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THE EFFECTS OF A TACTILE DISPLAY ON FIRST RESPONDER PERFORMANCE

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the School of Modeling, Simulation, and Training
in the College of Engineering and Computer Science
at the University of Central Florida
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Major Professor: Glenn Martin

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ABSTRACT

Firefighting is a dangerous and difficult task. Simulation affords researchers and practitioners the ability to examine performance and training in adverse conditions while preserving life, offering repeatable scenarios, and reducing costs. Multiple Resource Theory is used in this study as a model for assessing alternate sensory channels for information delivery when the optimal channel is not available. Specifically, this study tests the influence of a waist-worn vibrotactile display to assist navigation when visibility is reduced in a firefighter simulation. The present study measures participants' objective performance and self-reported workload while navigating a simulated fireground. Results from 70 research participants revealed statistically significant differences between the experimental and control conditions for completion time and overall workload scores. Workload and performance emerged as significantly correlated in both the experimental and control conditions; however, no statistically significant correlations were found for the spatial anxiety hypotheses. The results of this study indicate that participants engaged in a simulated search and rescue task in a low visibility environment benefit from the assistance of a vibrotactile display as a tool. Participants' performance scores and self-reports show that they had more mental resources to engage in the search and rescue task more quickly when assisted by a vibrotactile tool. Evidence was found to demonstrate a statistically significant association between workload and performance. The implications of this study have real world consequences for training for dangerous tasks to maximize performance and save lives while minimizing risks to personnel.

For Barbara

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CHAPTER ONE: INTRODUCTION

Firefighter Performance

Extreme environments require exceptional performance. Underwater, extraterrestrial, and arctic environments are areas not conducive to prolonged human exposure, much less task completion and goal seeking activities (Barnett & Kring, 2003). A burning building represents an extreme environment in several ways: air becomes too hot to breathe, smoke can be filled with toxic chemicals, structural integrity weakens, and electrical infrastructure often fails during the course of a fire, which leaves the interior in darkness and filled with smoke. As time in a burning building increases, the likelihood of survival decreases (Proulx & Fahy, 1997). Training for performance optimization in extreme environments can be as dangerous as the operational environment. Simulation can help practitioners prepare to perform in adverse conditions while preserving life, offering repeatable scenarios, and reducing costs. Therefore, simulating extreme environments and studying human performance is one way that simulation researchers can further scientific knowledge and save lives.

Firefighters perform tasks that are time-sensitive, extremely dangerous, and result in life-or-death outcomes. The ability to successfully complete critical operations is dependent on situation awareness (Endsley, 2017). Situation awareness (SA) was defined by Endsley (1995) as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (p. 36). Burning structures are dynamic environments; fires expand and move as they conflagrate, and this dynamism changes the tasks demanded of firefighters and the environment in which those tasks are performed. It is imperative that firefighters have as much relevant information as possible in an easily understood, accessible format when information is needed. Superfluous or inaccurate information, delayed responses, and too much information at once can all have negative consequences, such as increasing the cognitive workload required to perform tasks and crossing an operator's 'redline', the point at which performance deteriorates (Young, Brookhuis, Wickens, & Hancock, 2015). Lack of SA is the leading cause of firefighter injury and death in the line of duty (Moore-Merrell, Zhou, McDonald-Valentine, Goldstein, & Slocum, 2008). An important task for researchers and manufacturers of emergency personnel equipment is to understand what information is needed and when first responders need access to that information. Designers of first responder gear can then consider which sensory channel, or combination of channels, are optimal for delivering mission-critical information. When combating a fire, there are grave costs if a first responder lacks SA; these costs can be measured in death and injury. Improving firefighter SA can mitigate the costs of emergency operations. Therefore, the present research proposes to investigate the use of tactile displays to improve firefighter performance and decrease the workload of emergency operations.

Fires are accompanied by smoke and this presents a challenge to first responders. Smoke decreases visibility, especially in indoor environments. This reduction in vision can lead to disorientation and confusion for firefighters as they move through structures in which they have limited knowledge of the layout (Ramirez, Denef, & Dyrks, 2009). Disorientation leads to a lack of SA and, in dangerous, time-sensitive tasks such as firefighting, loss of life (Brennan, 2011). Firefighters must maintain awareness of where they are, where teammates are, and where the seat of a fire is located. When firefighters lose SA, they can no longer know where they are in relation to the fire, other sources of danger, and safe paths to exits. Firefighters are taught to maintain SA on the fireground, the firefighting battle space, by perceiving, comprehending, and predicting threats.

The first step of maintaining SA during firefighter operations is perceiving threats. Maintaining perception on the fireground begins with monitoring and controlling heart rate. An elevated heart rate can begin to diminish perceptual abilities, particularly the ability to maintain SA (Saus, Johnsen, Eid, & Thayer, 2012) The second step of maintaining SA is comprehending threats in the environment. Comprehension of threats is a complicated task for firefighters due to the varied nature of the services they provide (e.g., hazmat, EMS, auto collision response, search and rescue). High-stakes decisions must be made quickly and decisively. Practicing threat comprehension in a real-world scenario is limited by available opportunities and the possibility of harm to people. Virtual reality training can eliminate the physical risks (e.g., smoke inhalation, death) and provide repeatable scenarios in which to practice comprehension. Threat prediction is the third step in maintaining SA during fireground operations. Projecting the future state of threats in the environment means that firefighters can take steps to mitigate danger and increase the possibility of mission success without injury or loss of life.

The National Institute for Occupational Safety and Health (NIOSH) and the National Fire Protection Association (NFPA) have recognized disorientation as the primary cause of firefighters becoming lost, trapped, and injured (Fischer & Gellerson, 2010). In addition to individual SA there is collective SA, also known as team cognition (Toups & Kerne, 2007). Firefighters must communicate through words, roles, and shared histories to explicitly and implicitly coordinate tasks at the scene of a fire. Maintaining an awareness of where teammates are in relation to individuals and the seat of the conflagration aids firefighters in knowing how successful the team is being in combating the fire and where teammates are located if they call out for help. Firefighters have multiple ways of communicating and updating each other on mission progress, from technologies such as radios and flashlights to environmental cues such as fire hose signals. However, fire service employees may become incapacitated or suffer equipment failures and be unable to respond. A search and rescue mission is then initiated for any fallen firefighters.

The dynamic nature of the fireground dictates that firefighters must be able to adapt to variability in the environment and the mission in order to make quick decisions and save lives. Automated technologies can help firefighters maintain SA by informing them of changes in the mission and the environment. In firefighting operations, SA deteriorates as the mental workload required to navigate a spatially complex area increases (Parush & Rustanjaja, 2013). Therefore, automated aids that assist firefighters in navigating buildings by reducing the mental workload required to maintain SA may improve performance, reduce time spent in dangerous situations, and save lives. Young and Stanton (2005) defined mental workload as "*the level of attentional resources required to meet objective and subjective performance criteria, which may be mediated by task demands, external support, and past experience*." Low visibility combined with high mental workload can impede firefighters' ability to attend to critical elements in the environment. An inability to perceive elements means they cannot be comprehended, nor can the future state of elements be predicted. Mental workload is measured via behavioral assessments, physiological measurements, subjective measures, or some combination of these methods (Abich, 2013; Young et al., 2015). The present study uses the National Aeronautics and Space

Administration Task Load Index (NASA-TLX) to measure the participants' perceived workload while navigating a simulated fireground. Hart and Staveland's (1988) NASA-TLX is described in the methodology chapter of this research and is included in Appendix E.

Multiple Resource Theory

Multiple Resource Theory (MRT) provides a model for predicting performance in situations where humans are engaged in two or more simultaneous tasks (Wickens, 2002a; Wickens, 2008). However, MRT can also be used as a model for suggesting possible alternate sensory channels for information delivery when the optimal channel is not available (Allan, White, Jones, Merlo, Haas, Zets, & Rupert, 2010). Fireground conditions can overload or mask firefighters' auditory and visual channels. Smoke and failing electrical systems limit visibility. Fire alarms and self-contained breathing apparatus (SCBA) equipment can prevent firefighters from hearing information. The four dimensions of the MRT model can be seen in Figure 1.1 as sensory modalities, stages, visual information, and codes. Sensory modalities are visual or auditory. Stages are perceptual, cognitive, and responsive. Visual information is focal or ambient. Codes are visual or spatial.

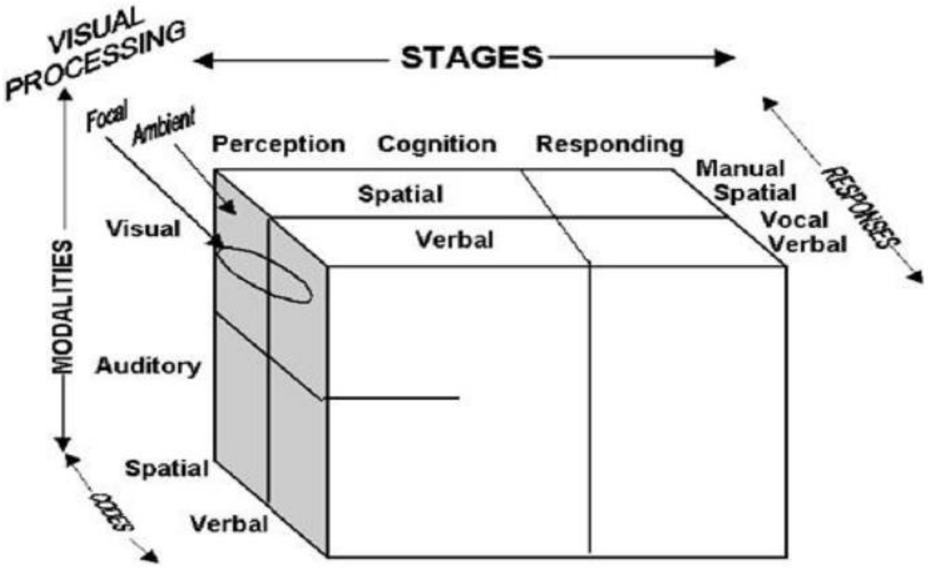


Figure 1.1. Wickens' (2002) Multiple Resource Model. Note the three stages are similar to Endsley's (1995) three steps of SA.

Multiple Resource Theory is not inclusive of humans' tactile sense; however, MRT does provide indications of when the tactile modality can be utilized to operators' benefit. Wickens' (2002, 2008) theory recommends delegating information from overtaxed or unavailable sensory channels to other available and adequate channels in order to reduce mental workload and optimize performance. The MRT model can be used by researchers and equipment developers to realize that when the primary sensory channel is overloaded, other channels are available and MRT suggests which channels may be available.

The purpose of the present research is to determine the effects of spatial anxiety and a tactile display on cognitive workload experienced during a simulated firefighter task and the subsequent effect on performance. It is hypothesized that the spatial anxiety inherent to participants and the extra information provided through tactile communication will influence the cognitive workload incurred by participants and will help or hinder wayfinding performance in a simulated burning building. The present research investigates the effects of a tactile display on human workload and performance in a simulated search and rescue task. Participants will be asked to search one floor of a virtual office building in order to find two non-player character (NPC) teammates and lead them to safe egress. The virtual environment will be filled with smoke and the sound of a smoke alarm, thus limiting participants' visual ability, and masking their ability to hear environmental cues. Each participant will perform the task twice: once with a worn vibrotactile device and once without. Research findings will be analyzed and discussed in the context of individual differences; namely, the level of spatial anxiety that participants bring to the study and with which they perform navigation tasks in their daily lives. The virtual environment is meant to simulate a situation in which dangerous tasks take place during a stressful event. Thus, it is expected that participants will incur a significant amount of workload and can benefit from the use of an automated aid to assist with wayfinding and task completion in the virtual environment. The findings from this dissertation will provide insight into ways firefighters' cognitive workload can be decreased while increasing effectiveness. The ultimate goal of this work is to provide useful information to designers and developers of first responder technologies who can produce equipment that will save lives.

