, 2001).

Spatial awareness regarding object orientation and distance information may be provided through exteroceptive tactile cues to represent object contact (e.g. contact furniture) or spatial relationships (e.g. active tactors represent direction of ground to pilots; navigational cues). For example, Lindeman, et al. (2005) used directional vibrotactile cues in a building-clearing exercise to indicate which areas of a building had not yet been cleared; thereby reducing exposure in uncleared areas and increasing the area cleared. Terrence, et al. (2005) found that spatial tactile displays are more effective than spatial auditory displays both in terms of reaction time and spatial localization. Coupling static tactile cues with awareness obtained through visual cues may thus enhance egocentric spatial awareness through redundant cue information regarding object location.

Temporal awareness may also be enhanced through exteroceptive tactile cues. Time instance and interval information may be provided through attention cueing to direct attention during critical task components (Tan, et al., 2003). Cueing, where one stimulus (in any modality) prompts a user to attend to future stimuli, directs attention, which is a critical component to the development of a temporal continuum (Rao, Mayer, & Harrington, 2001). Similarly, interval length may be presented through successive activation of tactors on the skin to provide temporal cues. While tactile systems may effectively display temporal information in isolation, it may also be used in combination with vision, as the haptic sense provides more accurate timing information compared to vision alone (ETSI, 2002). For example, a pacing cue may be given to MOUT trainees to dictate the speed at which they should travel through a building during a room clearing exercise.

Apparent Movement Tactile Cues: Apparent motion via exteroceptive tactile cues can provide spatial awareness, such as directional cues to trainees (Rupert, 1997) and information regarding object movement about a stationary observer. By activating a series of vibration tactors in a set pattern (i.e. straight line), movement of an entity around a static trainee or movement direction cues for trainees may be provided to enhance egocentric spatial awareness (e.g. location of self relative to where one has been/where one is going). Rupert (1997) developed a tactile vest that dynamically displayed the direction of 'ground' to pilots, and showed significant increases in pilot SA during in-flight maneuvers. This same technology could be applied to a MOUT training environment to provide an indication of moving objects within a training environment relative to a stationary trainee (e.g. enemy running towards trainee from behind), thereby enhancing egocentric spatial awareness.

In summary, exteroceptive tactile cues effectively:

- Provide factual information using coded signals (i.e. vibrations), thereby enhancing object recognition awareness;

- Provide object contact feedback, thereby enhancing egocentric spatial (i.e. distance) awareness;

- Represent spatial relationships and directional cues (e.g. indicate location of ground relative to self), thereby enhancing egocentric spatial (i.e. orientation and distance) awareness;

- Direct attention and provide rhythmic cues, thereby enhancing temporal (i.e. time instance and interval) awareness.

MOSA Model (Section B2): Negative Affective Factors

The MOSA model characterizes how negative stress can influence SA development, particularly through physical (i.e. stimulus-based; Staal, 2004) and psychological (i.e. response-based; Staal, 2004) stressors (see Figure 2, Section B2). As defined by Stokes and Kite (2001, p.109) stress is "…an agent, circumstance, situation, or variable that disturbs the 'normal' functioning of the individual…stress [is also] seen as an effect—that is the disturbed state itself". The MOSA model takes into consideration both of these definitions, where the stressors present in the environment (discussed in this section) cause an effect on the individual (i.e. stress response; see Figure 2, Section C2), yet focuses on factors that negatively impact 'normal' functioning of the individual (note that some stress may cause a positive response – this will not be discussed in this paper). Negative physical stressors cause direct activation of physiological responses, and include noise, heat, cold, and sleep deprivation (Orasanu & Backer, 1996). Psychological stressors, on the other hand, depend on interpretation for effect, and do not themselves relate directly to affective physiological responses. These stressors can be categorized as danger/threat stressors (e.g. perceived danger due to enemy presence) or limitations of cognitive/physical ability (e.g. time pressure). Regardless of the type of stressor, training environments should account for potential negative affective experiences (see Figure 2, section C3) that may impact training effectiveness.

In complex operational environments, trainees perform with various physical and psychological stressors (e.g. in MOUT: noise, time pressure, workload, competing tasks). In comparison, training environments are often relatively less stressful. Driskell, Johnston, & Salas (2001) note it is important to introduce stress to trainees to inoculate them from potentially

negative effects. Without affective cues, trainees may not have an opportunity to prepare for stressful operational scenarios, leading to performance decrements in a transfer environment due to stress (e.g attentional narrowing) (cf Keinan, Freidland, & Sarig-Naor, 1990). Given the consequences of degraded SA and human performance losses, strategies for decreasing such effects should greatly improve capacity to perceive, comprehend, and make future predictions upon incoming sensory stimuli, thereby enhancing SA development. An affective environment can provide trainees with realistic cues that facilitate the development of a desired emotional response to a situation.

Negative Physical Stressors: The MOSA model characterizes how negative physical stressors can influence SA development, particularly through such stressors as extreme temperatures, sleep deprivation, and noise (see Figure 2, Section B2). Exteroceptive cues can be utilized to design an affective environment by creating physical stressors within the training scenario. For example, Västfjäll (2003) incorporated sound via spatialized stereo and six channel reproduction that resulted in significantly stronger changes in emotional reactions than mono sounds. Västfjäll, Larsson, & Kleinberg (2002) found that emotion was systematically affected by different reverberation times: high reverberation time was found to be most unpleasant. Auditory cues used to evoke such reactions within a MOUT environment could include explosions, bullets impacting walls, enemy voices, grenades detonating, and weapons firing (Greenwald, 2002, Shilling, Zyda, & Wardynski, 2002; Wilfred, Hall, Hilgers, Leu, Hortenstine, et al., 2004). Wilfred, et al. (2004) used the sound of random explosions in a search and rescue task to create an affectively intense environment and found that those who trained in an affectively intense environment performed substantially better in the 'real' environment than those who trained in an affectively neutral environment. Similarly, tactile exteroceptive cues

could be used to create physical stressors (e.g. heat from explosions; impact from enemy contact). For example, Morie, Iyer, Valanejad, Sadek, Miraglia, & Milham (2002) used vibration via a rumble floor to create affective responses (i.e. stress) in a virtual, fully immersive reconnaissance patrol environment.

By implementing exteroceptive affective cues within a training environment, participants (through repeat exposure) may develop adequate coping strategies to minimize negative impacts of stressors on cognitive and behavioral responses, thereby optimizing SA development by maintaining high capabilities to perceive, comprehend, and predict entities in stressful environments.

Negative Psychological Stressors: The MOSA model characterizes how negative psychological stressors can influence SA development (e.g. a MOUT environment includes such stressors as the presence of enemies, time pressures, and injury) (see Figure 2, Section B2). For example, Insko, et al. (2001) found that adding a haptic platform (a 1" wooden platform) to a virtual scene depicting a ledge overlooking a room one floor below resulted in higher presence, more behaviors associated with pit avoidance, and increased heart rate and skin conductivity. Thus, exteroceptive cues can be used to elicit psychological stress within a virtual training environment.

In many operational environments such as the military, trainees will perform a task under fear for their life and extreme time pressure constraints. While time pressure can be easily reproduced in a research or training setting, it is challenging to create a stressor that evokes an emotional response equivalent to that of the fear experienced when one's life is in danger. The presence of the psychological stressor of 'threat' in research and training environments has been scarce in the past due to the sheer difficulty of creating it realistically. However, virtual

environments have brought researchers closer to this capability. Ulate (2002) performed an experiment which compared learning in a VE under a threat stressor condition with a no stressor condition, and found that those participants who had the added stressor of enemy attack performed better on recall tasks than did those who wandered through the scenario with no external stressors. Similarly, Shilling, et al. (2002) used enemy attack as a high stressor condition, and found that compared to a low stressor condition (participants traversed a VE on a mission to free prisoners of war), the high stress condition (participants under enemy attack who had to fight their way through a scenario) performed significantly better on subsequent recall tasks.

In summary, because negative affective factors can cause decrements in performance due to negative physiological responses, such stressors:

- Should be incorporated into training environments to allow trainees to recognize emotional and physical reactions and develop adequate coping strategies to minimize negative impacts of stressors.

- Should be considered for incorporation into training devices to increase learning and performance in operational environments.

MOSA Model (Section C): Individual Factors

The MOSA model characterizes how individual factors can influence SA development; particularly through interactivity and affective responses (see Figure 2, Section C).

MOSA Model (C1): Interactivity Cues

The MOSA model characterizes how interactivity can influence SA development, particularly through movement execution and movement feedback (see Figure 2, Section C1). Interoceptive cues created through movement execution are dependent on the type of interaction between human and system (indirect or direct). Indirect control refers to interaction via an intermediate device such as a mouse or joystick. Haptic cues provided by the kinesthetic sensory system when using an interaction device to control self-movement (e.g. joint/limb position, force) are not a direct indication of performance. For example, the motor program enlisted to move a joystick to its right-most position does not correspond to the perceived locomotion of self within the VE to the right (i.e. kinesthetic sensors in the arm are used to move self, and these signals do not relate to real world walking where activation of the lower limbs is required). Instead, users must rely on exteroceptor movement feedback (e.g. visual and/or auditory) to assess the situation. Direct interaction within a virtual world allows trainees to look around the environment, reach for objects, and move within the environment as they would in the real world (e.g. turn head to look left/right; move legs to walk), and can enhance object recognition, spatial and temporal awareness. Thus, in addition to updated exteroceptive cues created via interaction, trainees can also interpret interoceptive cues to enhance cue perception, comprehension, and prediction of all three awareness components.

Indirect Movement Execution: Providing haptic feedback through a mouse or desktop probe has resulted in enhanced spatial awareness as evidenced by reduced performance errors in dissection (Wagner, Stylopoulos, & Howe, 2002) and improved teleoperation performance (Murray, et al. 2003). Dennerlein, et al. (2000) found improved performance (decreased

movement time) when force feedback was added to a mouse during a steering task (force 'pulled' cursor towards center of path). Similarly, time to stop on target during a target selection task was enhanced when haptic feedback guiding cursor to target was provided (Akamatsu & MacKenzie, 1996). Using such a device within a multimodal VE can also enhance spatial awareness of the environment through the exteroceptive feedback provided. For example, movement of the visual scene in response to indirect movement execution creates optic flow, and can result in motion parallax (depth cue that results from motion) and vection (perception of self-motion), thus enhancing orientation and distance awareness and egocentric movement perception (Hettinger, 2002). Indirect control over movement also provides a cognitive memory trace of movement (Henry, 1986), leading to confirmation of self-motion (as opposed to movement of the surrounding world). This feedback may positively impact spatial and temporal awareness, by providing user control over distance traveled and speed of movement (i.e. timing of movement).

While indirect control allows movement and navigation throughout a virtual world, it does not provide a calibrated spatial reference frame. Darken, Allard, & Achille (1999, p. iii) point out that "navigation is not merely physical translation through a space, termed locomotion or travel, but that there is also a cognitive element, often referred to as wayfinding, that involves issues such as mental representations, route planning, and distance estimation". Thus, simply showing physical translation through a visual display does not provide multimodal input regarding egocentric spatial awareness such as wayfinding cues (e.g. travel path length, turning radius). These wayfinding cues are enhanced through direct movement interaction (see next section).

Temporal awareness may also be enhanced when haptic feedback is added to an interaction device. Studies have shown that positioning time is significantly reduced when tactile

feedback is provided (Akamatsu, MacKenzie, & Hasbrouq, 1995), and overall movement time and time to stop a cursor after entering a target are reduced for small and medium targets when tactile and tactile plus force feedback are added to a device (Akamatsu & MacKenzie, 1996). Tähkäpää and Raisamo (2002) found slight speed advantages when haptic feedback was provided through an interaction device to indicate when a cursor was over or close to a target on a graphical user interface.

In summary, indirect movement execution effectively:

- Creates exteroceptive feedback of motion (visual optic flow; audition), thereby enhancing spatial orientation, distance, and movement awareness;

- Streamlines spatial movements when haptic feedback is presented via an interaction device, thereby enhancing spatial (i.e. movement perception) awareness;

- Provides a cognitive memory trace, which may help spatial and temporal (i.e. affording control over speed of movement) awareness;

- Enhances movement time when tactile or tactile plus force feedback is provided via an interaction device, thereby enhancing temporal (i.e. time interval and period) awareness.

Direct Movement Execution: Direct movement execution involves trainees interacting within a virtual training environment as they would in the real world (i.e. turn head to update heading, reach and grab objects, walk). This review has divided direct movement execution into (1) rotational head movement and (2) limb movement (e.g. upper limb, locomotion). Each of these main categories uniquely impact object recognition, spatial, and temporal awareness components as outlined below.

Providing direct interaction of head rotation (i.e. tracking head movement: often achieved through HMD tracking) provides additional sensory cues by activating the semicircular canals within the vestibular apparatus in the inner ear (Lawson, et al., 2002), which detect angular acceleration (Howard, 1986). The addition of these vestibular cues enhances egocentric spatial awareness by providing a strong indication of direction of travel and heading (Pausch, et al., 1993, Loomis, et al., 1995, Bakker, et al., 1998, Klatzky, et al., 1998, Stackman, et al., 2002; however, also see refuting evidence by Ruddle & Peruch, 2004). The implication of head movements to SA component development is thus that rotational head tracking provides vestibular interoceptive cues which enhance egocentric spatial orientation awareness by providing more accurate heading information than vision alone.

