Towards a Tactile Display Design to Support Patient Monitoring in Anesthesia

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Abstract

Anesthesia providers are faced with the challenge of visual data overload as they must monitor a several visual displays while attending to various other visually demanding tasks. Failure to direct attention to the correct display may increase the risk of errors and adverse patient outcomes. This has led to the exploration of using the tactile channel which may be a promising means to alleviate data overload and communicate patient physiological monitoring information. However, if tactile displays are to be effective there is a need to understand how to support the three stages of information processing in the tactile channel: (a) *perception*, (b) *cognition*, and (c) *responding*.

This dissertation seeks to provide a better understanding of tactile perception and cognition to guide tactile display design which supports responding to tactile displays in anesthesia. The first study aims to understand the extent to which body movement affects tactile *perception*. The second study aims to understand how the tactile channel can be used to effectively represent physiological information in order to support *cognition*. In the third study, a tactile display is designed based on the findings of the previous studies and is evaluated for its effectiveness to support accurate *responding* when subject to concurrent task demands.

The results of this work show the importance of considering movement demands and effective information presentation in tactile display design to ensure proper perception and cognition. The findings add to the knowledgebase on tactile information processing and the results provide several design recommendations which can be considered in tactile display design to support effective communication in the tactile channel.

Chapter 1

Introduction

Anesthesia providers are faced with the challenge of visual data overload due to the large number of visual displays they must monitor to maintain a patient's health while attending to various tasks that compete for their visual attention (Betza et al., 2016; Miller & Pardo, 2011). Not directing attention to the correct display may increase the risk of errors, especially during high workload (Gaba, 2018; Loeb, 1993). Specifically, the failure to monitor patient physiological parameters frequently may result in missing critical changes in a patient's state which can result in adverse patient outcomes (Gaba, 2018; Zhang et al., 2002). Therefore, there is a need to explore alternative ways to minimize data overload to support improved attention allocation to patient physiological information from a patient safety standpoint.

One way to address challenges with visual data overload is to offload information presentation to other sensory channels, such as audition or touch (Ferris & Sarter, 2011; Sanderson, 2006). Auditory displays of information have been investigated as a means to communicate physiological information (Watson & Sanderson, 2001; 2004). However, auditory displays present certain challenges including that they may contribute to auditory data overload and alarm fatigue (Lacherez, Seah, & Sanderson, 2007; Purbaugh, 2014; Sanderson, Liu, & Jenkins, 2009). More recent work has explored the use of the tactile channel to communicate physiological information as tactile displays have been shown to alleviate challenges related to visual and auditory data overload (Dosani et al., 2012; Ferris & Sarter, 2009, 2011; Salzer & Oron-Gilad, 2015). If tactile displays are to be incorporated and effective in domains such as anesthesia, there is a need to better understand how to support three critical stages of information processing when using the tactile channel: (a) perception of the tactile stimulus, (b) cognition about the information communicated, and (c) responding to the tactile stimulus when subject to concurrent task demands. The body of work reported in this dissertation aims to provide a better understanding of factors which affect tactile perception and cognition to guide tactile display design which supports responding to tactile displays of physiological monitoring information by addressing the following:

(a) **Perception** – understand the extent to which movement affects tactile perception?

(b) **Cognition** – understand how the tactile channel can be used to effectively represent physiological monitoring information?

(c) **Responding** – evaluate the effectiveness of a tactile display design—which is informed by a better understanding of perception and cognition in the tactile channel—in supporting accurate responses when subject to concurrent task demands?

Tactile Displays to Address Challenges with Data Overload

Operators in complex, data-rich domains are subject to considerable and continually increasing attentional demands, which require them to divide their mental resources amongst numerous tasks and sources of information (Sarter, 2000; Woods, Patterson, & Roth, 2002). Technology advancements have also significantly increased our ability to collect, transmit, and access data creating a challenge of finding information and meaning where there is a large field of available data (Woods et al., 2002). Data overload—namely visual data overload—and its associated breakdowns already represent a major challenge in various environments and is expected to worsen with the adoption of new tasks, responsibilities, and technology.

One promising means of addressing challenges associated with data overload is through the use of multimodal displays, i.e., displays that distribute information presentation across various sensory channels including vision, audition, and touch. There is a considerable body of work which has demonstrated the potential benefits of multimodal displays and this work is grounded in the Multiple Resource Theory (MRT; Lu et al., 2013; Lu, Wickens, Sarter, & Sebok, 2011; Sarter, 2007; Wickens, Prinet, Hutchins, Sarter, & Sebok, 2011). MRT posits that the different dimensions of information processing (i.e., stages, codes, and sensory modalities; see edges along Figure 1.1) draw from separate cognitive resources. This suggests that tasks can be more effectively time-shared, allowing more tasks and information to be processed simultaneously, when they demand non-overlapping resources (e.g., different sensory modalities; Wickens, 1981, 2002, 2008). The notion that different sensory modalities comprise separate attentional resources is supported by studies showing there is no performance decrement to an ongoing visual task when performing a secondary task using audition (Lu et al., 2013; Wickens et al., 2011).