CHAPTER TWO: RELEVANT LITERATURE

Introduction

Firefighters perform dangerous tasks in extreme, dynamic environments. Recent trends indicate that firefighter line-of-duty injuries are increasing in North America, erasing safety improvements that were made in the period from 1970-1989 (Dow, Garis, & Thomas, 2013). Kunadharaju, Smith, and Dejoy (2011) found that causal factors to this phenomenon include inadequate funding and resources, failure to follow correct incident command procedures, failure to prepare for or anticipate adverse events, and not ensuring personnel readiness. Research exploring the causes of and ways to prevent firefighter injuries consistently indicates the importance of SA and decision making while conducting fireground operations. Over 90% of near-miss event reports state that SA was a contributing factor in the incident (Pegram, 2008). In order to prevent decrements in SA and avoid injuries or loss of life, it is imperative that firefighters have tools, tactics, and techniques to perform their work at the highest level possible while avoiding excessive mental workload.

The National Institute of Standards and Technology’s (NIST) Public Safety Communications Research (PSCR) Division is the federal laboratory in charge of research, development, testing, and evaluation for first responder communication interfaces and technologies. In 2019, NIST PSCR announced the need for firefighters to have embedded, wearable vibrotactile interfaces to assist with fireground operations in real-world scenarios and virtual reality (VR) based training for adverse events. The announcement publicized the 2019 Haptic Interfaces for Public Safety Challenge, an Open Innovation event that called on members of academia and private industry to partner in developing vibrotactile display prototypes for first responders. NIST’s Open Innovation Challenge resulted in multiple wearable prototypes: vibrotactile helmets, gloves, boots, belts, and collars. Prototype development is one major step in the process of developing, testing, and deploying next generation public safety gear. The impact of new equipment on first responder performance, safety, and feelings of satisfaction must be examined before any equipment is ready for use in the field. To that end, researchers have begun to examine the effects of worn technologies on human performance during fireground operations. NIST’s initiative demonstrates the serious need for embedded technological systems to aid first responders in the field and shifts the reality of vibrotactile prototype development from the lab to fielded systems in the fireground.

Firefighter Equipment

Applying technology to combat fires is a task that requires careful consideration. Firefighters already have numerous tools with which to extinguish fires, rescue civilians, and preserve their own relative safety. Adding another piece of equipment to the firefighting toolkit can lead to distraction and decrements in performance (Endsley, 2006). There are also material concerns when equipment is subjected to heat: batteries can explode, textiles catch fire, and plastics melt. Additional equipment can restrict movement, add weight to the loads firefighters already carry, and needs to have a demonstrable benefit to justify the financial and physical costs of operation. Firefighting technologies need to be functional, reliable, resilient, and versatile. Numerous technologies have been developed for helping firefighters navigate buildings, thus reducing the mental workload required to maintain and update one part of SA while fighting a fire.

Mission critical information is primarily conveyed to firefighters via the auditory channel by using radio communications; however, several prototype systems have been developed that communicate using the tactile modality. Carton and Dunne (2013) developed a vibrotactile glove (Figure 2.1) paired with an ultrasonic range finder for detecting obstacles and changes in the environment during fireground operations. Participants were able to detect the presence of obstacles and relative changes in the environment with 93% and 74% accuracy, respectively. Another study examined the effects of audio and haptic modalities on participants' ability to navigate in a low visibility environment (Kerdegari, Kim, & Prescott, 2016). Participants were able to successfully navigate in both conditions; however, participants performed better (i.e., deviated less from the route) and reported experiencing less mental workload in the haptic condition. Kerdegari and colleagues instructed participants to wear a helmet outfitted with tactile motors (tactors) in the haptic condition (Figure 2.2).

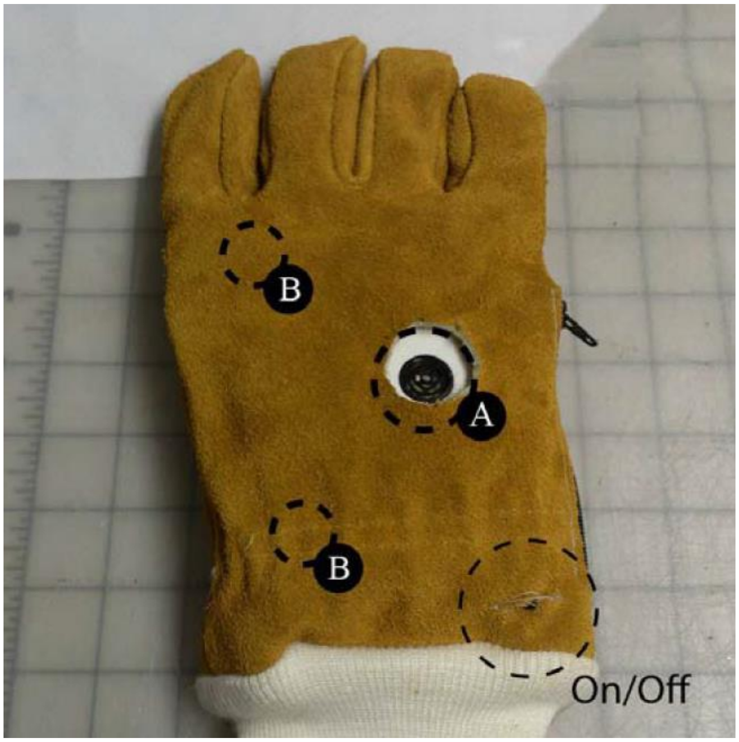


Figure 2.1. Vibrotactile glove from Carton & Dunne (2013). The dotted circles represent tactor locations.

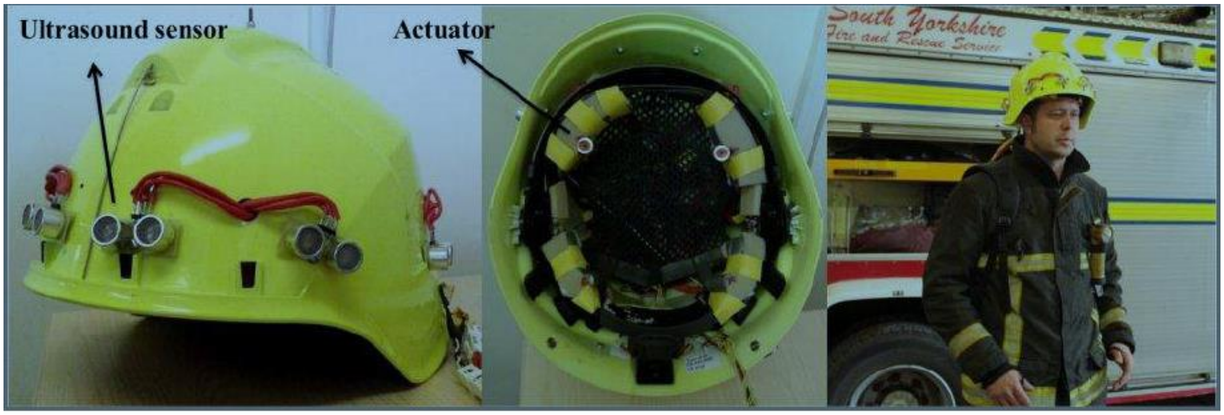


Figure 2.2. Vibrotactile firefighter helmet from Kerdegari et al. (2016).Kerdegari et al.'s helmet contained 12 ultrasonic range-finding sensors and six tactors.

Tactile Displays

Prior research emphasizes the danger firefighters experience is similar to the conditions experienced by soldiers on the battlefield. Firefighters, like soldiers, must perform high-stakes decision making tasks quickly in environments that are often filled with loud noises and smoke (Brill, Terrence, Stafford, & Gilson, 2006; Elliott, van Erp, Redden, & Duistermaat, 2010; Roady & Ferris, 2012). Therefore, it is worthwhile to review the state of the science of tactile displays in military contexts. Roady and Ferris (2013) compared verbal to tactile communication for directing soldiers engaged in a mission. The results indicated that participants were able to interpret navigation information sent through the tactile interface faster and more accurately than the audio interface. Merlo, Stafford, Gilson, and Hancock (2006) demonstrated that marine cadets operating in physiologically stressful conditions interpreted tactile communications with over 99% accuracy. Further research has found that soldiers given information about distance and azimuth of enemy targets had lower mental workload and improved performance in tactile cueing conditions compared to audio cueing (White, 2016). White replicated his findings in that same dissertation and demonstrated that multimodal cueing combinations containing a tactile cue resulted in lower mental workload and improved performance compared to cueing combinations that did not contain a tactile cue. Carlander and Eriksson (2006) investigated the ability of a tactile display and other communication interfaces to inform combat vehicle operators of threats in the environment. Results indicated that the tactile and 3D audio conditions produced the best performance due to the localization abilities of the displays. Tactile displays have been found to improve performance in both fatigued and rested pilots (Curry, Estrada, Webb, & Erickson, 2008). Gilson, Redden, and Elliott (2007) demonstrated that for soldiers engaged in a target detection task, auditory signaling resulted in higher reported workload and decrements in performance compared to tactile signaling. While performance deteriorated as difficulty increased in both conditions, the decrements in performance were more severe in the auditory condition. Tactile displays offer clear benefits for soldiers and pilots engaged in dangerous missions; the same can be expected for first responders. Firefighters, however, are often subjected to low visibility conditions due to the nature of smoke in burning buildings combined with failing infrastructure. It is therefore worthwhile to review the evidence on the ability of tactile displays to assist with visually impaired navigation.

Prior studies have demonstrated the value of tactile displays for assisting with visually impaired navigation. Ross and Blasch (2000) found evidence to indicate that a tactile display can improve performance on a wayfinding task where pedestrians had a visual impairment. The researchers found that the body-mounted tactile display resulted in the greatest performance improvement and participants preferred the tactile display over two auditory displays. Brock & Kristensson (2013) investigated workload incurred by blindfolded pedestrians during an obstacle avoidance task; however, their research did not examine wayfinding and involved navigating with an audible interface and not a tactile display. Ross and Blasch (2000) examined the ability of a worn tactile display and a worn audible display to reduce veering tendency in persons with a visual impairment; however, their research did not measure the workload incurred while attempting to walk across a street with and without a tactile device. Pielot and Boll (2010) investigated the impact of a worn tactile display on participants' navigation performance and attentional capabilities; however, the researchers did not examine workload. The relationship between spatial anxiety and workload incurred during a simulated visually impaired wayfinding task has not been examined. The scientific literature reporting on the ability of a tactile display to assist firefighters, soldiers, pilots, and blind pedestrians with navigating indicates that vibrotactile communication is intuitive, effective, and accessible.