Adding direct interaction via limb interaction (upper or lower [locomotion] limbs, e.g. using force feedback and positional sensor for upper limb; immersion in an augmented reality while traversing a city) provides kinesthetic interoceptive cues, including force feedback and limb position, in addition to exteroceptive feedback from motion. Object recognition awareness is likely enhanced through such multimodal interoceptive cues, as fundamentally different types of information about static objects are provided through individual modalities (Prytherch, 2002). Within the visual field of view, there are a number of attributes that can be identified instantaneously (e.g. size, form, topography, color). When objects are examined by the haptic sense alone, information is gathered less holistically than with vision, but rather progressively as the physical aspects (e.g. texture, weight, solidity, temperature) of an object and its surroundings are explored in detail (Prytherch, 2002). Thus, multimodal presentation may enhance object recognition awareness by providing unique, yet complementary information regarding objects. Direct haptic feedback through kinesthetic sensors may also enhance object recognition

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awareness by providing haptic details of object properties. For example, holding a weapon while traversing through a VE should enhance trainee presence by incorporating a haptic sense that is present in the real world.

Through direct movement execution of the limbs, the visual and/or auditory perspective of one's spatial surround can be coupled to key kinesthetic cues to aid the development of a calibrated spatial reference, thus enhancing spatial awareness. Visual depth issues may be eliminated when upper limb interaction is provided (e.g. able to reach and determine how close objects are based on anthropometric knowledge of limb length). Thus, upper limb interaction can enhance egocentric spatial orientation and distance awareness acquisition by providing additional kinesthetic cues regarding object location (i.e. distance one must reach to touch object).

Locomotion cues (i.e. repetitive limb motion for user self-propulsion) may also enhance spatial awareness acquisition; for example locomotion has been shown to calibrate visual distance judgments (Reiser, Peck, Ashmead, & Garing, 1995). This may be due to enhanced geometry and distance knowledge of an environment (Hollerbach, 2002) through multimodal sensory activation. Many studies have shown positive performance effects of physical locomotion over optic flow alone (cf Bakker, et al., 1998, Chance, Gaunet, Beall, & Loomis, 1998, Iwata & Yoshida, 1999). For example, Zanbaka, Lok, Babu, Xiao, Ulinski, & Hodges (2004) compared real walking while wearing an HMD (i.e. direct interaction) to using a joystick to manipulate self motion (i.e. indirect interaction) within a virtual room. Participants were asked to answer a number of questions pertaining to various cognitive levels (knowledge, understanding and application, higher mental processes) concerning objects found in the virtual room. Direct interaction within the room resulted in significantly higher cognitive scores and better sketch maps of the VE compared to joystick interaction. Thus, locomotion appears to

enhance distance perception, and plays a major role in spatial perception (Yang & Kim, 2004). Specifically, providing locomotion cues may enhance egocentric orientation, distance and movement awareness by activating kinesthetic and vestibular receptors which provide cues regarding egocentric heading, direction, and speed of travel.

Direct limb interaction can also enhance temporal awareness within a training environment. Direct upper limb haptic guidance can enhance timing performance of a complex, 3D motion (Feygin, Keehner, & Tendick, 2002). In terms of locomotion, three interrelated temporal parameters, stride length (distance from right-heel contact to following right-heel contact), cadence (number of steps per unit of time), and velocity (combination of stride length and cadence) combine to create a temporal component of motion (Ayyappa, 1997). Movement through an environment (natural locomotion) may enhance timing perception by calibrating the temporal environment using individual stride length and cadence information (i.e. self-selected walking rhythm) and creating an internal motor reference trace to evaluate performance. This may support temporal awareness acquisition for SA development.

In summary, direct movement execution effectively:

- Provides kinesthetic cues related to unique physical properties of objects (e.g. texture, weight, solidity), thereby enhancing object recognition awareness;

- Provides angular acceleration vestibular cues when rotational head motion is tracked, thereby enhancing egocentric spatial (i.e. orientation) awareness;

- Provides kinesthetic cues to calibrate the spatial surround, thereby enhancing egocentric spatial (i.e. distance, orientation and movement) awareness;

- Provides kinesthetic cues regarding rhythm, stride length and cadence, thereby enhancing temporal (i.e. time interval and period) awareness.

MOSA Model (Section C2): Affective Responses

The MOSA model characterizes how negative affective responses can influence SA development, particularly through physiological, cognitive, and behavioral responses (see Figure 2, Section C2). Negative affective responses may result from exposure to environments that create physical stressors or the perception of aversive or threatening situations (stressors, see Figure 2, Section B2). If human performance must take place in exceptionally stressful environments (e.g. battlefield), it is beneficial that the training environment create an appropriate affective environment to ensure trainees are able to develop and perfect coping strategies to deal with adverse stressors, and alleviate potential negative affective responses.

While some research has shown stress training successfully transfers to a novel environment (Driskell, et al., 2001), not all types of stressors operate through a similar process (e.g. noise, time pressure increase arousal; fatigue decreases arousal; Salas, Driskell, & Hughes, 1996). Thus, it is important to recognize that similarity between VE and real world affective stimuli is preferred in order to foster accurate perception and response to real world stressors via the adoption of learned coping strategies perfected in training.

Studies have shown that stress (and the secretion of glucocorticoids) can interfere with learning due to physiological, cognitive, and behavioral responses (e.g. increased heart rate, increased perspiration, attention lapses, decreased information processing, tunnel vision, increased anxiety; Orasanu & Backer, 1996), which may have a negative impact on situation awareness. However, affective responses to aversive stimuli can be influenced. One of the most important variables to determine whether an aversive stimulus will cause an affective response is control over the situation (Staal, 2004). If one can learn an effective coping response to avoid

contact with a stressor or decrease its severity, the associated affective response should disappear. Thus, by training in a VE where stressors are present, trainees can learn to ignore or control their emotional responses to stressors, and decrease their adverse behavioral responses in the real world, thereby decreasing the negative effect of stress on one's ability to perceive, comprehend, and make predictions upon incoming sensory stimuli.

In summary, negative affective responses:

- Can interfere with learning and SA development;

- Can be influenced, most effectively by having control over a situation;

- Can be minimized through repeat exposure within a virtual training environment that includes negative environmental and/or psychological stressors similar to those in the transfer environment by providing trainees an opportunity to learn and apply coping strategies.

Multimodal Display Design Guidelines

The theoretical review presented here outlines how a number of sensory cues may effectively be used to enhance specific awareness components within a VE training environment with the goal of optimizing SA development. Table 8 summarizes the comprehensive list of design guidelines that have been derived to assist designers in developing effective virtual training environments by outlining various methods for presenting critical sensory components to ensure desired training outcomes (Note: Based on past works [May & Badcock, 2002; ETSI, 2002], visual cues have been included in the multimodal design techniques presented in Table 10). Specifically, Table 10 presents theoretically-based multimodal design guidelines outlining how various awareness components may be enhanced through inclusion of environmental and individual

cues. Specifically, each awareness component (i.e. object recognition, spatial, temporal) is tied to design guidelines that specify how best to implement both exteroceptive (visual, auditory, tactile) and interoceptive (kinesthetic, vestibular) cues into a virtual training environment to optimize trainee SA development. Designers of training systems may use the guidelines presented here to optimize cue presentation for their operational environment by first identifying critical components required for optimal SA within the target training environment. Once defined, designers can then ensure each component is adequately represented via appropriate multimodal cues dependent on training goals and budget constraints. Implementing multimodal cues strategically to present all critical environmental and individual factors in some form (ecologically valid or metaphoric cues) while minimizing sensory bottlenecks (Stanney, Samman, Reeves, Hale, Buff, et al., 2004) and negative cross-modal effects (i.e. too much information in one modality, piercing auditory input that distracts perception of other sensory cues) should optimize training system design.

Table 10: Multimodal display design guidelines to enhance situation awareness within a VE

training environment

Desired Training Outcome(s)	Map Training Outcomes to Supporting Sensory Requirements	Training Solution: Multimodal Design Techniques	Recommended Assessment Techniques for Training Solution
Enhanced object recognition awareness	Exteroceptive cues	Various discriminatory visual cues (e.g. color, size, shape, features) can be used to provide identification of entities.	Accuracy in object identification
		Familiar, spatialized sound sources can enhance identification of entities, particularly when entities outside visual field of view.	Speed in object identification
		Coded vibration signals (e.g. indicate approaching entity from rear) can enhance identification of entities, particularly when entities outside visual field of view.	
	Interoceptive cues	Indirect user control of movement (e.g. using mouse/joystick) can provide kinesthetic force feedback to enhance object recognition awareness based on object contact.	
		Direct upper limb interaction can provide kinesthetic force feedback and limb position cues to enhance object recognition awareness based on form/shape/softness/weight.	

Desired Training Outcome(s)	Map Training Outcomes to Supporting Sensory Requirements	Training Solution: Multimodal Design Techniques	Recommended Assessment Techniques for Training Solution
Enhanced egocentric orientation and distance awareness	Exteroceptive cues	Pictorial cues can provide relative depth within a visual scene and enhance egocentric distance awareness.	Distance estimation
		3D visual scenes (e.g. stereoscopic displays) can provide absolute depth perception within 30 feet and enhance egocentric distance awareness.	Time to locate objects
		Static sound sources within 3D space provide relative orientation and distance cues, and can enhance egocentric orientation and distance awareness.	Indirect exposure (i.e. time spent in danger areas)
		Static tactile cues within 3D space (e.g. through a tactile vest) provide relative orientation and distance cues, and can enhance egocentric orientation and distance awareness.	Direct exposure (i.e. time spent in line of sight of enemies)
	Exteroceptive/ interoceptive movement feedback	User control over movement (either direct or indirect) provides self-motion confirmation, and can enhance relative egocentric orientation awareness through self-control of heading.	
	Interoceptive cues	Indirect user control over movement can provide force feedback when contact with objects is made to enhance relative egocentric distance awareness.	
		Rotation of the head (e.g. through tracked HMD) provides more accurate heading information, and can enhance egocentric orientation awareness.	
		Direct upper limb interaction where users can reach and touch objects can be used to calibrate distance to objects within reach, and can enhance egocentric orientation and distance awareness.	
		Locomotion can provide a kinesthetic memory trace of movement of heading and distance traveled based on stride length, cadence and velocity, and can enhance egocentric orientation and distance awareness.	

Desired Training Outcome(s)	Map Training Outcomes to Supporting Sensory Requirements	Training Solution: Multimodal Design Techniques	Recommended Assessment Techniques for Training Solution
Enhanced exocentric orientation and distance awareness	Exteroceptive visual cues	An aerial map of a virtual space provides a global view of objects and their spatial locations, and can enhance exocentric orientation and distance awareness.	Distance estimation Survey knowledge
Enhanced egocentric movement awareness (i.e. movement of self-and/or objects relative to self within the environment)	Exteroceptive cues	Optic flow/vection provides a sense of motion and can enhance egocentric movement awareness.	Time to navigate path
		A map of current position relative to past location (i.e. breadcrumb trail) or direction of travel (e.g. GPS map) provides a global perspective of location within an environment, and can enhance egocentric movement awareness.	Accuracy in path navigation
		Moving sound sources located within 3D space can enhance egocentric movement awareness by providing cues regarding movement of entities and/or self relative to environment.	Self-report SA questionnaire (e.g., SART)
		Moving tactile cues across the skin can enhance egocentric movement awareness by providing cues regarding moving of entities and/or self relative to environment.	Objective SA questionnaire (e.g., SAGAT)
	Interoceptive cues	Indirect user control (e.g. using mouse) over movement provides self-motion confirmation, and can enhance egocentric movement awareness.	
		Rotation of the head (e.g. through tracked HMD) provides vestibular feedback to enhance egocentric movement awareness.	
		Direct upper limb interaction provides kinesthetic distance feedback and self-motion confirmation, and can enhance movement awareness of objects relative to self.	
		Locomotion can provide a kinesthetic memory trace of movement of heading and distance traveled based on stride length, cadence and velocity, and can enhance egocentric orientation and distance awareness.	

Desired Training Outcome(s)	Map Training Outcomes to Supporting Sensory Requirements	Training Solution: Multimodal Design Techniques	Recommended Assessment Techniques for Training Solution
Enhanced exocentric movement awareness	Exteroceptive cues	A map that incorporates icons that dynamically update position to reflect location of entities and self can enhance exocentric movement awareness.	Route path and time estimation
Enhanced time instant and interval awareness	Exteroceptive cues	Visual cues (e.g. blinking dot, dynamic timeline) can be used to provide temporal cues and enhance time instant and interval awareness.	Response time Task pace
		Sound sources within 3D space can provide temporal cues (i.e. sound every 10 seconds) and enhance time instant and interval awareness.	
		Tactile cues within 3D space (e.g. through a tactile vest) can provide a temporal cue and enhance time instant and interval awareness.	
	Interoceptive cues	User control over movement (either direct or indirect) provides self-motion confirmation and temporal control over movement, and can enhance time instant and interval awareness.	
		Locomotion provides kinesthetic feedback via a calibrated time sequence (i.e. natural walk pace), and can enhance time instant and interval awareness.	
Enhanced affective training environment	Exteroceptive multimodal cues	Including negative affective physical or psychological cues via exteroceptive stimuli (visual: smoke; auditory: gun shots; tactile: incoming shots) in the training environment creates negative physiological responses, leading to negative reflexive actions and a negative impact on one's ability to perceive, comprehend and predict actions within the training and a transfer environment.	Physiological metrics (e.g. heart rate; GSR) Performance outcome metrics (i.e. indirect exposure, direct exposure, time to complete mission, fire accuracy)
	Exteroceptive multimodal cues	Providing single exposure to a negative affective training environment by incorporating real world stressors may negatively impact one's ability to perceive, comprehend and predict actions within the training and a transfer environment.	
Enhanced coping strategies for adverse stressors.	Exteroceptive multimodal cues	Providing repeat training to a negative affective environment by incorporating real world stressors may positively impact one's ability to perceive, comprehend and predict actions within the training and a transfer environment by enhancing coping strategies for adverse stressors.	