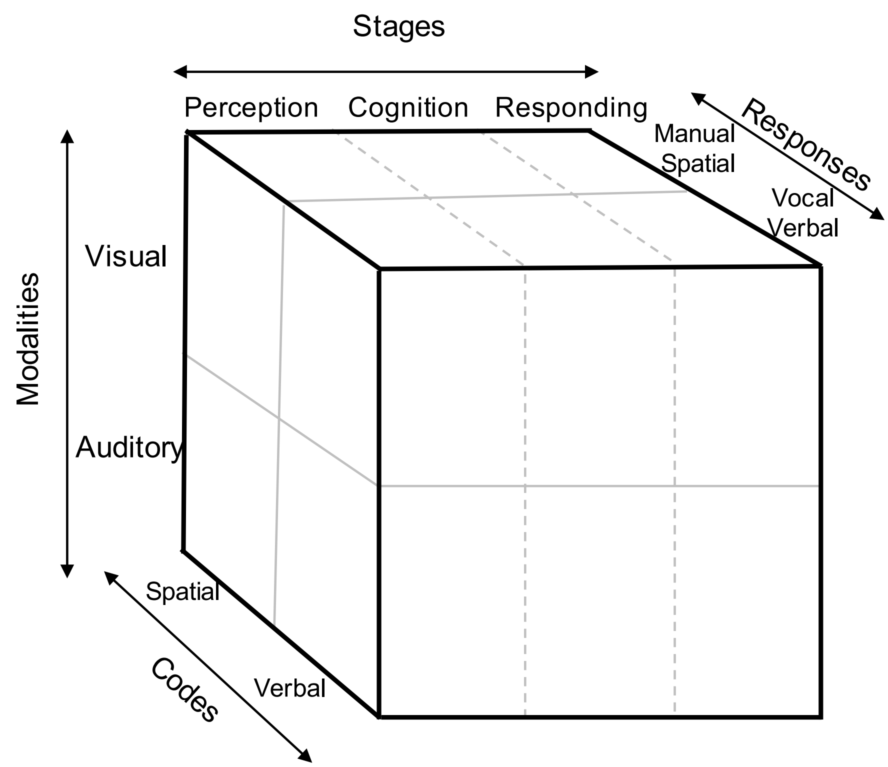

Figure 1.1 Three-dimensional representation of the multiple resource theory (MRT) model showing the different dimensions along the cube's edges (i.e., codes, modalities, stages, and responses) and the different levels of each (e.g., for stages: perception, cognition, and responding)

Early work on timesharing and MRT focused on investigating concurrent performance of visual and auditory tasks. As these two modalities become increasingly overloaded in many environments, more recent work has proposed the tactile channel as an additional resource within the MRT which may be able to time-share task load (Ferris & Sarter, 2011; Lu et al., 2013; Scerra & Brill, 2012). The results of a meta-analysis found a performance advantage for an ongoing visual task when the interrupting task is offloaded to the tactile channel, which supports that the tactile channel may be an additional resource in the MRT (Lu et al., 2013). The tactile channel also has several characteristics which make it desirable as an additional means of information presentation. These include that tactile stimuli are: (a) transient, (b) high in temporal and spatial sensitivity, (c) effective at capturing attention with minimal intrusiveness, (d) omnidirectional, and (e) able to be presented across a large area of the body (Lu et al., 2011).

Evidence of the tactile channel as an additional resource has led researchers to investigate the use of tactile displays to communicate information in various complex domains. Tactile displays have been shown to be able to support attention and interruption management in the context of various data-overload environments including aviation and military operations (Hameed, Jayaraman, Ballard, & Sarter, 2007; Hameed & Sarter, 2009; Oskarsson, Eriksson, & Carlander, 2012; Riggs et al., 2017; Salzer & Oron-Gilad, 2015). One study showed that using directional tactile cues during a helicopter flight mission improved response time and accuracy for collision avoidance and did not interfere with the ability to maintain control of the aircraft (Salzer & Oron-Gilad, 2015). In a simulated combat vehicle navigation task, the addition of tactile cues resulted in improved response times and accuracy of threat detection without hindering performance on other tasks (i.e., responding to radio calls; Oskarsson et al., 2012). To date, the tactile channel has been largely underutilized in complex domains despite the evidence demonstrating the potential to support timesharing and interruption management. In order to ensure the effectiveness of tactile displays and maximize their potential to support operators in complex domains, there is a need to ensure their design supports all stages of information processing (i.e., perception, cognition, and responding; see Stages in Figure 1.1) in the tactile channel.