Tactile displays may assist with information access when visual and audible displays cannot; however, haptic technologies have lagged behind technologies developed for the visual and auditory senses (Lazarus, Martin, Nayeem, Fowlkes, & Riddle, 2008). Vibrotactile communication has several advantages compared to visual signaling (Brill et al., 2006). Tactile interaction, similar to audio communication, is omni-directional and omni-present. As a sensory channel, touch is always available, and the skin is the largest organ on the human body. The Multiple Resource Theory model does not contain an explicit section for the sense of touch; however, it still provides implications of when to utilize the tactile sense. The visual and auditory modalities of the MRT model correspond to spatial and temporal dimensions; humans see objects in space and hear sounds over time. Whereas vision is spatial and hearing is temporal, touch is spatiotemporal. A vibration on the arm does not mean the same as a vibration on the leg and four vibrational pulses in quick succession is a different message than one long vibration. As prior research has indicated, tactile communication is an effective means of providing sensory substitution for overloaded sensory capabilities (e.g., vision, touch) because vibration can indicate when, where, and what an object of interest is. Thus, tactile displays are not intended to replace auditory and visual signaling mechanisms, but allow firefighters to have additional communication pathways when the primary channels are not available (Daly, Washburn, Lazarus, Reeder, & Martin, 2003).

Touch

Touch is classified as active or passive; the primary difference is the role of the individual experiencing tactile sensation (Gibson, 1962). Active touch is the sensation an individual experiences while touching a physical object. Passive touch occurs when an individual is touched by someone or something in the environment. Tactile displays communicate information through passive touch. Gemperle, Ota, and Siewiorek (2001) define a tactile display as any device that stimulates a person's skin in order to convey information. A commonly recognized example of a tactile display is a video game controller that vibrates to indicate a player has been impacted by or impacted on an object. This communication modality is important because the controller vibration communicates information via touch, which is the same modality a person recognizes they have experienced an impact. Vibration is also important for communicating information that may be unavailable to a person playing a video game, such as when a player is shot by another character not located in the current field of view. The game controller's vibration indicates to the player that he or she needs to shift their attention to another location in the environment and respond to the external threat. Tactile displays are used in the defense, entertainment, communications, and automotive industries; there will likely be expansion of these applications in the future.

Human Anatomy

Human skin can be classified into three categories: glabrous, mucocutaneous, and hairy (Greenspan & Bolanowski, 1996). Mucocutaneous skin is the skin inside the nose, mouth, and other entrances into the body. Glabrous skin covers the palms of the hands and soles of the feet. Hairy skin covers most of the human body. Cutaneous tissue contains four kinds of mechanoreceptors: rapidly adapting (RA) fibers, slowly adapting (SA) type 1 fibers, SA type 2 fibers, and Pacinian corpuscle (PC) fibers (Bolanowski, Gescheider, Verrillo, & Checkosky, 1988). Mechanoreceptors are responsible for sensing and transmitting information to the brain about deformations of the skin; these sensations are interpreted as pressure, vibration, and pain (Sekuler & Blake, 1994). Mortimer, Zets, Mort, and Shovan (2011) identified the Pacinian corpuscles as being very receptive to vibration. Vibration is most often utilized for transmitting information via tactile displays; pressure is rarely used (Cholewiak & Collins, 2003). Jones and Sarter (2008) found that mechanoreceptor response to tactile stimuli varies based on tactile parameters, such as location, duration, frequency, and amplitude of vibration. Tactile icons (tactons) use one or more parameters to present information to the user of a tactile display (Brown, 2007; Brown, Brewster, & Purchase, 2005).

Mental Workload

Prior research provides evidence that navigating with a visual impairment requires significantly more mental resources than navigating with unimpaired sight. Passini and Proulx (1988) found that participants with blindness planned their journeys in more detail than sighted participants, had to rely on more units of information while walking, and made more decisions along the route. Blind participants not only made more decisions than the control group of sighted participants, they also had to handle decisions that were exclusive to someone with blindness, such as maintaining direction (i.e., not veering). Results indicated that the amount of information processing required for maintaining direction was significantly higher for blind participants ($p < 0.001$), although this is likely due to a floor effect in the control group. Passini and Proulx hypothesized that the difficulty level of a task can be determined by the number of decisions required to successfully complete the task. Blind participants in Passini and Proulx's wayfinding study not only made more decisions (58% more, $p < 0.01$), they made a greater variety of decisions. Firefighters navigating through a building that is on fire and where visibility is limited due to smoke and failing electrical systems are likely to have impaired vision while walking or crawling through an unfamiliar building. As a result, firefighters are likely to incur a higher level of mental workload than they would experience if vision was not impaired. As Brennan (2011) has emphasized, firefighters also experience elevated heart rates while engaging in fireground tasks. If a person's heart rate exceeds a certain threshold, perception and comprehension of the environment are likely to deteriorate. Technologies, such as tactile displays, that can help firefighters maintain SA by managing the workload required to successfully complete fireground tasks can save lives; therefore, the investigation of how and when to employ first responder technologies is an issue of grave importance.

Spatial Anxiety

Anxiety can increase heart rate and workload and, thus, may contribute to decrements in SA. A person relying on local cues, meaning cues that are able to be perceived, is more likely to experience disorientation when local cues are absent. Becoming disoriented frequently can cause spatial anxiety, defined as anxiety about performing wayfinding tasks (Lawton, 1994). Lawton (1996) found that spatial anxiety and wayfinding strategy each uniquely and significantly contribute to accuracy in a task of real-world spatial ability. Winter (2016) indicates that higher levels of spatial anxiety result in navigation performance decrements due to not being able to pay attention to features of the environment. Additional research has produced an empirically validated Spatial Anxiety scale and shown that higher spatial anxiety scores predict lower objective performance on spatial tasks (Lyons, Ramirez, Maloney, Rendina, Levine, & Beilock, 2018).

Orientation

Maintaining spatial orientation requires supporting and sustaining a continuously updated awareness of environmental flow. Environmental flow is a term describing the changing distances and directions to objects in the environment that occur while moving (Guth & Rieser, 1997; Ross & Blasch, 2000). In sighted individuals, this process is done by referencing visual cues in the environment (e.g., signs, landmarks); however, for people with visual impairments, signage and other visual cues are often degraded or completely unavailable. Even sighted individuals can have problems with maintaining an awareness of environmental flow, as seen in studies of SA (Chiasson, McGrath, & Rupert, 2003). Multimodal interfaces can ameliorate the problems associated with maintaining SA while multitasking, such as navigating while driving or performing fireground operations. People with a visual impairment can benefit from multimodal interfaces by using one or more alternative sensory channels, such as listening to a GPS unit with a display and audio capabilities (Schwartz & Benkert, 2016). Simple information, such as a lane deviation warning, can be communicated via simple tones; more complex information can be transmitted via speech, such as turn-by-turn navigational instructions (Proctor & Van Zandt, 2008). Audible indicators have several disadvantages, however. Auditory information can be missed in noisy environments, can be ambiguous, and can take too long to transmit and interpret to be useful. Hancock et al. (2007) emphasize that auditory information is temporal in nature. More complex information will require more time to perceive and interpret. For a person with a visual impairment, information about dangers in the environment may not be interpreted in time to allow for a purposeful move toward safety. Firefighters operating in low visibility conditions need informative displays that offer fast, reliable, and intuitive information. Tactile displays overcome some of the disadvantages of auditory displays and have been recommended for applications where visual and auditory channels are masked or overloaded (Hancock, Mercado, Merlo, & Van Erp, 2013; Merlo & Hancock, 2011; Van Erp, 2007).

Tactile displays have been demonstrated as useful for directional cueing without increasing demand on visual and auditory resources (Brill, Terrence, Downs, Gilson, Hancock, & Mouloua, 2004). Additionally, tactile communication can reduce response time, false positives, and missed signals by directing visual attention (Merlo & Hancock, 2011). The tactile modality has been shown to be beneficial for obtaining directional information while visually impaired and can improve performance in high workload conditions (Rupert, 2000). Prior research has found significant performance improvements even in high stress conditions (Merlo, Stafford, Gilson, & Hancock, 2006). Tactile communications are limited in the amount of information that can be transmitted; however, selecting and adjusting the correct vibrotactile parameters for a task can optimize performance (Brown, 2007). The parameters of vibrotactile communication are intensity, frequency, waveform, duration, rhythm, and spatial location (locus). The current study focuses on the spatial location parameter because participants will be engaging in a task requiring spatial information.

The Current Research

The present study uses a virtual environment to investigate the variables of interest. Tate, Sibert, and King (1997) demonstrated that virtual environments (VE) can be effective at increasing knowledge of the environment for shipboard firefighter training. Naval service members in the VE condition made fewer wrong turns than service members who did not receive virtual mission training, indicating increased familiarity with a previously unfamiliar part of the ship. Another study used virtual reality to examine navigation time and number of wrong turns made by firefighters in three training conditions: blueprint, virtual environment and a no training control condition (Bliss, Tidwell, & Guest, 1997). Firefighters in the virtual environment condition performed as well as firefighters in the blueprint condition. Both groups made fewer wrong turns and navigated the building faster than firefighters in the control condition. The complex and dangerous nature of fire rescue operations means that opportunities to practice firefighting skills in the real world are rare, carry a significant financial cost, and are full of physical risks. Practicing skills in virtual reality allows for firefighter training to be affordable, repeatable, and risk-free.

This dissertation seeks to utilize a virtual reality simulation to investigate the effects of a worn vibrotactile display on the workload perceived by participants who engage in a fire search and rescue operation. The impact of the tactile display on participants' performance will be examined. Participants' level of spatial anxiety will be measured to determine the effect of spatial anxiety on performance and reported workload. Based on the results of prior research, I propose the following hypotheses:

Hypotheses

H1: Participants will have increased levels of performance in the vibrotactile condition compared to the control condition.

H2: Participants will report experiencing decreased levels of workload in the vibrotactile condition compared to the control condition.

H3: Participants who report experiencing increased workload will have decreased levels of performance (as measured by completion time) than participants who report experiencing decreased levels of workload across both the vibrotactile and control conditions.

H4: Participants who score higher on spatial anxiety will have decreased levels of performance (as measured by completion time) than participants who score lower on spatial anxiety across both the vibrotactile and control conditions.

H5: Participants who score higher on spatial anxiety will report experiencing increased workload than participants who score low on spatial anxiety across both the vibrotactile and control conditions.

CHAPTER THREE: METHODOLOGY

Participants

A total of 77 participants were recruited for this study. Participant data was excluded from analysis due to technical error (*n*=3), researcher error (*n*=2) and physical system malfunction (*n*=2). Participants ranged in age from 18 to 48 years old (*M*=22.51, *SD*=5.174) and reported genders of male (*n*=30), female (*n*=39) and other (*n*=1). Of the participants whose data were used, the majority reported using virtual reality systems sporadically (51.4%); the remaining participants reported using VR never (32.9%), occasionally (10.0%), frequently (2.9%), or very frequently (2.9%). Exclusion criteria were as follows: the participants had to be 18 years of age or older. Participants were university students and members of the public who were recruited through the Institute for Simulation and Training (IST) SONA, an online research recruitment system used at the University of Central Florida.

Experimental Apparatus

Equipment utilized in this study were a vibrotactile display (Figures 3.1 and 3.2), a desktop computer running Windows 10 with 4 GB of RAM, an HDMI and DisplayPort connection, a USB 2.0 port, an Intel Core i7 processor and a GeForce GTX 1060 graphics card, Additional materials included an HTC Vive headset with controllers and HTC base stations (Figure 3.1) and two virtual simulations provided by the National Institute of Standards and Technology (NIST). The NIST simulations are free, open-source, and were provided to the researcher when he took part in a first responder haptic interface design challenge during the Spring and Summer of 2019. The tactile display (Figure 3.2) contains twelve vibrotactile motors produced by Precision Microdrives, a battery pack produced by Anker, and an Arduino Uno microcontroller.