Conclusions

To optimize SA, an individual must accurately perceive and understand information concerning their environment, and use this awareness to create accurate predictions regarding future events. As outlined in the MOSA model, there are numerous environmental and individual factors that can be used to present critical data to support development and integration of the three awareness components (i.e. object recognition, spatial, and temporal) critical to SA development. Environmental factors include exteroceptive visual, auditory, and tactile cues, which can enhance awareness through presentation of requisite sensory stimuli and induce negative stress within a training environment to increase training realism. Individual factors include interoceptive cues that are created through interactivity, both direct and indirect interaction, as well as responses to stressors. Within a complex, dynamic operational environment, a multitude of multimodal stimuli are present and each cue must be accurately perceived and comprehended to ensure optimal performance. In developing training systems for such complex tasks, developers must strive to present all critical cues (i.e., those associated with awareness) that occur in the live environment *in some form* to provide trainees an opportunity to learn how to synthesize and consolidate incoming cues to optimize SA, performance and training transfer. Presented here is a theoretical framework and associated design guidelines for how a variety of environmental and individual sensory stimuli can positively impact SA development in a training environment. From this list of multimodal stimuli representations of awareness components, designers of training systems can represent critical environmental cues required for their operational environment and seek to present them in some form (ecologically valid or metaphorically) to ensure optimal training, SA, human performance, and training transfer.

CHAPTER FIVE: ENHANCING SPATIAL AWARENESS TRAINING AND TRANSFER THROUGH HAPTICS INTERACTION IN A VIRTUAL ENVIRONMENT

Introduction

While technological enthusiasts have already jumped on the bandwagon, it is time to deliberate two critical questions regarding virtual environment (VE) training systems: From where are the training benefits of VE technology derived and how do these training benefits positively impact development of complex KSA such as situational awareness (SA)? VE training systems offer ecological validity, view control, object manipulation ability, malleability of stimulus feedback and task complexity, real-time performance assessment, and replay ability (Brooks, Rose, Attree, & Elliot-Square, 2002; Dalgarno & Harper, 2003; Gaggioli, 2001). Perhaps of central importance, VEs offer multimodal interaction, where trainees can see, hear and feel the surrounding environment and interact in a natural, realistic setting. Such multimodal interaction within VEs offers unprecedented support of training tasks, where trainees may be exposed to complex training environments where their SA, including object recognition, spatial and temporal awareness (Hale, Stanney, Milham, Bell & Jones, in press [see chapter 4]), can be effectively engaged to maximize human performance within the VE and promote training transfer to real world tasks (Brooks, et al., 2002; Foreman, Stanton, Wilson, & Duffy, 2003; Kenyon & Afenya, 1995; Rose, Attree, Brooks, Parslow, Penn, & Ambihaipahan, 1998; Rose, Brooks, & Attree, 2002).

Yet, in order to fully realize their training potential it is essential to determine how best to leverage the multimodal capacity of VE training systems by determining how multimodal

training cues may advance the KSAs of trainees. In the real world, multisensory information is woven into the inherent properties of an operational setting. For VE training systems, designers must identify which qualities of the real world should be artificially crafted and incorporated into the system (Stanney, Cohn, Milham, Hale, Darken, & Sullivan, in press). This involves identifying which sensory cues are particularly appropriate when targeting specific training objectives, such as SA. In the latter case, designers must identify the essential environmental and feedback cues that support 1) accurate perception of elements in an environment, 2) comprehension of those elements in relation to one another, and 3) future prediction of events, which constitute the three levels of SA as defined by Endsley (1995). This paper focuses, in particular, on how best to incorporate tactile and vestibular cues into a complex VE training system to support SA development and enhance performance.

Background

Haptics interaction encompasses all aspects of touch and movement, and is bi-directional in nature in that either direct (e.g., head movement, locomotion) or indirect (e.g., movement via intermediary device such as a mouse) interaction will inherently create associated feedback cues (Biggs & Srinivasan, 2002). In the absence of movement, cutaneous sensors may be activated by a number of stimuli (e.g., vibration, pressure, temperature) and thus used as a sensory input channel to present information. Incorporating haptics interaction can increase development costs, as technology to support direct interaction within VEs is not widely available; thus it is important to identify those cues that are essential to support and those that can be forgone. Specific benefits to SA of incorporating haptic interaction and feedback are anticipated to be derived from: (1) providing object identification information that enhances knowledge about *who*

or *what* is in an environment (e.g., haptic feedback when hit a wall; increased temperature indicating danger), (2) providing spatial cues to enhance egocentric spatial awareness of *where* objects and self are within the environment and relationships between self and objects in the environment (e.g., providing vestibular cues of heading when using a head-mounted display [HMD] with head tracking; providing tactile cues spatialized on the torso to indicate where a target is relative to self), (3) providing time interval and/or pace cues to enhance temporal awareness of *when* events occur within the environment (e.g., the speed with which one moves through the environment), and (4) providing stress, either physical or psychological (e.g., cold, time pressure), to increase the realism of training and potential for development of appropriate coping strategies within the target operational environment, the latter of which is intended to alleviate or counterbalance stress responses (Hale, Stanney, Milham, Bell, & Jones, in press [see chapter 4]). The current study focuses on three of these; i.e., enhancing awareness of who, what, and where entities are relative to self and considering how haptics may affect stress conditioning. While there is research indicating that haptics cues may enhance spatial processing, little is known about its efficacy in stress conditioning.

Previous studies have shown that providing spatial information via tactile actuators on the torso resulted in a significant reduction in the percent of time participants spent in 'exposed areas' while increasing the percent of space cleared in a simplified building-clearing task (Lindeman, et al., 2005) and reducing the reaction time in directing visual spatial attention (Tan, et al., 2003). In addition, research has demonstrated that haptic displays can provide a spatial frame of reference within one's personal space (Mulgund, et al., 2002), enhance target pointing (Akamatsu, 1994), and enhance human performance under degraded visual conditions (Massimino & Sheridan, 1993). These studies investigated simple tasks; far less is known about

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the benefits of haptics in complex environments. One notable exception is work by Rupert (1997), which focused on using tactile actuators within complex aviation environments to enhance spatial awareness by providing cues to resolve spatial disorientation when visual and vestibular cues were absent or misleading. Results have demonstrated that the Tactile Situation Awareness System (TSAS) can improve navigation during complex mission conditions, increase SA, and provide more time to devote to other visual instruments and systems (McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004). In addition, decreased horizontal and height deviations (Cheung, Rupert, Jennings, Shultz, McGrath, & Craig, 2004) during flight have been observed when the TSAS was worn by pilots. Given that benefits have been seen for air navigation, the current study investigates if similar benefits in spatial awareness from haptic interaction can be realized during ground operations in complex environments.

When looking specifically at ground operations associated with military operations in urban terrain (MOUT), two key goals include negating enemy threat and avoiding casualties (Matthews, Pleban, Endsley, & Strater, 2000). How might tactile displays enhance the training of such activities within a simulated MOUT environment? Tactile cues could support the *who*, *what*, *where,* and *when* components of situational awareness. Specifically, to negate enemy threats, participants need to quickly and accurately assess *who/what* is in the environment (hostile or non-hostile), and respond appropriately by engaging hostiles and acknowledging non-hostiles. Dependent on distance to hostiles (i.e., *where* they are), soldiers may engage in long-range (engage with guns/tools), medium-range (engage with knives, punches, kicks) or close-range (grab each other) hand-to-hand combat techniques (Department of the Navy, 1999). Thus, accurate judgment of distance within a complex environment is required to determine which combat tactics should be employed. Given that VE training systems have known limitations in

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accurately representing depth visually (Witmer & Kline, 1998), metaphoric tactile cues could be put to use to indicate the distance to hostiles such that trainees could learn to differentiate distance ranges where the appropriateness of engagement tactics may differ.

To minimize casualties, participants need to avoid enemy line of sight (ELOS) and enemy fire. Tactile cues may be used as a sensory cue for indication of enemy fire – to identify *when* a participant is exposed to incoming fire - and the direction from *where* the shots are coming. This cue could provide spatial awareness of enemy location relative to self, and also impart a level of stress in the environment by providing a physical indication of incoming fire/threat exposure (physiological threat).

It is herein hypothesized that training with the presence of tactile cues indicative of incoming fire is expected to reduce ELOS exposure by increasing spatial awareness of enemy location (i.e., the critical who, what, and where within the MOUT environment). In addition, training with the presence of tactile cues that provide distance to target cues (i.e., indicate when participants are within target's range of vulnerability) is expected to provide increased spatial awareness that leads to decreased time required to neutralize targets and redundant fire (e.g., missed shots). Further, it is expected that rotational head tracking (i.e., vestibular cues that enhance orientation) will significantly reduce navigation errors, as more accurate heading information is provided than when interacting solely through a game device. A byproduct may also be that such training enhances overall performance as participants learn coping strategies to counterbalance negative reflexive (e.g., startle response) and behavioral (e.g., decreased concentration, increased anxiety) responses to the stresses of enemy threat. It is further expected that benefits seen during repeated training will transfer to a second virtual training environment. These hypotheses are further supported by a model of situational awareness developed under

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earlier work (Hale, et al., in press [see chapter 4]).   This model suggests that the spatial awareness component of SA can be enhanced via multi-sensory cues that support both static and dynamic distance and orientation information, including distance/orientation of entities in an environment relative to self (egocentric) and relative to a global space (exocentric), and that training with stressor cues can provide trainees with an opportunity to prepare for stressful operational scenarios by learning to control negative reflexive and behavioral responses to stress.

Method

To examine the hypothesis that tactile and vestibular cues enhance spatial awareness and stress conditioning in a complex training environment, an experiment was conducted in two parts. Part A examined the effectiveness of two distinct tactile display cues in enhancing spatial awareness within a virtual MOUT training environment: (1) a 'real world' tactile cue to simulate incoming fire, and (2) a metaphoric tactile cue to enhance visual distance judgments, and also examined the impact of rotational head tracking across training. Part B examined the transfer of spatial awareness skills from a training VE to a novel VE for each of the three cues used in Part A.

Participants

104 University of Central Florida students participated in this study. Of those, 80 participants (43M; 37F) completed the study (24 dropped out due to ill side effects). Participants ranged in age from 18 to 34 (mean=20.1; s.d.=3.68). All participants were in good health at the start of the experiment (Simulator Sickness Score [SSQ] of less than 7.68; Stanney, Kingdon, Graeber, & Kennedy, 2002), and had normal or corrected to normal vision. No significant differences in

spatial abilities, as assessed by two spatial abilities tests, were found between experimental groups.

Apparatus

Participants were seated in a laboratory for the entire study. During scenarios, participants donned a Virtual Research Systems V8 HMD with Sennheiser headphones and a six degrees of freedom (DOF) Intersense InertiaCube tracker that presented the visual environment, auditory cues, and monitored heading (for those in head tracked condition), and a tactile vest that provided spatialized tactile cues to participants. The vest was a neoprene vest with eight electromagnetic tactors (model C2 tactors from Engineering Acoustics, Inc.) affixed to the vest using Velcro attachments in two 360^0 arrays around the torso. Four tactors around the upper chest (located at approximately 1, 5, 7, 9 o'clock headings) were used to provide cues regarding incoming fire, and four tactors around the waist provided cues regarding distance to targets (activated when participants were within 3'-4' of target). Table 11 outlines the frequency and duration cycles for each tactor cue. These cues (including incoming fire) were not designed to simulate real world tactile experiences, but were instead included to examine the effectiveness of providing metaphoric information via the tactile sense regarding relative spatial information and stress. Each tactor was 30 mm in diameter and 8 mm deep, weighed 17 grams, and could be driven over a wide range of vibrotactile frequencies. In addition, the tactors could be driven individually, in groups, and/or sequentially. When activated, participants felt a 'buzzing' sensation at the tactor site, similar to that felt from a cell phone or pager set to 'vibrate' mode. The vest could be adjusted in size. Participants moved within the environment using a Saitek P2500 Rumble Pad gamepad controller.

Table 11: Tactile Vest Activation Descriptors

Cue Represented	Tactors Activated	Frequency	Pulse Rate (msec on; msec off)
Incoming Shot Cues (signal to identify when participant has been shot by enemy)	4 tactors around chest	258 Hz	100, 50, 100, 50, 100, 50, 100, 50, 100
Distance Cues (signal to identify when participant within range of target)	4 tactors around waist	258 Hz	100, 200, 100, 500 … (continues until target hit or participant exits range)

Questionnaires administered during the experiment included Spatial Abilities Metrics (Surface Development and Map Planning tests; Educational Testing Services, 1976a, b), the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum & Lilienthal, 1993), Presence Questionnaire (PQ; Witmer & Singer, 1998), NASA/TLX Workload Questionnaire (Hart & Straveland, 1988), modified Cooper-Harper Questionnaire to assess stress (Cooper & Harper, 1969; 0 – very low stress to 9 – very high stress), Situation Awareness Rating Technique (SART; Taylor, 1990) and Situational Awareness Global Assessment Technique Questionnaire (SAGAT; Endsley, 2000) that included questions regarding the current environment that targeted perception, comprehension and prediction of future events to assess subjective situational awareness.

Virtual Environment Training Scenarios

In Part A, there were four VE MOUT training scenarios and each had 7 rooms along a single level hallway in an indoor environment (see Figure 3). Each training scenario included 14 plate

targets (i.e., cardboard cutouts of hostile entities that could only be engaged within a set range of vulnerability [ROV]), five hostile computer generated forces (CGFs), three non-hostile CGFs, and one entrance to each room (all rooms had two plate targets and from one to three CGFs). Hostile CGFs could engage participants, and were a source of psychological stress (i.e., incoming fire).
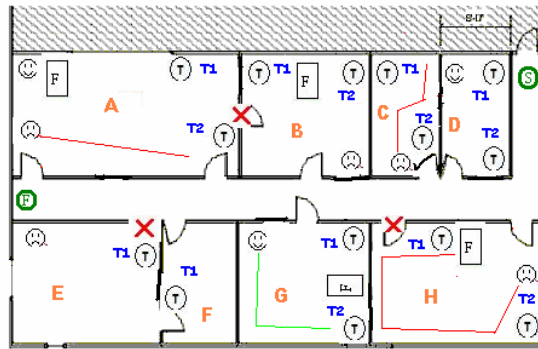
Figure 3: Example Room Layout for Training Scenarios. T represents plate target, happy face represents non-hostile CGF, sad face represents hostile CGF, F and D represent furniture and dividers respectively. S and F represent participant Start and Finish locations.

There was a single VE MOUT scenario used for baseline performance and Part B of the experiment, which had a 15 room single level indoor environment that included 28 plate targets, 7 hostile CGFs, 4 non-hostile CGFs, and 1 entrance to each room (all rooms had 2 plate targets and 0 to 2 CGFs [hostile and/or non-hostile]).

Tasks

Participants were immersed within a MOUT VE to complete a room clearing task. The task required participants to search through a series of rooms within a single floor indoor environment in an orderly fashion, clearing all rooms open to the hallway. Rooms were considered cleared when all hostile CGFs, non-hostile CGFs and plate targets were appropriately engaged. All participants wore an HMD throughout training. Those in the *no head tracking* condition used the gamepad to control their heading and translational travel within the environment. Those in the *head tracking* condition controlled their point of view (i.e., heading) within the VE by moving their head to activate the six DOF tracker to update the visual display and used the gamepad for translational control of the movement.

> Engage hostile CGF: Participants were required to fire upon hostile CGFs as soon as possible, as these entities posed a direct threat to self (i.e., could return fire). If participants came under fire, they heard gun shots (non-spatialized sound) and felt a tactile cue (spatialized to indicate which direction incoming fire was from) during baseline, training (if in tactile shot condition), and transfer scenarios. To successfully neutralize a hostile CGF (i.e., neutralize threat), participants had to aim their weapon and fire upon the hostile entity (i.e., press 'Fire' button). Hostile CGFs fell down when successfully neutralized.

> Acknowledge non-hostile CGF: Participants were required to acknowledge non-hostile CGFs after all hostile CGFs were neutralized. To successfully acknowledge a non-hostile CGF, participants had to aim their weapon at the CGF and press the 'Acknowledge' button. Non-hostile CGFs knelt when successfully acknowledged.

Engage plate target: Participants were required to neutralize plate targets as quickly as possible after the above two tasks were completed. To successfully neutralize plate targets, participants had to be within 3'-4' of the target and within +/- 45^0 of full frontal of each target, then aim their weapon at and fire upon the plate target. Plate targets turned red when successfully neutralized.

Procedure

Pre-exposure activities included an informed consent form, demographics form, spatial abilities tests and SSQ. Participants were randomly assigned to one of eight experimental groups. Each group was defined by the type(s) of cues provided (head movement [on/off]; tactile distance cues from targets [on/off], tactile incoming shot cues [on/off]). Participants were given a training session to familiarize themselves with the VE tasks via a slide presentation (i.e., covered room clearing techniques including how to consider room characteristics such as size, shape, and location of potential threats, entry 'pie' techniques, visual room scanning techniques, and avoiding danger areas, such as windows and doorways, as well as moving quickly to enter the range of vulnerability [ROV] of plate targets to minimize time in plate target line of sight and holding fire until within ROV to minimize redundant fire). Participants then completed a familiarization session within the VE to gain experience on how to use the gamepad to move self through the virtual environment, followed by a baseline test condition, during which participants performed the room clearing task within the 15 room VE facility with their assigned interaction mode (head tracking on or off). After the baseline VE interaction, participants completed the SSQ, PQ, workload and SART questionnaires.

Participants next completed four training scenarios in the 7 room VE, which constituted Part A of the experiment. Participants completed the four training scenarios in random order. Each scenario was paused three times, during which the SAGAT questionnaire was administered. Pauses took place in the same spatial location for each participant (independent of time elapsed) to ensure answers could be compared across groups. Throughout each scenario, participants were asked to move down the hallway clearing each room in order by (1) engaging hostile CGFs, (2) acknowledging friendly CGFs, and (3) engaging plate targets. Between each scenario, participants were given up to a five minute break. At any time during the session, participants were free to terminate participation early at their discretion without penalty - 24 dropped out prior to study completion due to ill effects of immersion. After the fourth training condition, participants completed the SSQ and PQ questionnaires.

During Part B of the experiment, participants who completed training sessions engaged in a transfer scenario within the 15 room VE facility as used in baseline (but with different location of entities and furniture) using the same interaction mode (head tracking on or off) as during baseline and training. The scenario was paused three times to administer the SAGAT questionnaire. At the end of the scenario, participants completed the SSQ, PQ, workload and SART questionnaires. Differences from baseline were used to evaluate training transfer.

Experimental Design

Part A

For evaluation of performance during training scenarios, a 2x2x2x4 (head tracking x incoming shot x distance x scenario) factorial with repeated measures on one factor experimental design

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was implemented. Between-subject factors included head tracking (none, 6 DOF), tactile incoming fire cues (not present, present) and tactile distance cues (not present, present). The within-subject repeated measures factor was training scenario (1, 2, 3, 4).

Dependent variables included subjective workload (NASA/TLX), stress (Modified Cooper-Harper), SA (SART, SAGAT), and performance (navigational performance, task accuracy, task efficiency). A repeated measures ANOVA was run for each performance metric to assess differences between experimental groups across scenarios. Post hoc analyses (e.g., least squares difference) were completed on significant main effects.

Part B

To evaluate training transfer, the experimental design was a 2x2x2 (head tracking, tactile incoming fire cues, tactile distance cues) full factorial between-subjects design. A 3-way ANOVA on the differences between the baseline and transfer was used to assess the effectiveness of the three haptics cues on SA, workload, presence and transfer performance.

Results

Part A

Across successive training scenarios, significant improvements were evident in performance time, accuracy, the number of times spent in danger zones, and the number of errors committed (Table 12). The duration participants were in a room ($F(3,76)=3.46$, $p<.02$), the time participants spent in a room until plate targets were neutralized ($F(3,76)=4.92$ $p<.003$), the time participants spent in plate target ROV ($F(3, 76)=3.69$, $p<.02$), and the time spent in ELOS before plate targets were neutralized ($F(3,76)=9.01$, $p<.001$) significantly differed across scenarios. Post-hoc

analyses revealed that participants spent significantly (LSD>0.80, p<.03) less time in a room during scenario 3 compared to scenarios 1 (14.5% less on average) and 2 (9.4% less on average) and significantly less time in a room before plate targets were neutralized during the later three scenarios (LSD>0.82, p<.001) compared to scenario 1 (12.1% less on average in scenario 2; 12.5% less in scenario 3; 14.7% less in scenario 4). In addition, participants spent significantly less time in plate target ROV during scenarios 3 (20.5% less on average) and 4 (25.0% less on average) compared to scenario 1 (LSD>0.08, p<.01). The number of redundant shots taken within a plate target's ROV significantly differed across training scenarios. Post-hoc analyses revealed that significantly fewer redundant shots were taken during scenario 3 compared to the first two scenarios (LSD>1.50, p<.02; 22.9% less on average for scenario 1; 20.6% than scenario 2). The number of times participants entered ELOS ($F_{(3,76)}=7.99$, p<.001) and the number of times participants were in ELOS greater than two seconds ($F_{(3,76)}=7.89$, p<.001) significantly differed across scenarios. Participants entered ELOS fewer times in scenario 4 compared to the other 3 scenarios (LSD>6.68, p<.01; 15.0% on average less than scenario 1; 9.5% than scenario 2; 7.7% than scenario 3). In addition, significant improvements were seen across scenario 1 and 3 (LSD=7.371, p<.01). In scenario 4, participants spent fewer times in ELOS greater than 2 seconds duration compared to the first three scenarios (LSD>3.49, p<.01; 12.6% on average less than scenario 1; 12.4% than scenario 2; 7.5% than scenario 3). Finally, the number of errors as captured by the number of friendly kills ($F_{(3,76)}=3.37$, p<.02) and the number of times participants were shot by enemy fire ($F_{(3,76)}=7.38$, p<.001) significantly differed across scenarios. Scenario 3 had a significantly lower average friendly kill rate than scenarios 1 and 4 (LSD>.10, p<.05; 68.8% on average less than scenario 1; 80.0% than scenario 4).

Table 12: Performance Results across Scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Performance Efficiency (s)				
Average time in room until plate target neutralized* (n=77)	5.05[a]	4.44[b]	4.42[b]	4.31[b]
	(2.20)	(2.05)	(1.82)	(1.45)
Average time in PT ROV* (n=77)	0.44[a]	0.39[a,b]	0.35[b]	0.33[b]
	(0.31)	(0.31)	(0.21)	(0.19)
Average time in room* (n=77)	9.33[a]	8.81[a]	7.98[b]	8.48[a,b]
	(3.03)	(3.74)	(2.51)	(4.94)
Time in PT ELS until PT neutralized* (n=77)	6.97[a]	6.13[b]	5.96[b]	5.69[b]
	(2.35)	(2.56)	(2.53)	(1.73)
Performance Accuracy				
Number of redundant shots* (n=77)	14.87[a]	14.44[a]	11.47[b]	13.00[a]
	(15.26)	(16.00)	(11.03)	(12.66)
Navigational errors (n=70)	0.67	0.67	0.59	0.59
	(1.00)	(0.99)	(0.97)	(0.92)
Percent PT neutralized (n=77)	92.10	90.95	91.84	92.49
	(10.12)	(12.20)	(10.79)	(9.89)
Percent hostile CGFs neutralized (n=77)	90.65	89.09	89.61	86.49
	(13.61)	(16.72)	(14.37)	(17.00)
Number of times in danger zones				
Number of times in ELOS* (n=77)	92.86[a]	87.26[a,b]	85.51[b]	78.95[c]
	(25.36)	(25.36)	(20.91)	(18.51)
Number of times in ELOS >2sec* (n=77)	48.39[a]	48.30[a]	45.71[a]	42.30[b]
	(10.73)	(12.65)	(9.62)	(9.33)
Errors				
Number of friendly kills* (n=77)	0.16[a]	0.13[a,b]	0.05[b]	0.25[a]
	(0.40)	(0.50)	(0.22)	(0.59)
Number of missed shots (n=77)	12.01	10.10	8.88	8.77
	(23.24)	(10.03)	(7.59)	(7.41)
Number of times shot* (n=77)	16.65[a]	13.36[a]	12.90[a]	8.79[b]
	(17.09)	(12.07)	(12.74)	(8.28)

( ) denotes standard deviations
*denotes significance at p<.05 level

Participants were shot significantly fewer times during scenario 4 compared to the first three scenarios (LSD>4.13, p<.003; 47.2% on average less than scenario 1; 34.2% than scenario 2; 31.9% than scenario 3).

In addition to significant differences found from repeated training, significant main effects were found for the tactile and vestibular cues examined during this experiment. Tactile metaphoric cues that indicated when participants were within a plate target's ROV were related to a significant decrease in the number of missed shots (F(1,76)=4.53, p<.04) and the number of redundant shots when participants were within ROV (F(1,76)=10.15, p<.002). Figure 4 shows that across successive training sessions, those who trained with distance cues took less redundant shots than those with no distance cues, and showed improvement in the number of redundant shots, while those without distance cues did not show a similar pattern of improvement. No significant differences in performance time were found based on the presence of the ROV cues.
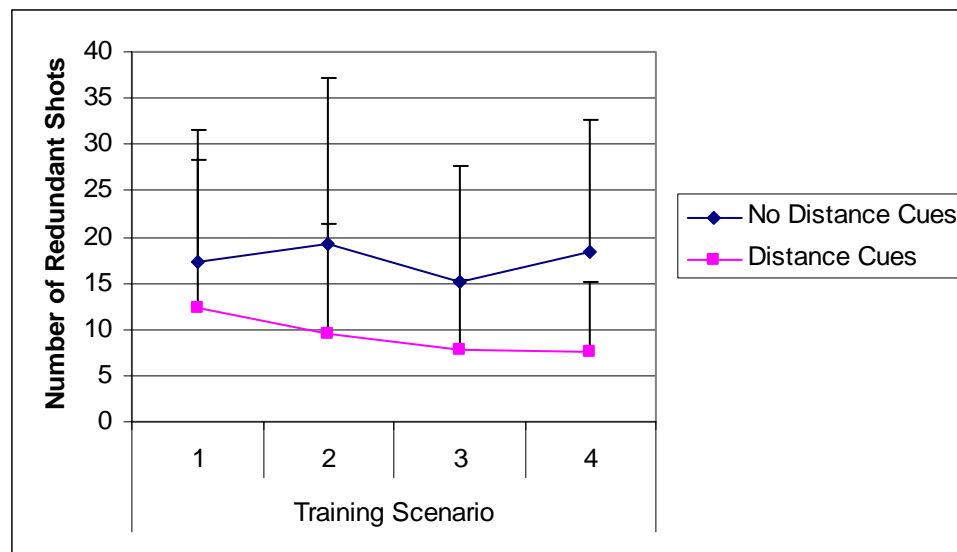

Figure 4: Number of Redundant Shots across training scenarios for participants who trained with distance cues versus that those who trained without distance cues