Figure 3.1. The HTC Vive Cosmos, a VR headset with two controllers. Picture taken by the author.

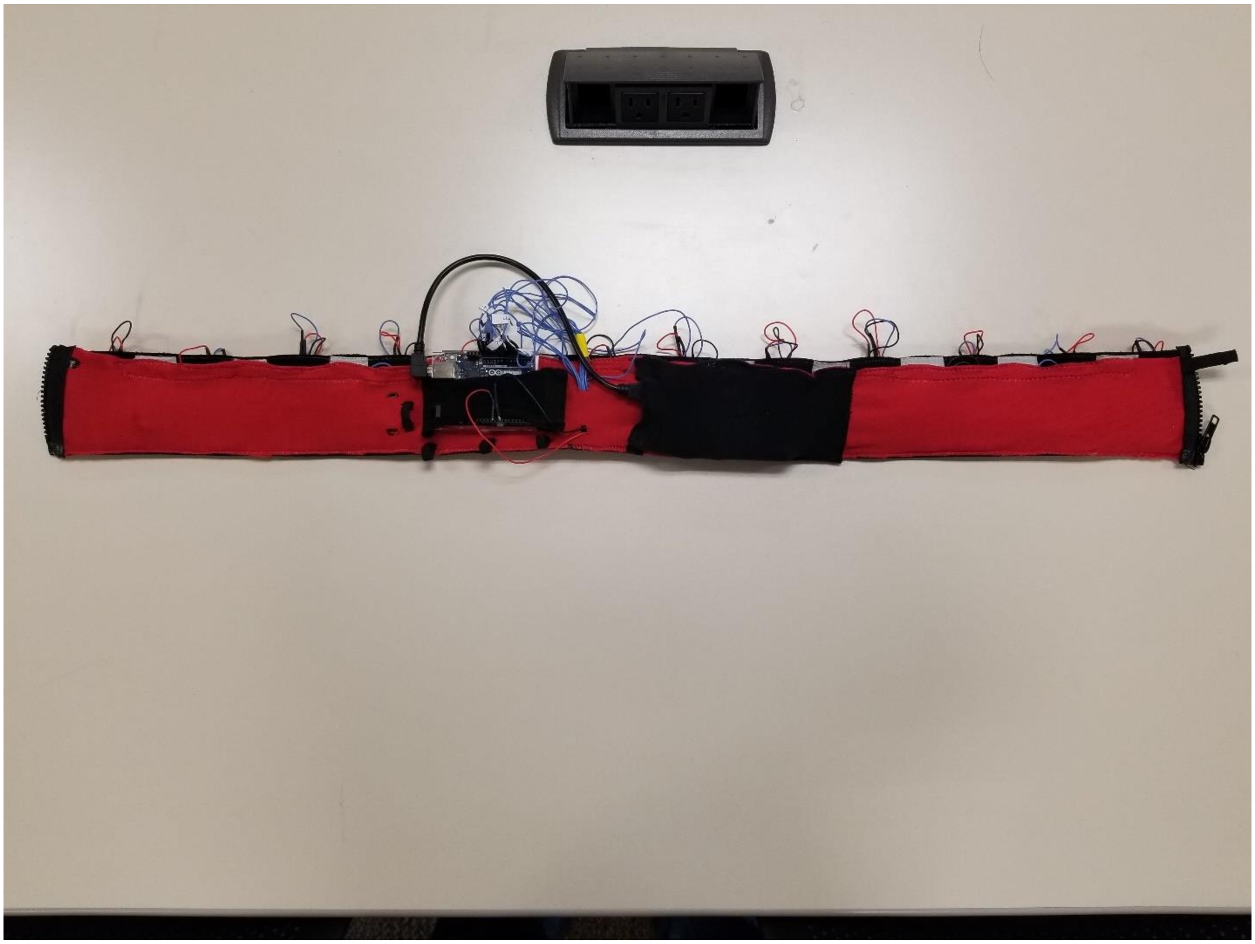


Figure 3.2. A waist-worn vibrotactile display. Picture taken by the author.

Experiment Design

The present study examined the effect of a worn vibrotactile display on performance and workload. This experiment assessed the impact of three independent variables. The independent variables consisted of navigation condition (with and without tactile display), wayfinding strategy (route-learning or orientation strategy), and level of spatial anxiety (high or low). The dependent variables in this study were workload as measured by the NASA-TLX and time (in seconds) to successful completion of experiment trials. A 2x2 repeated-measures design was utilized to investigate the effect of device condition on performance and workload. A Latin Squares randomization protocol was used to counterbalance the presentation of experiment conditions. The experiment investigated the effect of spatial anxiety level on performance across device conditions. A 2x2 between-subjects design was used to assess the impact of spatial anxiety on performance and workload (Table 3.1).

Table 3.1. Experimental design for examining the effect of spatial ability on performance variables.

	High Spatial Ability	Low Spatial Ability
Control	Control (High SpA)	Control (Low SpA)
Tactile display	Tactile display (High SpA)	Tactile display (Low SpA)

Independent Variables

Tactile Display

A tactile display in the form of a belt or vest was utilized in the current study. The two levels of the tactile display, the independent variable, were presence or absence of the device. In one of the experimental conditions a vibrotactile belt of the researcher's design was used.

Spatial Anxiety Score

Participants' individual levels of spatial anxiety were assessed prior to starting the experiment trials in order to establish a baseline level of anxiety related to wayfinding. Spatial anxiety was operationalized according to Lyons and colleague's (2018) Spatial Anxiety Scale.

Wayfinding Strategy

Participants' individual wayfinding strategies were assessed according to Lawton's (1996) Wayfinding Strategies scale and completed prior to taking part in experiment trials. Wayfinding strategy for each participant was coded dichotomously as either a route-learning or orientation strategy.

Dependent Variables

Completion Time

Performance was assessed as a function of trial completion time. In each experiment condition, participants were asked to find two simulated firefighter teammates and escort them to the exit of a building, thereby bringing them to safety. The location of the simulated teammates varied randomly across trials.

Workload

Workload is the demand on an operator's ability to cope with task and environmental demands (Hart & Staveland, 1988). For the purposes of the current research, participants' workload was assessed using the NASA-TLX immediately after each of the two experiment conditions.

Questionnaires and Surveys

Demographic Questionnaire

A demographics questionnaire was administered to participants at the beginning of the experimental session (see Appendix B). This measure included items related to age, gender, handedness, whether the participants had first responder or military experience, and if they were wearing glasses or contacts. The pre-trial measures were administered on a laptop computer.

Spatial Anxiety Scale

The Spatial Anxiety Scale (SAS) assesses the level of anxiety that people experience in situations requiring navigational or spatial skills, such as attempting to navigate a new route without a map. The SAS consists of eight questions answered with a 5-point Likert scale; the end points on the scale are labeled *very much* (4) and *not at all* (0). The Spatial Anxiety Scale has been found to be high on external validity (r = .97) and a Cronbach’s alpha of .83 was observed (Lyons, Ramirez, Maloney, Rendina, Levine, & Beilock, 2018). Internal reliability was demonstrated for all three subscales of the SAS: Mental-Manipulation Ability (α = .877), Navigation Ability (α = .864), and Imagery Ability (α = .810). The SAS is available in Appendix C.

Wayfinding Strategy Scale

The Wayfinding Strategy Scale (WSS) is a 5-point Likert scale developed to assess which of two strategies participants use while navigating: a route-learning strategy or an orientation strategy. An orientation strategy requires someone to monitor one's own position in the environment relative to points of reference, or landmarks. The WSS comprises 14 strategies for wayfinding, such as how to track compass directions while mobile. End points on the scale are labeled *extremely typical of me* and *not at all typical of me*. Cronbach alpha for the WSS was .65 for route-learning strategies and .73 for orientation strategies (Lawton, 1994). The WSS is available in Appendix D.

Workload

The current study measured participants' self-reported workload immediately following each condition via the NASA Task Load Index (Hart & Staveland, 1988). The NASA-TLX comprises six items, which provide workload assessments for mental demand, physical demand, temporal demand, perceived performance, perceived effort, and frustration, as well as an overall measure of global workload based on the mean of the six subscales (Hart, 2006; Hart & Staveland, 1988). Each subscale is scored between 0 and 100, with lower scores indicating lower levels of workload and higher scores indicating higher levels of workload. The test-retest rating was .83 for the NASA-TLX (Hart & Staveland, 1988). The NASA-TLX can be found in Appendix E and was administered in paper form after each experiment scenario.

Simulation

The simulation used in this dissertation was originally developed by NIST and offered to the researcher as part of his participation in a first responder haptic interface competition. The researcher and his team further developed the simulation using the Unreal Engine 4 (UE4) development platform. Additional development involved modifying the UE4 files such that data from the simulation could be communicated wirelessly to the Arduino Uno driving the vibration motors. An example of the logic pathway data traveled through the system can be viewed in Figure 3.3.

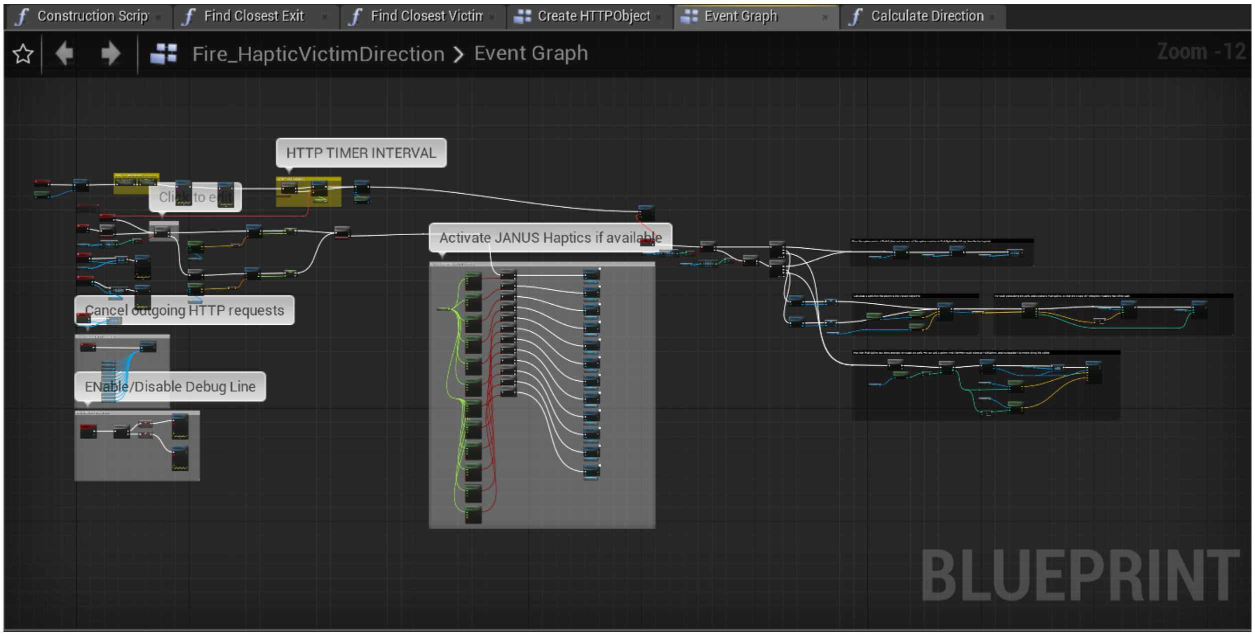


Figure 3.3. UE4 logic pathway.