Tactile cues that indicated incoming fire were related to a significant decrease in the number of shots taken from the hall (i.e., prior to entering the room; $F(1,76)=4.77$, $p<.04$). No significant differences in performance time were found based on the presence of the incoming fire cues. The addition of rotational head tracking was related to a significant increase in the number of times participants entered ELOS ($F(1,76)=11.77$, $p<.001$) (see Figure 5), but did not significantly impact the number of times participants were in ELOS greater than 2 seconds. In terms of accuracy, a significantly lower percent of plate targets were neutralized when head tracking was present ($F(1,76)=5.66$, $p<.02$), although both head tracking and no head tracking conditions produced accuracies over 90%.
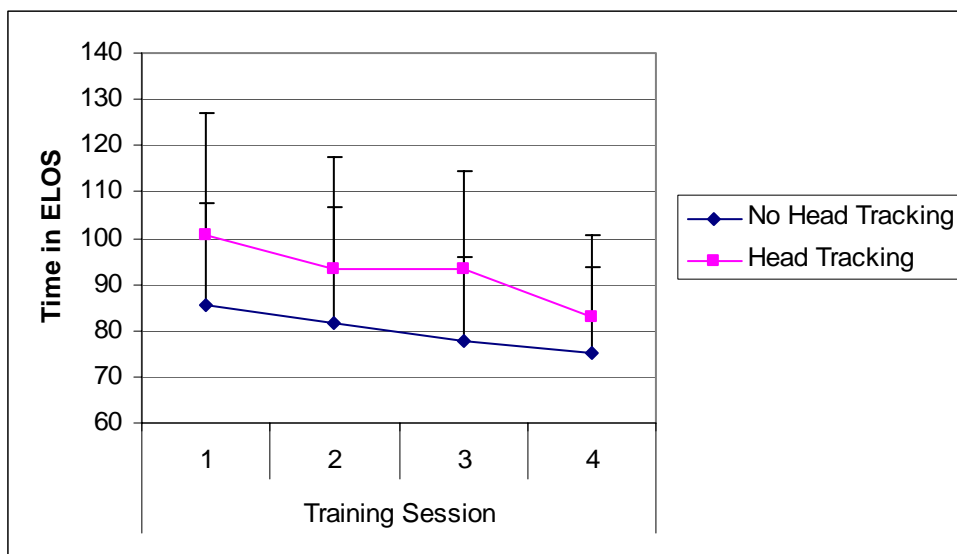
Figure 5: Number of times participants entered ELOS across training sessions

In addition to the main effects discussed above, interaction effects were evident from the data between head tracking and incoming shot cues for average time in room ($F(3,76)=5.38$, $p<.03$) and average time in plate target line of sight until neutralized ($F(3,76)=4.91$, $p<.03$). With head tracking, participants spent 19.9% less time, on average, in rooms when shot cues were

provided during training than when no shot cues were provided. Of participants in the no head

tracking condition, those who trained with incoming shot cues spent 11.7% more time in room,

on average, than participants who received no incoming shot cues during training (see Figure 6).
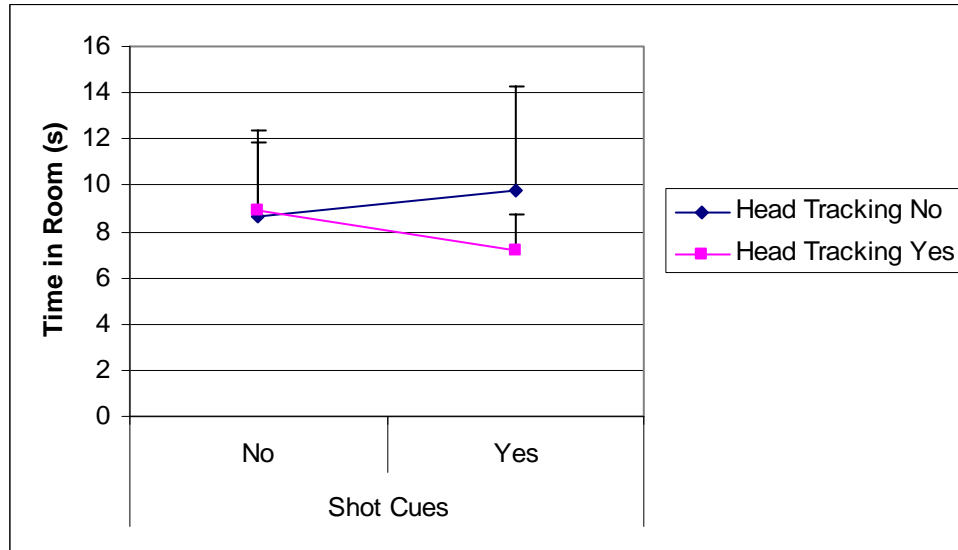
Figure 6: Average time in Room until Plate Target Neutralized

A second interaction effect occurred between training with distance cues and training

with incoming fire cues for the percent of hostile CGFs neutralized ($F(3,76)=5.43$, $p<.03$) and

average time to shoot ($F(3,76)=4.12$, $p<.05$). Figure 7 shows that training with either no tactile

cues or both cues in combination resulted in the highest percentages of CGFs neutralized across

training scenarios 1, 2 and 3 (5.3% higher than other training conditions, on average). However,

training with both cues in combination showed a steady decline in accuracy across training

scenarios (from 93.68% in scenario 1 to 84.21% in scenario 4). Figure 8 shows that while

incoming shot cues had little effect on time to shoot when distance cues were present, they had a

larger effect when presented in isolation (compared to no incoming shot cues; an improvement, on average, of 20% time to shoot).

Figure 7: Percent hostile CGFs neutralized

Figure 8: Average time to Shoot

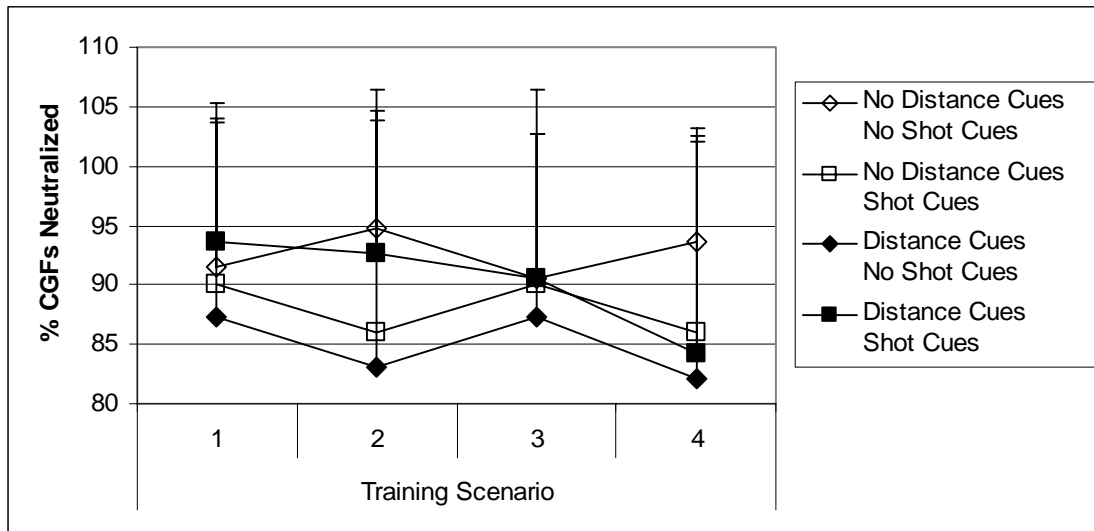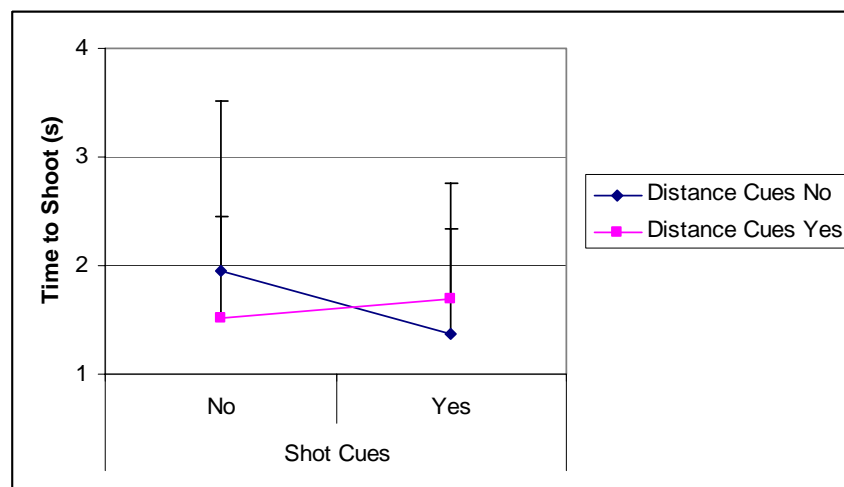Average subjective stress, as measured using a Modified Cooper-Harper scale, ranged from 2.7 to 3.4 out of 9.0 across scenarios, and significantly differed across the four training scenarios ($F_{(72,3)}=7.40$, $p<.001$). Post-hoc analyses revealed that stress was significantly higher

during scenario 4 compared to earlier scenarios (LSD>.28, p<.003; 17.7% higher on average than scenario 1; 16.8% than scenario 2; 9.3% than scenario 3); with scenario 3 having 9.2% higher, on average, reported stress than scenario 1 (LSD=.29, p<.001).

The three cues included in this study did not significantly influence stress, SSQ scores, SART ratings or average workload; however a significant interaction between all three factors occurred for the SAGAT questionnaire ($F(1,79)=14.04$, $p<.01$; Figure 9). The training scenarios that included no head tracking and incoming shot cues increased the percent of correct SAGAT answers; being 59.1% on average higher than when head tracking and no incoming shot training cues, 50.7% higher than when head tracking and incoming shot cues, and 49.3% than no head tracking and no incoming shots. Benefits were 52% greater when distance cues were also provided, in addition to incoming shot cues with no head tracking.
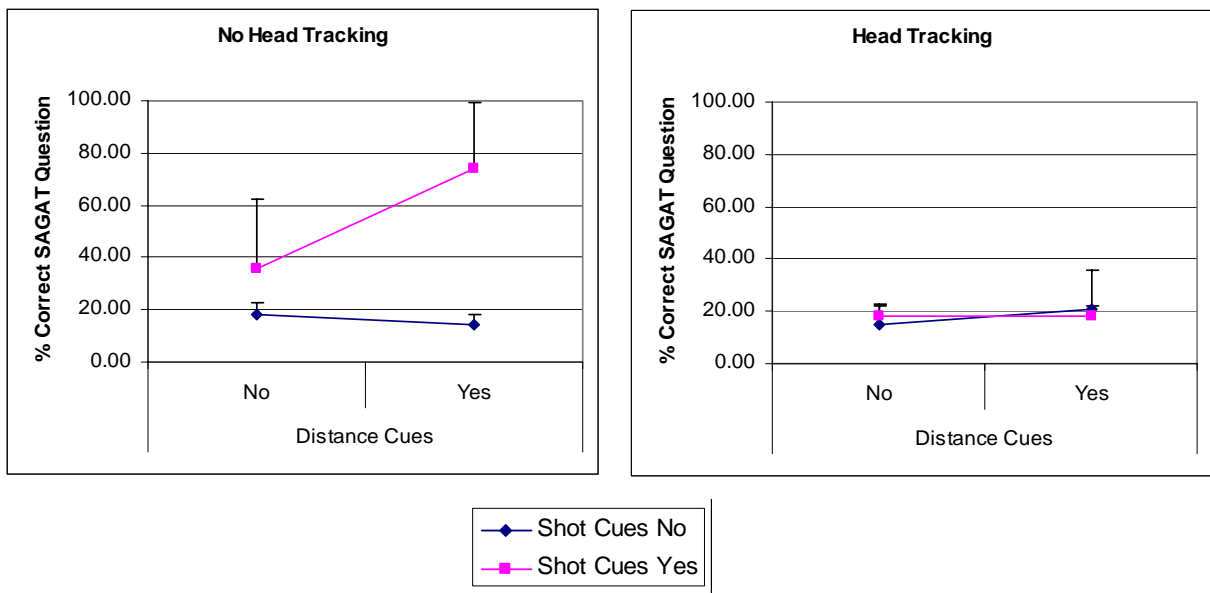
Figure 9: Percent Correct Scores from Modified SAGAT Questionnaire

In addition, a significant interaction ($F(1,78)=4.28$, $p<.05$) occurred between incoming shot cues and distance to plate target cues for frustration as measured on the NASA/TLX

questionnaire. As Figure 10 shows, the highest frustration scores occurred when both distance and incoming shot cues were provided during training, where frustration scores were 30.0% to 34.3% higher than the three other experimental conditions.
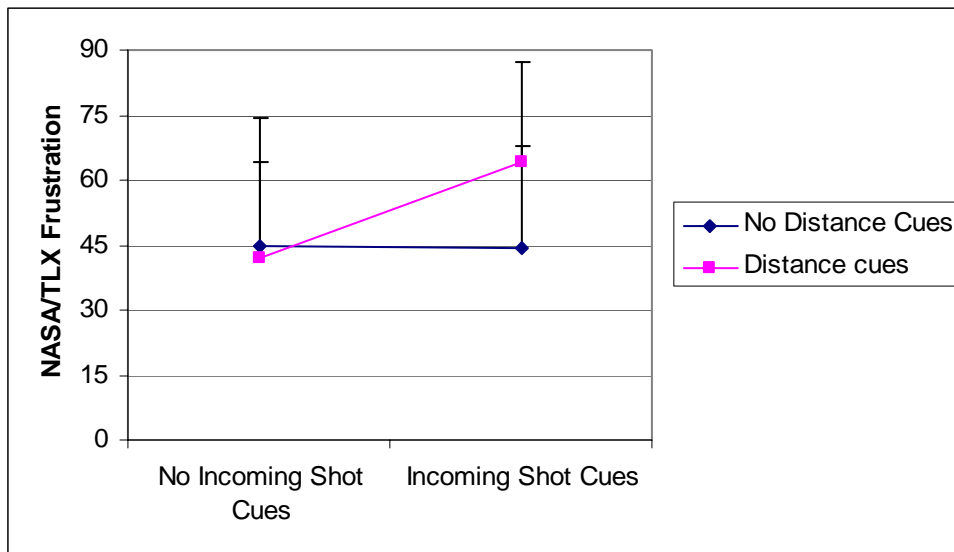
Figure 10: NASA/TLX Frustration scores post-training