Procedure

Participants were briefed on the purpose of the study and given an informed consent form to sign, which indicated the purposes of the study. Upon indicating consent, participants completed a demographic survey, a Wayfinding Strategies Scale, and a Spatial Anxiety Scale. Participants were then instructed on how to navigate by way of a tactile display. Participants donned a tactile display and wireless VR headset and then completed a practice scenario. The practice scenario began with the participant on a firing range. By using the handheld Vive controllers, participants familiarized themselves with how to use the controllers to control a simulated rifle. The participants demonstrated competence with the Vive headset and controllers by successfully hitting five targets in a row. The second part of the practice scenario consisted of a simulation where multiple shooters are shooting at the participant, in the role of a police officer, who is in an underground parking garage. As non-player characters (NPCs) fire at the participant, the tactile display vibrated, indicating the location of the NPC currently shooting. Participants demonstrated competence with navigating through the use of a tactile display by successfully engaging five or more of the ten shooters. If participants did not initially demonstrate competence with the active shooter part of the training condition, they were allowed up to two additional tries to achieve a satisfactory score. Upon successful completion of the practice scenario, the experiment trials commenced.

Participants were instructed that they may end any trial at any time by stopping in place, removing the VR headset, and telling the researcher they wish to stop the trial. If the participant wished to end the trial but continue with the study, they could still complete the NASA-TLX for each condition, even if they did not finish, as failure to complete the trial may indicate a high level of stress, which was a variable of interest in this study in the form of workload. Participants were randomly assigned to one of two counterbalanced experimental blocks. In both blocks the participants completed the same simulation. One block was completed utilizing a tactile display and the other was completed without the tactile display.

Participants were tasked with finding two NPC firefighter teammates in a virtual simulation of a smoke-filled building and leading them to safety. Participant performance was recorded as time to complete the scenario and was also coded dichotomously: success or failure. Participants failed either experimental trial if they ceased use of the tactile display and VR headset before completing the trial or took longer than eight minutes to find and rescue both NPCs. Proulx and Fahy’s (1997) fire evacuation data indicate a six-minute cutoff is reasonable; however, the choice to use an eight-minute cutoff was made by the researcher after consulting with his committee. Participants were allowed an extra two minutes because of the novelty of the tactile display and VR headset. When taking part in the experiment trials, vibratory signals were automatically initiated by each participant’s movement through the simulation. A signal consisted of three vibrations in rapid succession: 0.4 seconds of vibration and 0.4 seconds of no vibration. The signal was repeated until a reorientation of the body was required. The location on the body where the participants felt the vibrations corresponded to the direction in which they should have moved upon feeling the vibration. Figure 3.4 depicts a participant view of the simulation. A simulated victim NPC can be viewed in Figure 3.5.

Figure 3.4. A view of the elevators in the virtual, smoke-filled office building.

Figure 3.5. A simulated victim.

Upon completion of each condition, participants were immediately instructed to remove the Vive Cosmos Elite VR headset and complete a paper version of the NASA-TLX to indicate the workload required to complete the trial. Participant completion times were recorded with a stopwatch and recorded in second units. Upon completing the NASA-TLX for the first trial, participants were offered a five-minute break. After taking a five-minute break or declining to rest, participants were instructed to don the VR headset again and begin the second trial. Upon finishing the second trial, participants completed a second NASA-TLX and then were debriefed and compensated for their time and participation. No participants ended their participant before the study concluded and none reported experiencing simulation sickness. The experiment took approximately one hour to complete each session.

CHAPTER FOUR: RESULTS

Results were analyzed for data from 70 participants in SPSS 28. Prior to testing the mainline hypotheses, the data were tested for normality and homogeneity of variance. The results of the Shapiro-Wilk (1965) test for the workload and time variables can be viewed in Table 4.1. The results of Levene's (1960) test for the workload and time variables can be viewed in Table 4.2.

Table 4.1. Tests of normality.

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
TLX Mental	0.096	140	0.003	0.963	140	0.001
TLX Physical	0.158	140	0.000	0.857	140	0.000
TLX Temporal	0.093	140	0.005	0.970	140	0.003
TLX Performance	0.127	140	0.000	0.890	140	0.000
TLX Effort	0.112	140	0.000	0.959	140	0.000
TLX Frustration	0.117	140	0.000	0.928	140	0.000
TLX Total	0.077	140	0.042	0.978	140	0.023
Stop Time	0.110	140	0.000	0.937	140	0.000

a. Lilliefors significance correction

Table 4.2. Homogeneity of variance analyses.

Tests of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Stop Time	Based on Mean	0.861	1	138	0.355
TLX Mental	Based on Mean	6.462	1	138	0.012
TLX Physical	Based on Mean	0.005	1	138	0.944
TLX Temporal	Based on Mean	4.007	1	138	0.047
TLX Performance	Based on Mean	13.392	1	138	0.000
TLX Effort	Based on Mean	12.685	1	138	0.001
TLX Frustration	Based on Mean	2.231	1	138	0.138
TLX Total	Based on Mean	3.232	1	138	0.074

Preliminary analyses indicated the data were non-normal and heteroscedastic. The research plan to use a repeated measures *t*-test was modified to use the Wilcoxon sign rank test to account for unequal population variances. Analyzing the data for symmetry in the distribution of differences, the data were found to be nonsymmetrical for all variables; thus, the data analysis plan was further modified to account for skewed data and the researcher determined the sign test was the optimal analytical method to pursue (Mendenhall, Wackerly, & Scheaffer, 1989). Results indicated significant differences between the experimental and control conditions for completion time ($z = -6.57$, $p < .001$) and overall workload scores ($z = -7.53$, $p < .001$; Table 4.3). The results of TLX subscales are contained in Table 4.4.

Table 4.3. Sign test results for TLX subscales.

Test Statistics[a]						
	CTLXMent - BTLXMent	CTLXPhys - BTLXPhys	CTLXTemp - BTLXTemp	CTLXPerf - BTLXPerf	CTLXEff - BTLXEff	CTLXFrus - BTLXFrus
Z	-6.353	-2.981	-4.445	-7.262	-7.016	-6.912
Asymp. Sig. (2-tailed)	0.000	0.003	0.000	0.000	0.000	0.000
a. Sign Test						

Table 4.4. Means and standard deviations for time and workload variables.

Descriptive Statistics					
	N	Mean	Std. Deviation	Minimum	Maximum
BTLXMent	70	37.64	24.133	0	90
BTLXPhys	70	17.21	19.367	0	80
BTLXTemp	70	41.71	24.000	0	90
BTLXPerf	70	21.14	23.899	0	95
BTLXEff	70	40.29	23.171	0	85
BTLXFrus	70	23.07	23.067	0	75
BTLXTotal	70	30.14	16.562	0	72
BStopTime (seconds)	70	323.5200	132.51441	92.01	853.87
CTLXMent	70	67.6429	19.12433	10.00	100.00
CTLXPhys	70	21.5714	19.25314	0.00	80.00
CTLXTemp	70	59.1429	20.01759	5.00	100.00
CTLXPerf	70	62.6429	32.45645	0.00	100.00
CTLXEff	70	69.8571	16.52779	25.00	100.00
CTLXFrus	70	56.8571	27.45446	0.00	100.00
CTLXTotal	70	56.2857	14.05410	19.17	82.50
CStopTime (seconds)	70	561.5990	166.11148	186.31	1300.00

The means for TLX and time data indicate a trend toward decreased workload and time scores for the experimental condition, suggesting the use of a tactile display improves performance by assisting the participants with completing the task in less time. Further, workload scores also decreased, indicating that participants reported experiencing less workload than in the control condition while also displaying improved performance. The trend toward lower completion times and lower workload scores is further observed by the *z*-scores, all of which have a negative value.

Due to the non-normal distribution, the decision was made to conduct correlation analyses using Spearman's correlation test (de Winter, Gosling, & Potter, 2016; Zar, 2005). Results for the relationship between workload and performance were found to be significant. Evidence suggests that for both the experimental and control trials the more quickly participants completed the simulation, the lower the level of overall workload they self-reported experiencing. A positive correlation was found in the experimental condition, $r(70) = .482$, $p < .001$ (Table 4.5). Results for the control condition demonstrated a positive correlation, $r(70) = .238$, $p = .047$ (Table 4.6).

Table 4.5. Workload and Performance Correlations.

Correlations				
			Belt TLX Total	Belt Stop Time
Spearman's rho	Belt TLX Total	Correlation Coefficient	1.000	.482**
		Sig. (2-tailed)		0.000
		N	70	70
**. Correlation is significant at the 0.01 level (2-tailed).				

Table 4.6. Workload and Performance Correlations.

Correlations				
			Control TLX Total	Control Stop Time
Spearman's rho	Control TLX Total	Correlation Coefficient	1.000	.238*
		Sig. (2-tailed)		0.047
		N	70	70
*. Correlation is significant at the 0.05 level (2-tailed).				

Spatial anxiety data were checked for normality and homogeneity of variance. The data were found to be normally distributed (Table 4.7) and heteroscedastic (Table 4.8). The descriptive statistics for spatial anxiety are displayed in Table 4.9.

Table 4.7. Normality analysis for spatial anxiety data.

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
SASTotal	0.064	70	.200*	0.988	70	0.761
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

Table 4.8. Homogeneity of variance analysis for spatial anxiety data.

Tests of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Belt TLX Total	Based on Mean	1.895	17	30	0.061
	Based on Median	0.570	17	30	0.888
Control TLX Total	Based on Mean	2.165	17	30	0.031
	Based on Median	0.609	17	30	0.858

Table 4.9. Spatial anxiety descriptive statistics.

Descriptive Statistics							
	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
SASTotal	70	64	24	88	57.69	14.327	205.262

Although the spatial anxiety data were found to be normal, the hypotheses called for comparisons with data found to be nonparametric. Therefore, the decision was made to continue analyzing data using Spearman’s rho. Results did not demonstrate a significant relationship between spatial anxiety and performance (Table 4.10). The evidence suggests that participants’ individual level of spatial anxiety brought to the task does not influence task performance.

Table 4.10. Correlation analysis for spatial anxiety and performance.

Correlations					
			Spatial Anxiety Total	Belt Stop Time	Control Stop Time
Spearman's rho	Spatial Anxiety Total	Correlation Coefficient	1.000	0.117	0.006
		Sig. (2-tailed)		0.334	0.958
		N	70	70	70

Spearman's correlation was also used to analyze the relationship between spatial anxiety and workload due to the non-normality of workload data in this study. Results did not demonstrate evidence of a significant relationship between spatial anxiety and participants' self-reported workload. Table 4.11 displays the correlation results for the spatial anxiety and workload data.

Table 4.11. Correlation analysis for spatial anxiety and workload.

Correlations					
			Spatial Anxiety Total	Belt TLX Total	Control TLX Total
Spearman's rho	Spatial Anxiety Total	Correlation Coefficient	1.000	0.211	0.233
		Sig. (2-tailed)		0.079	0.052
		N	70	70	70
**. Correlation is significant at the 0.01 level (2-tailed).					