Part B

Part B examined differences between post-training and baseline scenarios. Significant main effects were found on task performance across the three independent variables. Participants who trained with distance cues showed a significant decrease in the number of times ELOS was entered $(F1,79)=4.16$, $p<0.5$; 55.7% less on average), and the number of times in ELOS longer than 2 seconds $(F(1,79)=4.06$, $p<.05$; 48.2% less on average) from baseline to post-training scenario compared to those who did not receive distance cues during training. Participants who trained with incoming shot cues showed a significant decrease in the time spent in CGF ELOS

within a room (F(1,79)=12.58, p<.001; 80.4% less on average) compared to participants who received no shot cues during training. Participants with no head tracking showed a significantly greater decrease in average time in room from baseline to post-training scenarios (F(1,79)=7.02, p<.010; 32.6% less on average) compared to participants with head tracking. Figure 11 shows that during baseline, participants with head tracking spent significantly less (F(1,79)=5.64, p=.02) time in room compared to those with no head tracking. During the transfer condition, there was no significant difference in time in room between the two groups. In addition, participants with head tracking showed a significant difference (F(1,79)=5.68, p<.02) from baseline to transfer condition in the number of shots they took from the hall (average increase of 0.625 shots) compared to participants with no head tracking who showed an average decrease of 0.05 shots from baseline and post-training performance.
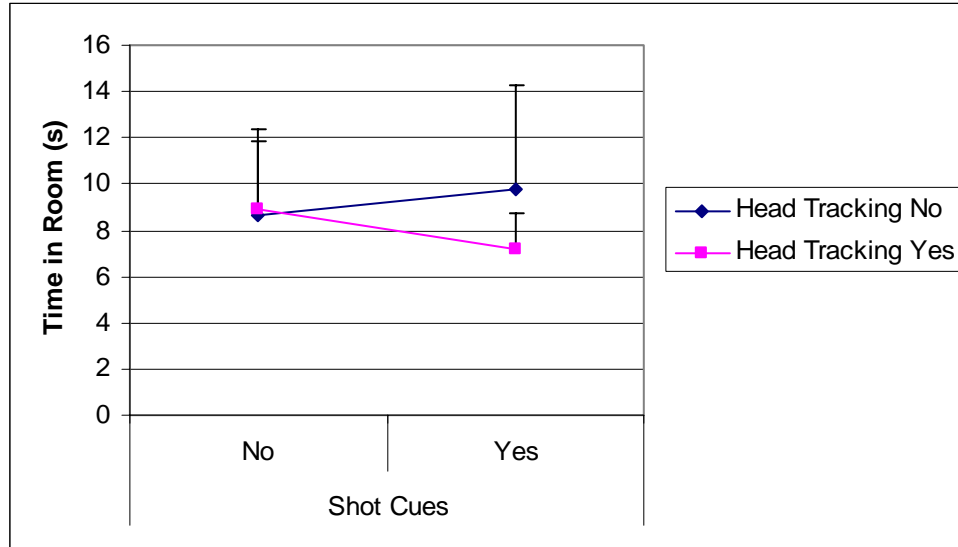
Figure 11: Average time in room during baseline and transfer conditions

An interaction effect between head tracking and distance cues occurred for the difference in the number of friendly kills from baseline to post-training scenarios (F(1,79)=8.731, p<.01;

Figure 12). Participants with no head tracking showed a 60% decrease in friendly kills from baseline to transfer scenario when no distance cues were provided, while those with distance training cues showed little difference in performance. Participants with head tracking showed an opposite effect, where those that trained with distance cues showed an 100% decrease (from average of 0.3 to 0 friendly kills) in errors, while those that did not train with distance cues showed an 100% increase (from an average of 0 to 0.45 friendly kills) in errors.
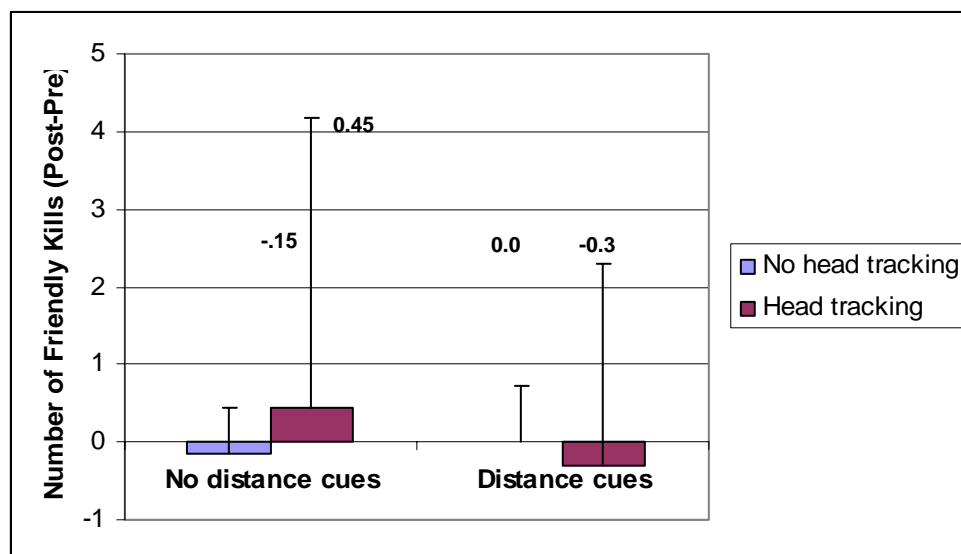
Figure 12: Difference in Number of Friendly Kills between Baseline and Post-training Scenario

Some workload variables as scored using the NASA/TLX questionnaire were significantly impacted by the three independent variables examined in this study. Participants who received tactile cues indicating distance to targets reported a slight decrease (1.6% on average) in effort during the transfer scenario compared to baseline, which significantly differed $(F(1,78)=4.07, p<.05)$ from the reported 12.0% average increase in effort for those who received no tactile cues indicating distance (Figure 13).

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Figure 13: NASA/TLX Effort Score (Post-Pre)

Participants who received incoming shot cues reported a significantly ($F_{(1,78)}=4.04$), $p<.05$) greater increase (12.8% on average) in total workload from baseline to transfer scenario compared to participants who received no incoming shot cues (3.4% on average).

Frustration ($F_{(1,78)}=7.30$, $p<.01$) and effort ($F_{(1,78)}=4.58$, $p<.04$) significantly increased (11.4% on average for frustration and 13.6% on average for effort) from baseline to transfer environment for participants who had head tracking as compared to those with no head tracking who rated slight decreases in both frustration (17.0% on average) and effort (1.8% on average) in the transfer environment compared to baseline (Figure 14).
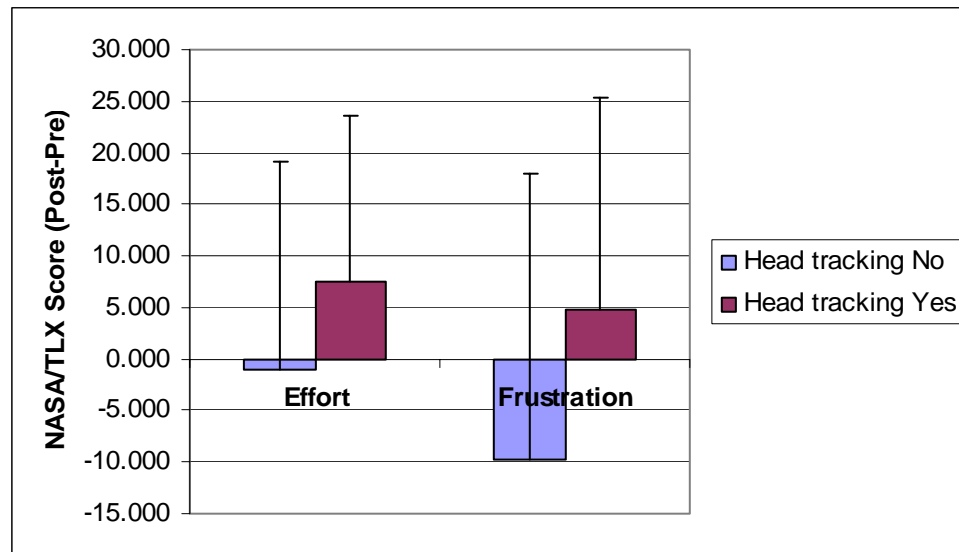
Figure 14: NASA/TLX Scores for Frustration and Effort (Post-Pre)

Head tracking and incoming shot cues showed a significant interaction effect on the SART Resource Supply Score ($F_{(1,78)}=4.87$, $p<.04$). As shown in Figure 15, participants with head tracking and incoming shot cues reported an 8.0% increase, on average, in SART Resource Supply from baseline to transfer scenario, while participants with no head tracking yet incoming shot cues reported a 13.0% increase, on average. However, those with head tracking and no incoming shots reported a reduction (10.0% on average) in Resource Supply from baseline to transfer scenario, while those with no head tracking or incoming shot cues reported an increase (24.0% on average) in Resource Supply across the two scenarios.
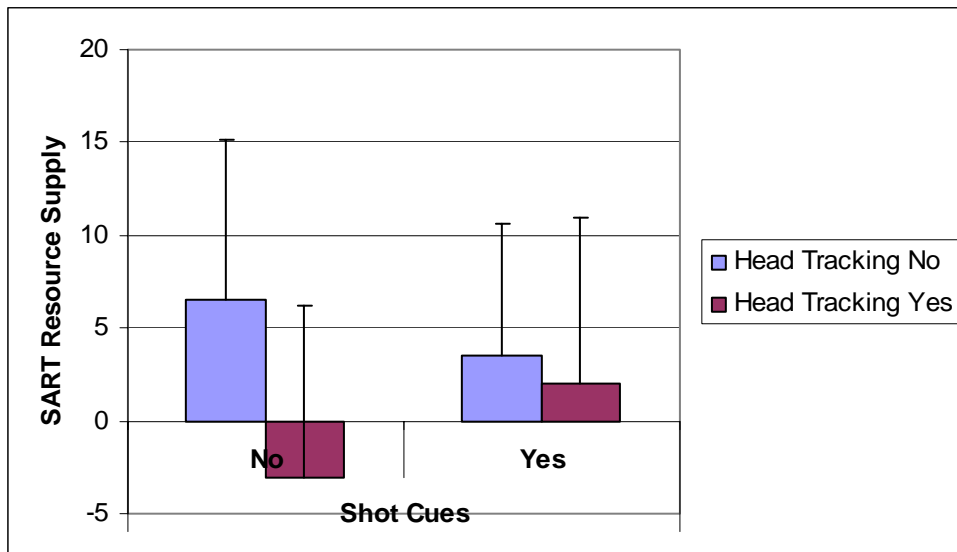
Figure 15: SART Resource Supply Scores (Post-Pre)

A second significant interaction effect was seen for the SART Resource Demand score (sum of instability, complexity and variability scores; Shamo, Dror & Degani, 1999) between incoming shot cues and distance to target cues (F(1,78)=4.34, p<.05). As Figure 16 shows, participants reported a significantly higher increase in Resource Demand from baseline to transfer scenario when either both training cues (34.5% on average) or no training cues (32.1% on average) were included during training in isolation; a smaller increase was seen when incoming shot cues (10.6% on average) were provided in isolation and when distance cues were provided in isolation during training (13.3% on average).
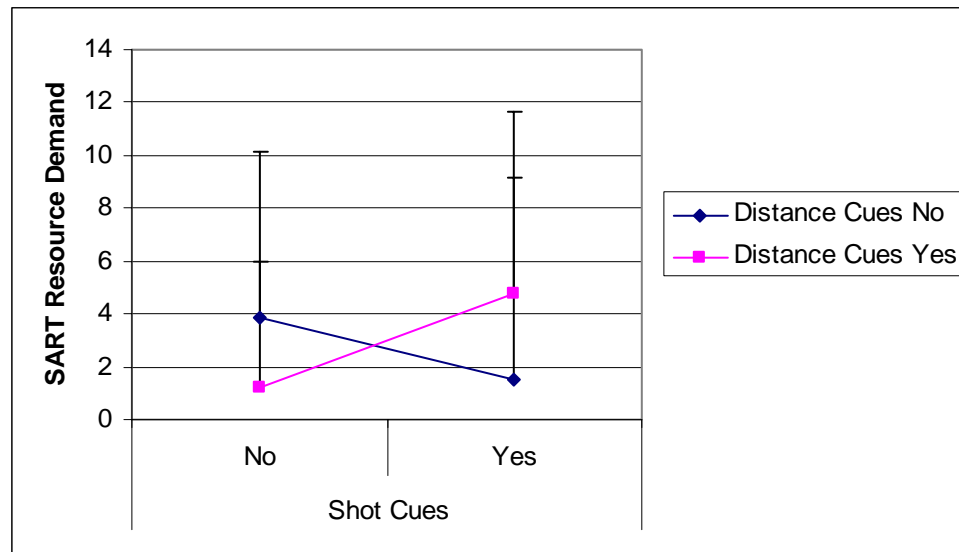
Figure 16: SART Resource Demand Scores (Post-Pre)

Post to pre differences in SAGAT, stress, SSQ and sense of presence questionnaires were not significantly impacted by the tactile and vestibular variables examined in this study.

Discussion

This study examined the benefits associated with two distinct tactile feedback cues and using rotational head tracking as an interaction technique (combined with translational movement control through a gaming device). One tactile cue provided metaphoric cues to enhance distance judgment in a training environment, while the second provided environmental fidelity (incoming shot cues). The haptic interaction technique was designed to increase interface validity via rotational head tracking (Waller, et al., 1998). The primary question considered how virtual training environments, and the training cues provided therein, may be used to enhance spatial awareness across training sessions and enhance training transfer to a novel environment.

Part A

Results from Part A showed that significant benefits were evident in performance time, accuracy, the number of times spent in danger zones, and the number of errors committed across repeated training. Performance efficiency and accuracy showed significant improvements by scenarios 2 or 3 (8.8% improvement on average by scenario 2; 16.2% improvement on average by scenario 3), while the number of times in danger zones and errors showed significant improvements by scenarios 3 or 4 (26.1% improvement on average by scenario 3; 25.5% improvement on average by scenario 4). Thus, 4 repeated trials appeared to provide substantial improvements in training the specific KSA inherent in this room-clearing task. In terms of subjective stress, participants reported an increase across scenarios, with significantly higher stress levels during scenario 4 than earlier scenarios. However, even during scenario 4, average ratings were less than 3.5/9, indicating that stress did not reach high levels. This increase in stress could represent an increase in ecological validity, as the participants may have become more aware of the imminent dangers in the environment, how to detect them, as well as how to avoid them, thereby perceiving more stress. Further research is necessary to identify the source of this increase in stress and how to capitalize upon it during training.