Due to the lack of evidence indicating significant correlations between spatial anxiety and workload or performance, exploratory analyses were conducted to determine the underlying nature of these findings. Prior research found evidence for a significant association between spatial anxiety and performance (Lawton, 1994, 1996; Lyons et al., 2018). Those studies, however, did not investigate workload. Workload and performance are multifaceted concepts, as indicated by the subscales for both the NASA-TLX and the Spatial Anxiety Scale (Hart, 2006; Lyons et al., 2018). The NASA-TLX comprises six subscales: mental workload, physical workload, temporal workload, performance, effort, and frustration. The Spatial Anxiety Scale is composed of three subscales: mental manipulation, imagery, and navigation.

Spearman correlation analyses were conducted for all Spatial Anxiety Scale and NASA-TLX subscales to determine the underlying nature of the relationship between spatial anxiety and workload. An additional set of analyses was conducted for the Spatial Anxiety subscales and performance. Of the three subscales, two emerged as having a significant association with workload and only one achieved significance when calculated with performance completion time. Imagery was found to be significantly correlated with temporal workload in the experimental condition, but not the control condition ($r(70) = -.285$, $p < .02$ and $r(70) = .002$, $p < .99$, respectively). Evidence for a significant correlation was found between mental manipulation and mental workload, effort, frustration, and overall workload in the experimental condition. In the control condition, mental manipulation was found to be significantly correlated with performance, frustration, and overall workload. The values for the significant correlations in the experimental and control conditions can be seen in Tables 4.12 and 4.13, respectively.

Table 4.12. Subscale correlations in the experimental condition.

Correlations

			Belt TLX Mental	Belt TLX Physical	Belt TLX Temporal	Belt TLX Performance	Belt TLX Effort	Belt TLX Frustration	Belt TLX Total
Spearman's rho	SAS Mental Manipulation	Correlation Coefficient	.237*	0.062	0.130	0.192	.248*	.276*	.294*
		Sig. (2-tailed)	0.049	0.611	0.284	0.111	0.039	0.021	0.013
		N	70	70	70	70	70	70	70
	SAS Imagery	Correlation Coefficient	-0.122	-0.029	-.285*	0.078	0.074	0.051	-0.045
		Sig. (2-tailed)	0.314	0.813	0.017	0.521	0.541	0.676	0.710
		N	70	70	70	70	70	70	70
	SAS Navigation	Correlation Coefficient	0.229	0.140	0.122	-0.027	0.230	0.125	0.217
		Sig. (2-tailed)	0.056	0.248	0.313	0.826	0.055	0.302	0.072
		N	70	70	70	70	70	70	70

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.13. Subscale correlations in the control condition.

Correlations									
			Control TLX Mental	Control TLX Physical	Control TLX Temporal	Control TLX Performance	Control TLX Effort	Control TLX Frustration	Control TLX Total
Spearman's rho	SAS Mental Manipulation	Correlation Coefficient	0.087	0.062	0.119	.265*	-0.071	.243*	.273*
		Sig. (2-tailed)	0.475	0.610	0.328	0.026	0.557	0.043	0.022
		N	70	70	70	70	70	70	70
	SAS Imagery	Correlation Coefficient	0.014	0.008	0.002	0.084	0.072	0.122	0.129
		Sig. (2-tailed)	0.911	0.946	0.986	0.487	0.556	0.314	0.287
		N	70	70	70	70	70	70	70
	SAS Navigation	Correlation Coefficient	0.140	-0.078	0.184	0.091	0.030	0.059	0.153
		Sig. (2-tailed)	0.249	0.519	0.128	0.454	0.807	0.626	0.205
		N	70	70	70	70	70	70	70

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Interestingly, the navigation subscale of spatial anxiety was not significantly correlated with any workload subscales in either condition. This finding was unexpected considering participants were asked to self-report their workload on a series of wayfinding tasks. Upon analyzing the spatial anxiety subscales and performance correlations, mental manipulation emerged as the only significant correlation with performance in the experimental condition, but not the control condition ($r(70) = .30$, $p < .01$ and $r(70) = .03$, $p < .81$, respectively). Mental manipulation's statistically significant associations with self-reported workload in the experimental and control conditions and with performance in the experimental condition indicate that an individual's anxiety about rotating or modifying images in one's own mind is related to the person's ability to perform a wayfinding task in a visually impaired scenario while using a navigation tool. This same component of spatial anxiety also related to the person's self-reported mental workload and effort expended in the experimental (navigation tool) condition and self-ratings of performance in the control condition. Frustration experienced and overall workload incurred were correlated with mental manipulation in both conditions, which may indicate that participants who report high levels of spatial anxiety about mental manipulation ability found the search-and-rescue task to be arduous with and without a navigation aid.

CHAPTER FIVE: CONCLUSION

Establishing and maintaining SA is a vital skill for firefighters. Workload and SA are connected, and researchers are still seeking to understand the intertwined nature of the two constructs (Wickens, 2002b). This dissertation is a step toward understanding how tactile displays affect self-reported workload on a simulated firefighter search-and-rescue task. Participants in this study completed a series of questionnaires asking about their demographics, preferred wayfinding strategies, and levels of spatial anxiety. Upon completion of the surveys, participants attempted two firefighter search-and-rescue simulations: one with and one without a tactile display in the form of a vibrating belt. Participants were then asked to report the levels of workload experienced during each search-and-rescue task using the NASA-TLX. Workload and performance results indicated support for the first, second, and third hypotheses. Evidence was not found to support a relationship between spatial anxiety and workload or performance variables (Table 5.1).

Table 5.1. Hypotheses Outcomes.

	Hypotheses	**Supported**	**Effect Size**
H_1	Participants will have improved levels of performance in the vibrotactile condition compared to the control condition.	Supported	0.15
H_2	Participants will report experiencing lower levels of workload in the vibrotactile condition compared to the control condition.	Supported	0.18
H_3	Participants who report experiencing higher workload will have lower levels of performance than participants who report experiencing lower levels of workload across both the vibrotactile and control conditions.	Supported	C: 0.24 D B: 0.48 D
H_4	Participants who score high on spatial anxiety will have lower levels of performance than participants who score low on spatial anxiety across both the vibrotactile and control conditions.	Not Supported	N/A
H_5	Participants who score high on spatial anxiety will experience more workload than participants who score low on spatial anxiety across both the vibrotactile and control conditions.	Not Supported	N/A

C = control condition, B = experimental condition

Performance

Hypothesis 1, the effect of vibrotactile display on performance completion time, was supported (Table 5.1). Participants completed the simulated search-and-rescue task faster when assisted by a vibrotactile belt as a tool. When attempting the control condition, participants had no indication of where victims were located or the suggested path to find the victim. It is important to note that the participants used a novel vibrotactile display for completing the search-and-rescue task in a novel virtual environment. Participant performance was not affected by experience with the vibrotactile belt due to a lack of prior experience. The novelty of virtual reality interaction may have influenced performance completion time; however, this dissertation used a within-subjects design to control for as many individual difference variables as possible across the control and experimental conditions. If novelty of interaction format influenced performance completion time, participants' results could still be compared across conditions. Presentation of the tactile display was counterbalanced across participants to minimize the effect of the first trial exposure for each participant on their second trial exposure.

Workload

Hypothesis 2, the effect of tactile display on workload, was also supported. Evidence suggest that participants reported lower levels of overall workload for the search and rescue task when assisted by the vibrotactile display than in the control condition. Mean scores on the NASA-TLX subscales indicated participants reported experiencing lower levels of workload on all subscales in the vibrotactile condition compared to the control condition (Table 4.4). Results of the sign test for the TLX subscales demonstrate that participants, on average, reported experiencing lower levels of workload on all NASA-TLX subscales when rating their experience in the experimental condition compared to the control condition. This finding suggests that participants reported experiencing lower levels of workload while completing the search-and-rescue task with a tactile display as a navigation tool than when completing the same task unaided.

Workload and Performance

Hypothesis 3, the relationship between workload and performance, was also supported. Results suggests that across conditions the faster participants completed the experimental and control trials, the more likely they were to self-report experiencing lower levels of workload. These results do not indicate a causal relationship; rather, a correlational link. More research is required to determine if participants complete search-and-rescue tasks faster due to experiencing lower levels of workload or if lower levels of workload are experienced because participants spent less time completing the task. Additional research involving subscales for performance, fatigue, and workload are required to parse variables with a finer degree of granularity. This dissertation demonstrates that a correlational relationship exists; however, further research is needed to determine the nature of the relationship between workload and performance.

Spatial Anxiety and Performance

Evidence for a significant association between spatial anxiety and performance was not found. Prior research used mental rotation and spatial perception tasks completed on a sheet of paper (Lawton, 1996) or on a computer (Lyons, 2018). The current study compared spatial anxiety scores to workload incurred and performance during a search-and-rescue task in a virtual environment. It is possible the novel and different format presented by the VR world influenced scores in such a manner that statistically significant results were not discovered. Lawton (1994, 1996) and Lyons et al. (2018) investigated the effect of spatial anxiety on performance during mental rotation and spatial perception tasks; the researchers did not investigate the relationship between spatial anxiety and workload. An exploratory analysis of the Spatial Anxiety subscales revealed a statistically significant association between mental manipulation and performance in the experimental condition, but not the control condition. One possible explanation for this finding, when analyzed in context with the exploratory analyses of the Spatial Anxiety and NASA-TLX subscales, is that participants who self-reported high levels of spatial anxiety about their ability to mentally manipulate objects spent more time trying to keep a mental map of the virtual environment in their mind while navigating. More research is needed to determine the nature of the relationship between spatial anxiety about mental manipulation and performance on a virtual wayfinding task.

Spatial Anxiety and Workload

The lack of a significant relationship between the spatial anxiety and workload variables, across conditions, is an interesting finding due to the lack of a significant relationship between spatial anxiety and performance. This dissertation presents a first step toward establishing a link between workload and spatial anxiety; however, no evidence was found to support the existence of a link between the two constructs. Participants' self-reported workload was influenced by the presence of a tactile display in this study. Lawton (1994, 1996) and Lyons et al. (2018) examined performance but did not examine workload and did not investigate the use of a tactile display used by participants. The differences between prior research and the current study may explain the differences in research findings. Lawton (1994) investigated the relationship between spatial anxiety and performance on a mental rotation task and a spatial perception task and asked participants to complete a spatial anxiety questionnaire after engaging in the mental rotation and spatial perception tasks. The current study asked participants to complete a spatial anxiety questionnaire before engaging in the experiment trials because the researcher designed the study such that performance on the spatial task would not affect self-report of spatial anxiety.

Exploratory analyses of the Spatial Anxiety subscales and the NASA-TLX subscales revealed an interesting pattern. Participants who scored higher on the mental manipulation subscale were more likely to self-report higher levels of workload on the frustration subscale and higher levels of overall workload across both conditions. These findings may indicate that participants recognized the search-and-rescue task was difficult and frustrating, whether a navigation tool was used or not. This proposed explanation is further supported by the differences in subscale results across conditions. In the experimental condition, mental manipulation was significantly correlated with the mental workload and effort subscales; in the control condition, mental manipulation was significantly correlated with the performance subscale. One reason for the differences in significant correlations between the subscales across conditions may be due to the inability of participants to locate victims in the control condition (Appendix F). Participants who scored higher on the mental manipulation subscale and were unable to locate victims may have attributed their high levels of workload to their performance on the search-and-rescue task. When using the tactile display, participants who scored higher on mental manipulation may have attributed their workload to the effort and amount of mental resources required to successfully complete the search-and-rescue task. More research is required to confirm these hypotheses.