In the current study, tactile and vestibular cues were implemented within a training environment to provide information to enhance knowledge associated with room clearing. Cues that indicated distance to targets were designed to enhance spatial knowledge by letting trainees know when they were 'in range' of a plate target (3'-4' away). This metaphoric training cue was only provided during training scenarios. Studies have shown that visual depth perception in virtual environments does not match that in the real world (participants tend to underestimate in

a virtual world; Witmer & Kline, 1998). It was expected that trainees who received the additional metaphoric tactile distance cue would learn to associate the visual distance from plate target when 'in range', and be more efficient in neutralizing plate targets (i.e., take fewer shots to neutralize) across successive training scenarios. Results from Part A of the current study supported expected results, as participants who trained with metaphoric distance cues were more accurate in shots fired (i.e., 40.4% less missed shots, on average) as compared to those who trained without such cues. In addition, these participants showed consistent improvement in the number of redundant shots taken across successive training sessions, reducing the number of redundant shots by 39.5% by scenario 4. In contrast, participants who were not exposed to tactile distance cues took significantly more redundant shots across all scenarios, and did not show any learning across scenarios. Thus, repeat training with metaphoric distance cues appears to have been effective in enhancing efficiency of ammunition use by notifying participants when they were within the ROV (i.e., enhancing spatial awareness), indicating when fire would engage threat. Improved performance across training scenarios could be attributed to (1) over-reliance on the tactile cues provided (i.e., where tactile cues became a 'training crutch'; participants waited until tactile signal received before shooting) or (2) enhanced visual distance judgments whereby participants associated the appropriate target vulnerability range from targets to the visual distance cues displayed. Part B will examine whether training transfer occurred, which would support the second line of reasoning, where participants were able to learn to judge distance from plate targets using visual cues alone.

     Cues that indicated incoming fire provided additional information (beyond a spatialized gunshot sound) that a trainee was being shot at (i.e., was in ELOS) and these cues were present during the baseline and transfer scenarios. This was done to ensure baseline and transfer

environments included ecological validity of incoming shots as would be present in the real world. It was expected that participants who also received these cues during training would have more opportunity to gain spatial knowledge from shot cues, and to develop adequate coping strategies to negate negative behavioral responses (e.g., startle reflect that may increase reaction time) related to incoming shot cues.

This incoming shot cue represented a real world haptic sensation of being shot, although it was tactile sensors that were activated instead of norciceptors (i.e., pain receptors). Research has shown that participants are quicker to respond, and more accurate in spatial localization when a spatialized haptic cue is provided compared to a spatialized audio cue (Terrence, et al., 2005), however it is not clear how repeat exposure to such cues affect performance in a complex virtual training environment. It was anticipated that participants who trained with incoming fire (as opposed to those with no incoming fire cue) would spend significantly less time in ELOS across successive training scenarios because they were given an additional cue identifying when they were in a danger zone. While a significant main effect was not seen for time in danger zones in the current study, improved task efficiency was seen when incoming shot cues were included in training for those with head tracking. Participants with head tracking spent significantly less time in room (19.9% less on average) and time in plate target ELOS before neutralization (19.2% less on average) compared to participants with no head tracking when incoming shot cues were provided during training. This may have resulted from more accurate spatial information provided by incoming shot cues (i.e., location of enemy CGFs) combined with vestibular cues created from head tracking that can provide an increased awareness of heading (Loomis, et al., 1995, Bakker, et al., 1998; however, also see refuting evidence by Ruddle & Peruch, 2004). The spatial awareness benefit was not apparent when indirect haptic control over movement was used

(i.e., no head tracking). The lesson-learned from this result is that spatial awareness benefits from a single point indicator may be impacted by the interaction mode adopted in the virtual environment. Using a more natural interaction mode (i.e., direct interaction where heading in environment is indicated by head direction) may allow for quicker investigation of a single point indicator of spatial location as opposed to indirect movement, thereby rendering such cues more effective.

In addition, results showed that training with incoming shot cues resulted in significantly fewer shots taken from the hall (25.9% less on average). This could indicate that incoming shot cues provided better awareness of which hostile CGFs were within line of sight from the hall, and only those within line of sight were targeted. Thus, receiving tactile cues representative of incoming fire appears to have significantly impacted room-clearing procedures and spatial awareness by encouraging participants to implement correct room-clearing strategies (e.g., reading room, 'pie' technique, avoiding danger areas) that resulted in less time in room for those with head tracking, and fewer shots taken from the hall. The lesson-learned from this result indicates that additional cues indicative of target spatial location (i.e., location of CGFs that are visible from the hall) may enhance spatial awareness of enemy location relative to self and improve room-clearing strategies and performance (e.g., engage more enemies from hallway). In a more general sense, such cues may enhance egocentric orientation and distance awareness and result in improved performance in target location within a complex, multi-room virtual environment.

A significant interaction effect occurred between incoming shot and distance to target cues for the percent of hostile CGFs neutralized, average time to shoot and subjective frustration. This finding is not surprising given that distance cues focused attention on plate targets, while

incoming shot cues focused attention on hostile CGFs. Training with only distance to target cues resulted in the lowest percent CGFs neutralized, which may be due to emphasis on plate target neutralization as opposed to CGF neutralization. With no additional haptic cues, some of the highest percent CGFs were neutralized across the four scenarios, with this condition showing the highest accuracy during scenario 4. This could indicate that in the absence of additional information, CGFs were considered high priority and dealt with accordingly. When both incoming shot and distance haptic cues were provided, accuracy over ninety percent was seen across the first three scenarios, yet performance decreased from scenario 1 (93.7% CGFs neutralized) to scenario 4 (84.2% CGFs neutralized). Thus, while performance was high during initial scenarios, where incoming shot cues may have taken precedence and focused attention on hostile CGFs, performance during scenario 4 was closer to that observed for participants who received only distance cues. Over repeat trials, participants with both cues may have acclimated to the incoming shot cues over successive training scenarios, and focused more heavily on plate targets, ensuring they were in the correct range to engage these targets instead of focusing on hostile CGFs.

Looking at time to shoot data, all groups showed increased performance from scenario 1 to scenario 4, with those that received either incoming shot or distance tactile cues in isolation showing the fastest shoot times during scenario 4. Participants who received both incoming shot and distance tactile cues showed the slowest shoot times across all scenarios.

In addition, frustration was rated significantly higher after training when both tactile cues were provided compared to conditions having no cues or one cue in isolation. Thus, having both tactile cues present, which directed attention to two types of enemies simultaneously (i.e., incoming shot cues: hostile CGFs; distance cues: plate targets), may have distracted participants

during training scenarios and caused increased frustration and decreased performance (e.g., time to shoot). Some participants reported focusing on entering a plate target's ROV in the room when they were "distracted" by incoming shot cues. Participants in this condition appear to have either chose to ignore incoming shot cues and neutralize the plate target (incorrect focus) or turn to address the hostile CGF, which invariably increased response time to both targets (as CGF should have been dealt with prior to plate target, if rules of engagement were followed).

Thus, having tactile cues that increased spatial awareness for either plate targets or CGFs improved response time, yet decreased performance and increased frustration were seen when cues were simultaneously provided in training. Taken together, the lesson-learned from these results is that caution is advised when implementing cues that, in isolation, focus attention on entities that are not of highest priority. In the current study, distance cues focused attention on plate targets, which were second in priority to CGF enemies, and resulted in a decreased percent of CGFs neutralized. Providing both cues appears to have decreased focus on the higher priority CGFs over successive training scenarios, and showed increased shoot times and subjective frustration compared to other training conditions. Thus, for this specific application it may have been better to implement tactile cues only in isolation during training so each scenario focused attention on one main goal: enhancing CGF localization and neutralization by providing incoming shot cues, or enhancing distance estimation by providing metaphoric distance cues to plate targets. By providing multiple scenarios that cover individual goals, greater benefits may have been seen across both CGF and plate target performance towards the end of training. In general, designers must critically assess specific training goals and ensure training cues, in isolation or combination, maintain training goal priority and do not lead to increased attention

splitting across high priority targets, which may lead to increased frustration and decreased performance. To do this, the current study suggests that principles presented in Table 13.

Table 13: Design guidelines for incorporating spatial tactile cues in repeated virtual training scenarios to enhance spatial awareness.

Metaphoric distance cues can enhance performance accuracy across successive training scenarios.
Within training, instructors should encourage trainees to not rely on metaphoric cues as a 'training crutch', and instead learn to interpret other multimodal cues as an indication of correct performance (e.g., correct spatial positioning).
Spatial awareness benefits from a single point indicator may be impacted by the interaction mode (e.g., direct movement using head tracking vs. indirect movement using an interaction device) adopted in the virtual environment.
Additional cues indicative of target spatial location can enhance spatial awareness of enemy location relative to self and improve room-clearing strategies and performance (e.g., engage more enemies from hallway).
Caution is advised when implementing multiple cues that, in isolation, focus attention on entities that are of differing priority, as this may lead to decreased performance for higher priority targets, increased overall response times, and increased frustration.

Rotational head tracking provides enhanced interface fidelity (Waller, et al., 1998), but has also been associated with higher incidences of cybersickness (Stanney, et al., 2002). In a complex training environment that is focused on enhancing higher-order knowledge (e.g., avoidance of danger areas, procedures), the impact of adding 6 dof head tracking is unknown. Results from Part A of the current study showed that while participants with head tracking entered ELOS significantly more times across all training scenarios (13.7% more on average), there was no significant difference in the number of times in ELOS greater than two seconds. Those with head tracking also neutralized significantly fewer plate targets, although average accuracy for both groups was over ninety percent. When head tracking was combined with single

point indicators of entity location, however, performance benefits (i.e., less time in room; less time in PT ELOS) were significant across repeated training scenarios. These benefits are similar to those found by Waller, et al. (1998), who noted that given sufficient training time, immersive VE training on tasks requiring route knowledge may surpass map training and be indistinguishable from training in the real world. Thus, rotational head tracking appears to be effective in enhancing spatial awareness, particularly when additional cues are included that provide spatial awareness of entities. This may be attributed to the fact that head tracking in such situations taps innate, natural interaction, where participants are free to turn their head and look in the direction of a single point indicator of location (e.g., when tapped on shoulder, humans instinctively turn head in that direction) as opposed to using an indirect method (i.e., game controller) to face identified spatial points.

The current study found no significant differences in simulator sickness scores between those with head tracking and those without for those who completed the study. Of the 104 students who participated, 24 dropped out prior to study completion. Those that did complete the study are most likely representative of a less-susceptible population, and thus differences in simulator sickness scores were not expected.

Part B

Beyond benefits within a training scenario, this study examined training transfer, where participants were placed in a different virtual environment and the effects of training with tactile feedback were assessed. The current study focused on near transfer, where skills and knowledge were applied in a new environment with closely related context and performance but higher complexity (i.e., 7 versus 15 rooms) (in contrast to far transfer, where different context and

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performance are encountered; Perkins & Salomon, 1992). Specifically, spatial awareness of potential danger areas (e.g., ELOS) and distance estimation (i.e., distance to plate target) were examined. In examining the different tactile cues provided, one question that comes to mind is whether training cues are used simply as a crutch or used to propel trainees towards expertise? Specifically, the goal was to teach participants a set of behaviors that should enhance performance of the task in a transfer environment. Results from Part B of the current study showed positive training transfer for both tactile training cues, indicating that training cues did propel trainees towards expertise, and were not simply training crutches. Participants who trained with incoming shot cues spent significantly less time than those without such cues in CGF ELOS in rooms, thus showing that there was decreased time spent in danger zones related to the incoming shot cues (as CGFs were only entities capable of producing incoming fire). Participants who trained without the additional cue may not have had the opportunity to build as solid a spatial knowledge base of potential ELOS danger areas as they only received spatialized auditory cues, which have been shown to be less effective than tactile cues as localization aids (Terrence, et al., 2005) and/or may not have had the opportunity to develop adequate coping skills to negate negative behavioral responses related to stress (e.g., unexpected cue may cause startle response, which can negatively impact performance). Despite increased performance, those who trained with incoming shot cues reported an average increase in total workload of 7.68 (+/-12.91), which was significantly higher than other participants (1.97 +/-12.31). Higher perceived workload may reflect higher ecological validity as participants with incoming shot cues were provided more information regarding enemy location, which may have enhanced their spatial mental model thereby making them more fully aware of the complexity of the task (i.e., higher workload) but

at the same time enabling them to handle this increased workload more effectively (i.e., better performance as evidenced by less time spent in danger zones).

Participants who trained with distance cues entered ELOS significantly fewer times (55.7% on average) compared to participants who were not exposed to this training cue. In addition, those who trained with distance to target cues reported a slight decrease (1.6% on average) in effort in the transfer environment (compared to baseline), which significantly differed from the increase in effort reported by those who did not train with distance cues. Thus, metaphoric distance cues included during training were effective at enhancing performance and decreasing perceived effort in a transfer environment. This decrease in effort was reported in spite of the increased complexity of the transfer environment (15 rooms) compared to the training environment (7 rooms). This supports the theory that participants learned to associate visual cues to appropriate distance judgments, and did not rely on haptic cues as 'training crutches'. The lesson learned here is that when metaphoric cues are integrated into a virtual training environment with appropriate guidance as to their intended purpose (in the current study, goal was to enhance visual distance judgment), trainees may be able to effectively use these cues to guide training of spatial awareness, and transfer learned knowledge to an environment that does not include metaphoric cues, thus using such cues as a training support, not a 'training crutch'.

Rotational head tracking is expected to increase ecological validity by increasing interface validity (Waller, et al., 1998) by providing a more natural interaction mode. While head tracking showed significantly less improvement in time in room from baseline to transfer environments, time in room during baseline was significantly less for those with head tracking (13.9% less on average). Those with no head tracking may have had to focus on more than just

the training task, but also on the interaction mode, which could have potentially taken attention away from the main objectives of the training task. Within the transfer environment, both groups showed similar times in rooms (10.0 seconds and 10.5 seconds for those with head tracking and without, respectively). Thus, the greater improvement from baseline to transfer environments for those with no head tracking may have been attributed to the increased difficulty associated with indirect movement control (i.e., using game controller to control heading) compared to direct movement control (i.e., turning head to control orientation) during this task, which resulted in less efficient performance during initial exposure (baseline performance). Repeated training allowed these participants to reach comparable performance levels within a transfer environment to those with head tracking.

Although more shots were taken from the hall by those with head tracking during the transfer environment compared to baseline performance, it is unclear how many hall shots were effective at neutralizing targets as the current study did not capture the accuracy of individual shots. It may be that those with head tracking were more effective at neutralizing hostiles specifically from the hall compared to participants with no head tracking, which may account for the larger number of hall shots. Future experiments should capture individual shot effectiveness to better gauge whether more hall shots are indicative of a higher percentage of missed shots (i.e., wasted ammunition indicating poor performance) or a higher percentage of neutralizations from the hall (i.e., effective use of ammunition by engaging enemies from further distances indicating good performance).

<u>Conclusions</u>

The objective of this study was to evaluate the effectiveness of incorporating tactile and vestibular cues into a complex training environment to enhance training. The study examined the impact of incorporating two independent, spatialized tactile cues designed to enhance spatial awareness within a MOUT virtual training environment by (1) providing metaphoric distance cues to plate targets, and (2) providing incoming shot cues from hostile CGFs, thus enhancing egocentric distance and location awareness for plate targets and hostile CGFs, respectively. In addition, the impact of head tracking (i.e., vestibular cues) in combination with single point indicators of entity location was examined. The experiment consisted of two parts; Part A examined how haptic interactions influenced learning across 4 successive training sessions, while Part B examined how haptic interactions influenced training transfer. In summary, the implications from this study are:

- Metaphoric cues may enhance performance accuracy across successive training scenarios, and promote effective training transfer performance with lower perceived effort when instructions encourage participants to use metaphoric cues as guidance to interpret other multimodal cues as an indication of correct performance (e.g., learn to associate visual cues with desired distance from targets) as opposed to relying on metaphoric cues as a training crutch.

- Tactile cues that enhance egocentric orientation and distance awareness to entities may result in improved performance in target location within a complex, virtual training system.

- Training with spatialized tactile cues indicative of stressful danger areas (e.g., incoming fire cues used in this study to increase stress) may enhance performance in transfer environments, indicating that participants may learn adequate coping behaviors from repeat exposure to stressors.

- Head tracking is beneficial in enhancing spatial awareness and performance both across repeated training scenarios and within a transfer environment, particularly when single point indicators of spatial location are included in the environment.

- Repeated training may enhance performance when indirect movement interaction is used (i.e., no head tracking), at times reaching similar performance levels as those with head tracking, thus suggesting that indirect movement control may be used to train higher-order complex knowledge development such as spatial awareness.

- Caution is advised when implementing multiple training cues that, in isolation, focus attention on entities that are of differing priority as performance may suffer due to divided attention across sub-tasks.

The current study showed benefits of training with tactile cues, where performance gains were seen both during repeated training and within a transfer environment. In general, adding information cues via the haptic modality enhanced spatial awareness as theorized by Hale, et al. (in press [see chapter 4]), however designers are advised to consider that adding multiple tactile cues to one scenario may negatively impact one another by directing attention to different tasks. Given that training transfer occurred when distance to target cues were removed, this supports including metaphoric cues into scenarios to train specific aspects of the task that are hindered in a virtual world (e.g., distance judgment), and demonstrates that these cues are not simply a crutch used during training, as positive transfer occurred when cues were removed. The inclusion

of tactile cues and head tracking appears to have increased the ecological validity of the training environment by more closely mimicking the stressful MOUT environment, which resulted in increased perceived workload. Despite this, however, performance gains were evident, showing that subjective reports of workload did not negatively impact performance. This may be an indication of stress conditioning.

While the current study focused on near transfer, the ultimate goal of such research is to examine transfer to the real world (i.e., far transfer). Future research should examine whether the benefits demonstrated in this study during training and those that transferred to a second virtual environment are apparent during far transfer.

CHAPTER SIX: GENERAL DISCUSSION

The human haptic and vestibular senses offer a wealth of information during everyday interaction that combined with input from other sensory systems provides an integrated understanding of the environment. Virtual training systems are just beginning to realize the potential of incorporating haptic and vestibular sensations to enhance the overall multimodal experience, with the objective being to enhance performance, training, and training transfer. Figure 2 of Chapter 4 introduces the Multimodal Optimization of Situation Awareness (MOSA) model, which integrates additional spatial and temporal awareness components into the traditional SA model, thereby providing a more prescriptive characterization of the SA construct from which design guidelines can be drawn regarding the benefits of incorporating different sensory cues into a training system (i.e., based on filling in gaps where a training system is not effectively supporting SA components). While many cues may be used to enhance SA within a training environment as outlined in Chapter 4 in the MOSA model, the current empirical work focused on two types of cues and the impact they have on spatial awareness: static tactile cues presented to the torso (MOSA Model Component B1: Tactile Exteroceptive Cues) and vestibular cues provided by head tracking technology (MOSA Model Component C1: Interoceptive Cues).

As the MOSA model proposes, static tactile cues (MOSA Model Component B1: Tactile Exteroceptive Cues) may be used to enhance object recognition, spatial and temporal awareness dependent on the way such cues are implemented. For example, a tactile cue may use coded vibrations to provide identification information (i.e., hostile vs. non-combatant), spatialized vibrations to provide indication of self-position (i.e., hit a wall) or location of entities (i.e., hostile to the right of participant) within a given space, or rhythmic vibrations to indicate pacing

or timing of events. Focus in this work was placed on two tactile cues used to enhance egocentric distance and location awareness of entities within the environment: one cue that provided spatialized incoming shot cues that notified participants when they were within danger zones (i.e., ELOS), and one cue that provided spatialized distance to target cues that indicated when participants were within a plate target's ROV, and could thus neutralize the target. Both cues were theorized to enhance spatial awareness by providing additional cues that focused attention on critical aspects of the MOUT training environment (i.e., avoid casualties and negate enemy threat).

Results presented here showed that spatialized tactile cues did enhance egocentric distance and location awareness, as well as enhanced performance both across repeated virtual training and within a virtual transfer environment, particularly when one of the two cues was presented in isolation during training. The benefits in enhanced distance judgment seen here should be generalizable to other distance-to-target ranges, where participants have to be a specified distance from target to properly complete tasks. These findings support previous work of Lindeman, et al. (2005) and Terrence, et al. (2005), both of whom found value in adding tactile cues that provided a single source of information (i.e., location of uncleared corners in rooms; location of enemy) to spatialized navigation and orientation tasks. Beyond the work of these past studies that looked at tactile cues in isolation, the current study looked at the efficacy of coupled tactile cues. When both training cues were provided simultaneously during training, participants showed decreased performance and reported increased frustration. As implemented, the combination of training cues did not always direct attention to the highest priority task. For example, if a participant entered a plate target's ROV by backing up into a space, they received a tactile cue on their back indicating that they were within ROV of a plate target. This often

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resulted in participants turning around to neutralize the plate target prior to clearing the room of hostile CGFs (which were of higher priority). In doing so, they left themselves vulnerable to incoming shots. Future implementations of multiple training cues that are directed at independent tasks of varying priority may consider first providing cues in isolation across repeated training scenarios to provide adequate practice of skills in isolation prior to incorporating cues together into a single training scenario. If incorporated simultaneously in a scenario, the priority of cues should be accounted for in real-time, and a cue related to a higher priority task should take precedence over lower priority tasks. With real-time assessment of cue presentation, careful consideration is needed to ensure smooth, seamless transitions from one cue to another to ensure participants are not confused by simple on/off transitions. These results provide a source of validation for Component B1 of the MOSA model. Specifically the results suggest that exteroceptive *tactile* cues can enhance egocentric spatial awareness in that enhanced orientation and distance judgments to entities within a virtual environment were significantly improved with tactile cues when included during training (particularly when cues were provided in isolation).

Research suggests that the addition of vestibular cues via rotational head tracking to a virtual training environment should enhance egocentric spatial awareness by providing a strong indication of direction of travel and heading (Bakker et al., 1998; Klatzky et al., 1998; Loomis et al., 1995; Pausch et al., 1993; Stackman et al., 2002). The goal of the current empirical study was to examine the impact that additional vestibular cues had on spatial awareness and performance when combined with static tactile cues that provided single point indications of spatial location of surrounding entities. Results demonstrated that head tracking was beneficial across both repeated training and transfer scenarios, particularly when coupled with either spatialized tactile cue in isolation. There were some performance decrements found for those with heading

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tracking, such as decreased accuracy in neutralization of plate targets, where those with head tracking neutralized significantly fewer compared to those with no head tracking (although both groups were over 90% accurate). This decreased accuracy may be attributed to the limited ROV space associated with each plate target (participants had to be within 3'-4' and within +/- 45^0 full frontal to engage plate targets) combined with the limited field of view provided by an HMD. If participants with head tracking were too far from full frontal of the plate target, they had to turn their head to reorient themselves in front of the target, which often forced participants to lose view of the plate target due to the limited field of view. In contrast, those with no head tracking could maintain the plate target in view while manipulating controls to update both orientation and distance from plate targets. Despite this challenge in entering plate target ROV, however, those with head tracking cleared rooms in a comparable amount of time during transfer and did not spend significantly more times in ELOS greater than two seconds. The current study, while focused on enhancing visual distance judgments from the front of plate targets, constrained successful performance by limiting ROV. Future studies may consider incorporating less stringent spatial positioning required for proper performance (i.e., ROV of 3'-4' without regard to angle from full frontal), which should closely mimic real world tactics, where enemies may be engaged from any direction. In addition, incorporating CGFs throughout the environment as opposed to using a combination of CGFs and plate targets may enhance the realism of the training environment, and ensure training goals more closely mimic those of the real world (i.e., engage all enemies from the safest possible distance, as opposed to combining a distance judgment task within the same scenario as engaging CGFs from the safest possible distance). These results provide a source of validation for Component C1 of the MOSA model. Specifically, interoceptive vestibular cues related to rotational acceleration of the head were

found to enhance egocentric spatial awareness in that performance benefits were seen for those with head tracking both during training and transfer environments, particularly when coupled with either spatialized tactile cue in isolation.

The current study validated two paths outlined in the MOSA model that led to enhanced egocentric orientation and distance spatial awareness: (1) tactile exteroceptive cues, and (2) vestibular interoceptive cues. The work set forth in the MOSA model also provides a framework through which numerous empirical studies can be conducted to better understand how relationships between environmental and individual factors positively impact situation awareness. Also, consideration of how multiple cues across various modalities combine into a single percept of SA is required, as there are known complications when incorporating combinations of cues (e.g., modality dominance, cross-modal illusions; O'Callaghan, 2006).

CHAPTER SEVEN: CONCLUSIONS AND FUTURE RESEARCH

Empirical results from this study support the inclusion of tactile and vestibular cues in virtual training environments to enhance SA and performance not only within training sessions, but also within virtual transfer environments. Benefits of including head tracking to a desktop trainer were evident, particularly when single point indicators of spatial location of enemies were also included. Head tracking in such environments provides a more natural interaction mode to orient oneself and direct heading, particularly when tactile cues provide spatial indications of enemy locations. This interaction may be similar to human's natural tendency to turn their head in the direction of a tap on the shoulder. Thus, when training goals include enhancing spatial awareness, head tracking is a beneficial technology to incorporate into the virtual training environment.

In looking at spatialized tactile cues on the torso, benefits were seen both across repeated training scenarios as well as within a transfer environment when a metaphoric distance cue was provided during training or when a simulated real world cue to indicate incoming fire was incorporated into training. In isolation, both training cues showed significant performance gains within training and showed significant training transfer. Thus, metaphoric cues provided within a training environment can effectively train the desired behavior, and not be relied on as a training crutch. Further benefits may be seen when such metaphoric cues are implemented using a training wheels paradigm, where cues are prevalent initially during training, and faded over successive sessions to ensure cues are not over-relied on for effective performance. Similarly, simulated real world cues can effectively train spatial awareness of potential danger zones (in

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this study, ELOS), and may also provide adequate exposures to effectively train coping behaviors that reduce negative responses to stressors present in virtual environments.

While both tactile cues were effective at enhancing spatial knowledge related to their independent tasks, decreased performance and increased frustration were evident when cues were presented simultaneously during training scenarios. Future studies should critically assess relationships between multiple training cues, and ensure that if presented within one training scenario, they are implemented in such a way that attention is driven to highest priority tasks, and multiple cues are considerate to one another (e.g., lower priority cues may be minimized and/or transitioned off if a higher priority cue comes into effect). This should ensure trainees are clearly guided to critical acts, and not confused by multiple cues directing attention to more than one task simultaneously.

When developing virtual training scenarios, the MOSA model can provide theoretical guidance as to which multimodal sensations could be implemented to enhance various aspects of SA. To be effective, designers must first define clear training objectives and goals (i.e., which aspect(s) of SA are targeted in the training environment), which will then drive appropriate selection of cues that support specific SA components. Additional empirical work is required to validate other theorized relationships presented in the MOSA model, and to examine tradeoffs between individual modalities, as well as implications for incorporating multimodal cues simultaneously with the goal of enhancing SA within a virtual training environment.

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