General Discussion

The results of this study indicate that participants engaged in a simulated search and rescue task in a low visibility environment benefit from the assistance of a vibrotactile display as a tool. Performance improved as a result of using the vibrotactile belt as indicated by faster completion times. Further, while participants completed the task in less time in the vibrotactile condition, the participants also reported experiencing lower levels of workload when using the vibrotactile belt as a tool. This means that participants self-reported that they had more mental resources to engage in the search and rescue task when assisted by a vibrotactile display. Evidence for a relationship between spatial anxiety and workload or performance was not found. More research is needed to determine the nature of the link between spatial anxiety and workload or performance on a spatial task in a virtual environment.

A better understanding of how individual differences, such as individual spatial anxiety level, influence firefighter performance could lead to improved firefighter selection and training. Becoming overwhelmed while navigating a complex and dynamic environment may be fatal for a first responder. Understanding if and how automated aids, such as vibrotactile displays, could help firefighters perform their tasks quicker and more safely, even if an individual reports being highly anxious about spatial tasks, could lead to more lives saved. Adding another item to a first responder's toolkit is not sufficient for improved performance. The effects of that tool on the operator, such as workload experienced, must be thoroughly understood to ensure the costs of use do not outweigh the benefits and actually lead to improved performance and desirable outcomes.

Data collection, analysis, and reporting for the current study took place during the COVID-19 pandemic of 2020-2021. Necessary precautions were taken to ensure the safety of study participants and the researcher, and the safeguards were approved by the IRB. No transmission of respiratory illness as a result of participation in this study was reported.

Implications

The implications of this study have real world consequences such as casualty rate. Firefighting is a dangerous task that can claim the lives of both victims and firefighters. In these cases, time is of the essence and places a maximum ceiling on recovery of victims before there is risk of fatality for both victims and firefighters. Therefore, firefighters rely on every possible tool to maximize their performance within this critical time period. The results of this study, when translated into real-world performance, are measured in lives saved and risks minimized to firefighter personnel. Tactile navigation aids can also aid evacuees in the event of a disaster, particularly when building electrical systems fail or when the environment becomes filled with obscurant substances. This dissertation found evidence to demonstrate the benefits of tactile displays to first responders. More research is needed to determine how and when tactile displays can benefit other populations in different scenarios.

Recommendations

The results provide evidence that tactile displays are a useful tool for assisting people with spatially complex tasks in visually degraded conditions. One recommendation from this study is that first responder agencies should devote more resources to understanding the effects, costs, benefits, and outcomes of tactile displays on personnel. If beneficial outcomes are demonstrated, training programs will need to be developed and the methodology described in this study can serve as a starting point for instructional system designers. A specific recommendation for trainers, system designers, and equipment manufacturers is to seek first responder input from the beginning and throughout the development process. Researchers of tactile displays should keep simulations and equipment simple, have spare tools and parts for as much of the equipment as possible, and develop a troubleshooting guide for resolving issues that may arise during the research. The current study encountered many issues during the piloting and data collection processes and institutionalized knowledge was useful in reducing the amount of time until the system regained functionality. This reduction in system downtime was important for collecting data safely and efficiently during the COVID-19 pandemic. More research in the area of tactile displays for first responders is needed to make specific recommendations for firefighter agencies and designers of first responder equipment.

Limitations

Simulation is a useful tool for minimizing risks to personnel while studying and training for dangerous tasks; however, a lab-based study cannot fully replicate the conditions experienced in the field. The current research subjected participants to a stressful task in a stressful, but virtual, environment. Certain nuances of an emergency search-and-rescue situation were not experienced, such as performing the task while carrying a full load of firefighter gear, carrying victims to safety, or feeling the heat radiating from flames. While this dissertation examined the effect of a tactile display on performance and workload, an operator's available bandwidth is only one aspect of SA. The role of SA on firefighter workload and performance needs to be studied more thoroughly to determine how tactile displays can aid firefighters in the many tasks they perform. Participants in the current study did not carry a full firefighter load or an unconscious victim and, thus, were not physically exerting themselves strenuously under a load.

More research is needed to determine the role of spatial anxiety on workload and performance in a search-and-rescue task. The current study did not find significant correlations between spatial anxiety and performance or workload; however, this line of research needs to be replicated and applied in different scenarios before more definitive conclusions can be drawn. Members of the general public participated in this study, therefore, the results may not be applicable to trained firefighters. While the simulation used for this dissertation was designed with feedback from firefighter subject matter experts, data need to be collected from experienced firefighting personnel to increase the external validity of findings.

Several difficulties arose during data collection due to the many parts and systems integral to the research. The simulation was developed in Unreal Engine 4, viewed on an HTC Vive VR headset, and sent data over a wireless network to a proprietary tactile display powered by an Arduino Uno. During the design and data collection phases of the dissertation, technical difficulties were experienced with each piece of equipment and had to be resolved for research to continue. While technical difficulties did affect the ability to collect data, data were not affected because the simulation and tactile display were not modified due to troubleshooting electrical equipment or repairing physical components. The system allowed for data to be collected uniformly when the system was functional. Any technical issues experienced resulted in a loss of system functionality and the inability to collect data.

Technical error

During data collection, the researcher experienced difficulty pairing the Arduino Uno with the simulation computer. This issue occurred for three research participants and resulted in premature termination of the experiment sessions. The underlying cause was the desktop computer was running low on storage and the researcher resolved the issue by moving earlier versions of the UE4 files to an external hard drive.

Physical system malfunction

Connector pins on the tactile display were snapped by two participants while using the display. This resulted in a loss of communication between the Arduino and the vibrotactile motors. The researcher resolved this by soldering new pins on to the connection wires.

Researcher error

Data collection for two participants proceeded normally even though the researcher made an error. Immediately following the experiment sessions, the researcher noticed that data had not been recorded. The solution to this issue was to update the lab checklist to ensure no steps were skipped during data collection.

Future Research

Firefighters and victims die in preventable circumstances every year. Any tool used by firefighters must undergo extensive testing both in the laboratory and the field before widescale deployment is advisable. The current study required participants to locate victims by themselves in a low visibility virtual environment. Firefighters often work in pairs and future research should examine the ability of a pair of vibrotactile devices to assist firefighters working together on shared goals. Disasters that require firefighter intervention are dynamic situations with changing environmental conditions. The current study maintained a low visibility environment throughout trials. Future research should examine the dynamic settings where the first half of a trial is high visibility and the second half of the trial is low visibility, such as may be the case when a building is filling with smoke or experiencing electrical failure. Future research should also examine the ability of a vibrotactile belt to assist firefighters in a no visibility environment. The role of SA on firefighter performance and workload requires further study in order for researchers to be able to make recommendations that will benefit firefighting personnel.

Cardiac events are the primary cause of firefighter fatalities, and more research is needed to understand if tactile displays may be able to help prevent unnecessary deaths by reducing time and increasing resources in dangerous situations. Before the results of this dissertation can be applied more widely, field research is needed on physical simulated firegrounds. Another next step in this line of research is to examine how tactile displays can aid firefighters training on a physical fireground while using augmented reality technology. The research presented in this dissertation involved civilians playing the role of a simulated firefighter. Future research should recruit experienced first responders to see how the performance and workload of veteran firefighters is impacted by a tactile display.

Lyons et al. (2018) did not measure state anxiety and the authors mention that researching state anxiety may more clearly elucidate how spatial anxiety manifests in situ. The current study had a within-subjects design such that if spatial anxiety affected performance when completing a search-and-rescue task without a tactile aid, that effect would be reflected in participants' control condition performance scores. No such effect was discovered; however, spatial anxiety is a trait characteristic, and a state measure of spatial anxiety may find different results. Future research should investigate the relationship between state anxiety and workload experienced and performance during a simulated search-and-rescue task. Lyon et al.'s (2018) Spatial Anxiety Scale is one method for assessing spatial anxiety; other such measures exist and may elicit different results.

Conclusion

Firefighters must rely on every tool and technique available to accomplish their tasks while maintaining safety for civilians and themselves. Every piece of equipment must be thoroughly tested before deployment for field use to ensure that firefighting personnel can perform their tasks effectively while minimizing risks to themselves and others. This dissertation investigated the impact a tactile display, in the form of a vibrotactile belt, can have on firefighter performance and workload in a search and rescue scenario. Additional analyses investigated the effect of spatial anxiety on performance and workload. Evidence was found to demonstrate that a tactile display can benefit firefighter performance and workload; however, no evidence was found to indicate a link between overall spatial anxiety and overall workload or performance. Exploratory analyses of the spatial anxiety and workload subscales found significant correlations; however, more research is needed to determine the nature and directionality of these associations. This dissertation is one step among many that are needed to develop firefighting tools that improve first responder performance and save lives.

APPENDIX A: IRB APPROVAL LETTER

IRB Approval Letter

September 21, 2020

Dear Michael Schwartz:

On 9/21/2020, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	The Effects of a Tactile Display on First Responder Performance
Investigator:	Michael Schwartz
IRB ID:	STUDY00001996
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	• 1.0, Category: Faculty Research Approval; • Demographic Questionnaire.docx, Category: Survey / Questionnaire; • firefighter.PNG, Category: Other; • First Responder Tactile Display Protocol, Category:IRB Protocol; • NASA TLX.docx, Category: Survey / Questionnaire; • Recruitment Info, Category: Recruitment Materials; • Research Consent Form_IRB edits TRACK CHANGES_Clean.pdf, Category: Consent Form; • saved metrics.PNG, Category: Other; • smokeyroom.PNG, Category: Other; • Spatial Anxiety Scale.docx, Category: Survey / Questionnaire; • Training Scenario , Category: Other; • Training Target, Category: Other; • Vibrotactile belt, Category: Device Attachment; • victim photo.PNG, Category: Other; • victim rescued.PNG, Category: Other; • WAYFINDING STRATEGY SCALE.docx, Category: Survey / Questionnaire;

The IRB approved the protocol on 9/21/2020.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRBLibrary within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in are detailed in the manual. Whenyou have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Racine Jacques, Ph.D.
Designated Reviewer

APPENDIX B: DEMOGRAPHIC QUESTIONNAIRE

Demographic Questionnaire

Date: _________________Participant ID: _________

1. Age: _____(years)

2. Gender:

  a. Male

  b. Female

  c. Other

3. Handedness:

  a. Right handed

  b. Left handed

  c. Ambidextrous

4. Do you have first responder experience?

  a. No
  b. Yes (explain):____

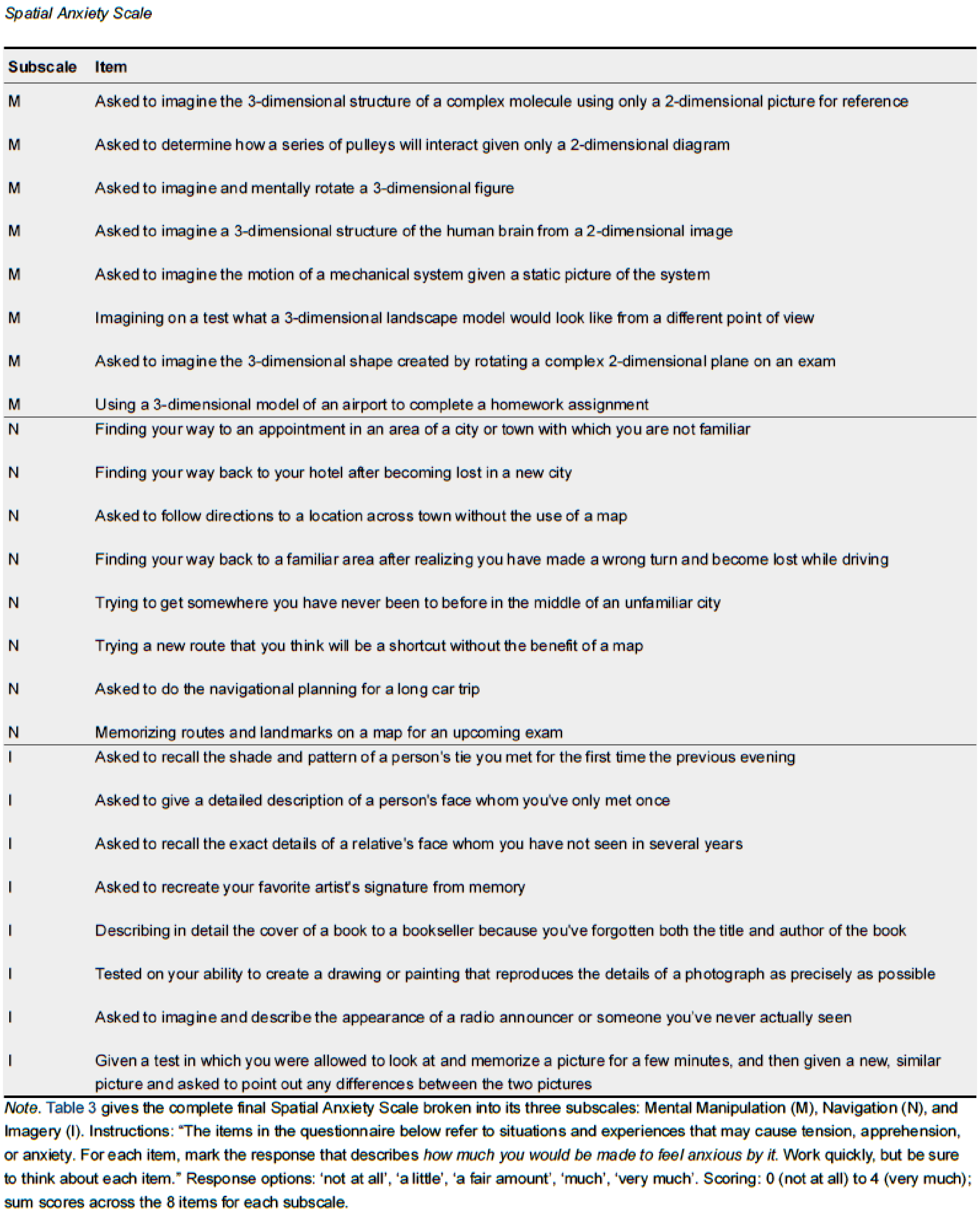
5. Do you wear glasses or contacts to correct your vision?

  a. Yes
  b. No

6. Are you wearing them now?

  a. Yes
  b. No

APPENDIX C: SPATIAL ANXIETY SCALE



Spatial Anxiety Scale

Subscale	Item
M	Asked to imagine the 3-dimensional structure of a complex molecule using only a 2-dimensional picture for reference
M	Asked to determine how a series of pulleys will interact given only a 2-dimensional diagram
M	Asked to imagine and mentally rotate a 3-dimensional figure
M	Asked to imagine a 3-dimensional structure of the human brain from a 2-dimensional image
M	Asked to imagine the motion of a mechanical system given a static picture of the system
M	Imagining on a test what a 3-dimensional landscape model would look like from a different point of view
M	Asked to imagine the 3-dimensional shape created by rotating a complex 2-dimensional plane on an exam
M	Using a 3-dimensional model of an airport to complete a homework assignment
N	Finding your way to an appointment in an area of a city or town with which you are not familiar
N	Finding your way back to your hotel after becoming lost in a new city
N	Asked to follow directions to a location across town without the use of a map
N	Finding your way back to a familiar area after realizing you have made a wrong turn and become lost while driving
N	Trying to get somewhere you have never been to before in the middle of an unfamiliar city
N	Trying a new route that you think will be a shortcut without the benefit of a map
N	Asked to do the navigational planning for a long car trip
N	Memorizing routes and landmarks on a map for an upcoming exam
I	Asked to recall the shade and pattern of a person's tie you met for the first time the previous evening
I	Asked to give a detailed description of a person's face whom you've only met once
I	Asked to recall the exact details of a relative's face whom you have not seen in several years
I	Asked to recreate your favorite artist's signature from memory
I	Describing in detail the cover of a book to a bookseller because you've forgotten both the title and author of the book
I	Tested on your ability to create a drawing or painting that reproduces the details of a photograph as precisely as possible
I	Asked to imagine and describe the appearance of a radio announcer or someone you've never actually seen
I	Given a test in which you were allowed to look at and memorize a picture for a few minutes, and then given a new, similar picture and asked to point out any differences between the two pictures

Note. Table 3 gives the complete final Spatial Anxiety Scale broken into its three subscales: Mental Manipulation (M), Navigation (N), and Imagery (I). Instructions: "The items in the questionnaire below refer to situations and experiences that may cause tension, apprehension, or anxiety. For each item, mark the response that describes *how much you would be made to feel anxious by it*. Work quickly, but be sure to think about each item." Response options: 'not at all', 'a little', 'a fair amount', 'much', 'very much'. Scoring: 0 (not at all) to 4 (very much); sum scores across the 8 items for each subscale.

APPENDIX D: WAYFINDING STRATEGY SCALE

1. **I keep track of the direction (north, south, east, or west) in which I am going.**

   Not at all typical of me Extremely typical of me

   1 2 3 4 5

2. **Before starting, I ask for directions telling me whether to go east, west, north, or south at particular streets or landmarks.**

   Not at all typical of me Extremely typical of me

   1 2 3 4 5

3. **I keep track of where I am in relationship to the sun (or moon) in the sky as I walk.**

   Not at all typical of me Extremely typical of me

   1 2 3 4 5

4. **I keep track of the relationship between where I am and the center of town.**

   Not at all typical of me Extremely typical of me

   1 2 3 4 5

5. **As I drive, I make a mental note of the mileage I travel on different roads.**

   Not at all typical of me Extremely typical of me

   1 2 3 4 5

6. **Before starting, I ask for directions telling me how far to go in terms of mileage.**

   Not at all typical of me Extremely typical of me

   1 2 3 4 5

7. **I keep track of the relationship between where I am and the next place where I have to change direction.**

Not at all typical of me Extremely typical of me

1 2 3 4 5

8. I visualize a map or layout of the area in my mind as I drive.

Not at all typical of me Extremely typical of me

1 2 3 4 5

9. I refer to a map or GPS unit as I drive.

Not at all typical of me Extremely typical of me

1 2 3 4 5

10. Before starting, I ask for directions telling me whether to turn right or left at particular streets or landmarks.

Not at all typical of me Extremely typical of me

1 2 3 4 5

11. Before starting, I ask for directions telling me how many streets to pass before making each turn.

Not at all typical of me Extremely typical of me

1 2 3 4 5

12. As I drive, I make a mental note of the number of streets I pass before making each turn.

Not at all typical of me Extremely typical of me

1 2 3 4 5

13. Before starting, I ask for a map (hand-drawn or GPS link) of the area.

Not at all typical of me Extremely typical of me

1 2 3 4 5

14. I make a mental note of landmarks, such as buildings or natural features, that I pass along the way.

Not at all typical of me Extremely typical of me

1 2 3 4 5

APPENDIX E: NASA-TLX QUESTIONNAIRE

NASA-TLX Questionnaire

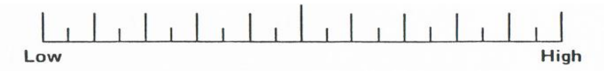
Please rate your overall impression of demands imposed on you during the exercise.

1. Mental Demand: How much mental and perceptual activity was required (e.g., thinking, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

2. Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

3. Temporal Demand: How much time pressure did you feel due to the rate or pace at which the task or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

4. Level of Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?



5. Level of Frustration: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

6. Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

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APPENDIX F: VICTIM RESCUE TIMES

Victim Rescue Times

Values indicate seconds to navigate to victim. N/A = no victim found.

Experimental		Control	
Victim 1	Victim 2	Victim 1	Victim 2
214	356	114.46	n/a
62	165	n/a	n/a
80.62	173.51	413.47	n/a
268.41	109.2	n/a	n/a
82.89	168.35	589.62	861.48
40.63	165.23	n/a	n/a
294.19	415.27	n/a	n/a
115.73	334.69	n/a	n/a
249.31	442.08	355.02	n/a
53.64	127.15	32.46	n/a
85.2	186.16	179.25	n/a
n/a	n/a	n/a	n/a
120.48	205.39	452.63	n/a
109.68	240.5	363.14	641.4
55.54	124.4	114.98	398.84
48.52	192	59.14	n/a
241.13	357.82	640.26	791.63

107.68	279.59	91.13	281.72
74.47	123.16	228.07	457.25
73.21	112.53	378.17	467.81
96.16	357.7	348.83	n/a
24.42	82.83	393.91	393.91
142.08	220.31	n/a	n/a
47.45	103.89	76.53	269.98
114.57	197.65	267.36	n/a
111.02	236.02	n/a	n/a
82.7	298.13	444.97	636.95
48.83	154.92	217.14	n/a
256	829.46	438.91	845.42
145.7	229.86	n/a	n/a
64.1	194.72	91.16	231.75
81.86	197.92	159.71	n/a
112.35	211.04	100.44	n/a
78.85	205.41	161.97	500.13
60.32	409.06	n/a	n/a
74.01	184.1	162.37	n/a
70.06	182.14	479.95	n/a
153.63	221.63	n/a	n/a

77.47	338.06	n/a	n/a
270.93	371.48	339.19	n/a
111.35	184.21	51.16	72.89
77.77	175.52	n/a	n/a
73.01	157.97	n/a	n/a
99.78	151.56	625.86	n/a
68.86	264.11	237.41	n/a
89.75	146.82	n/a	n/a
84.22	126.62	117.32	401.84
152.54	246.31	181.01	n/a
82.07	119.09	57.69	n/a
138.11	196.24	n/a	n/a
180.98	489.38	701.83	n/a
88.7	126.53	n/a	n/a
32.29	72.54	285.08	440.2
164.74	398.25	n/a	n/a
98.9	168.97	283.62	n/a
231.54	396.66	292.39	n/a
100.5	152.45	268.8	n/a
160.23	103.93	425.52	n/a
293.75	n/a	n/a	n/a

79.43	126.71	107.68	n/a
68.7	168.27	618.12	n/a
81.46	175.23	192.55	n/a
106.88	198.87	350.83	n/a
154.23	224.73	n/a	n/a
228.11	270.94	223.74	n/a
61.17	137.16	50.67	388.05
65.56	138.24	n/a	n/a
112.08	174.67	294.65	476.89
102.86	569.1	379.24	n/a
91.85	220.93	136.95	n/a

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