Limitations of Perception in the Tactile Channel

Although tactile displays are a promising means to alleviate data overload and support operators, their effectiveness may be compromised if their design does not consider limitations of human perception—the first step of human information processing in the MRT model. One such limitation is the phenomenon called change blindness, i.e., the failure to detect changes in a stimulus when changes coincide with an event or disruption (Simons, 2000). There is limited evidence that the tactile modality may be subject to change blindness, especially in the presence of movement (Gallace, Zeeden, Röder, & Spence, 2010). If tactile change blindness occurs during movements, this raises concerns about the robustness of tactile displays and their use.

Change blindness has been primarily documented in vision using *visual transients* (i.e., a disruption to stimulus continuity). This includes complete (e.g., flickers; Rensink, O'Regan, & Clark, 1997) and partial (e.g., mudsplashes; O'Regan, Rensink, & Clark, 1999) occlusions to the visual scene during the period in which a change occurs, as well as in the absence of any transient (e.g., gradual changes; Simons, Franconeri, & Reimer, 2000). The auditory analog to change blindness—change deafness (the failure to detect auditory changes)—has also been documented (Dickerson & Gaston, 2014). There has been limited work demonstrating change blindness in the tactile channel (Hayward, 2008). Tactile change blindness has typically been demonstrated using a *tactile change detection task* where participants are tasked to determine whether they felt a change in tactile stimuli under multiple trials (Gallace, Tan, & Spence, 2006). Detecting changes in tactile intensity is shown to be adversely affected when the change coincides with *tactile transients* that include tactile flickers and mudsplashes (i.e., the activation of all or a few vibrating devices in a tactile display; Riggs & Sarter, 2016) as well as in the absence of transients (e.g., gradual changes; Ferris, Stringfield, & Sarter, 2010).

To date, the majority of tactile change blindness studies have required participants to remain stationary by having them sit or stand. However, this is not representative of the tasks found in most real-world domains. Currently, little is known about the effects of movement on tactile change detection. Gallace et al. (2010) found evidence of tactile change blindness during a tactile change detection task while engaging in a secondary task that elicited movements (i.e., pressing a button, turning a steering wheel). They also found that arm movements resulted in decreased perceptual sensitivity (*d'*) to changes in tactile stimuli and increased response bias (*c,* i.e., more likely to indicate the tactile stimulus changed; Gallace et al., 2010).

The effects of tactile change blindness during movement may be attributed to sensory suppression, i.e. decreased tactile sensitivity in the moving body part during movement (Chapman, Bushnell, Miron, Duncan, & Lund, 1987; Juravle, Binsted, & Spence, 2017). This phenomenon has been demonstrated using a *tactile detection task*, where participants indicate whether they felt a tactile stimulus or not, in the presence and absence of movement (Juravle & Spence, 2011; Williams & Chapman, 2000, 2002). These studies have shown that absolute detection thresholds for tactile stimuli increase during movement, resulting in decreased perceptual sensitivity to tactile stimuli.

Several studies have shown that sensory suppression can occur before, during, and after movement (Colino & Binsted, 2016; Juravle, Deubel, Tan, & Spence, 2010). Evidence has shown that tactile suppression begins in the time immediately preceding movement and becomes more pronounced over the time course of the execution of a movement (Williams & Chapman, 2000, 2002). There has been limited work examining the effects of sensory suppression with continuous movements aside from juggling (e.g., Juravle & Spence, 2011). Voss et al. (2006) showed that stimulus intensity presented to a hand while moving needs to be 2.6 times greater than the intensity when the hand is at rest for it to be perceived as equivalent in magnitude. Therefore, it is critical to understand the extent of the effects of sensory suppression to ensure tactile changes are able to be detected during movement.

The majority of studies investigating tactile sensory suppression during movement have focused on the highly sensitive fingertip area (Juravle et al., 2010; Williams & Chapman, 2000, 2002); however, sensitivity to tactile stimuli is shown to vary across different body locations (Morioka, Whitehouse, & Griffin, 2008; Wilska, 1954). For instance, tactile cue identification accuracy was found to be higher with tactile cues presented to the back compared to the forearm (Piateski & Jones, 2005). Sensory suppression was shown to be less pronounced at body locations relevant to the goal-directed task being performed (e.g., fingertips for a reach-to-grasp tasks; Colino, Buckingham, Cheng, van Donkelaar, & Binsted, 2014) whereas another study demonstrated it is more pronounced at locations near the moving body part (e.g., worse tactile detection accuracy for lower-body locations while walking; Karuei et al., 2011). Therefore, it is important to understand the extent to which movement-related sensory suppression affects sensitivity at different *body locations*.

One limitation which may also affect information processing is that there are limits to the amount of information which can be effectively transmitted, which may limit the level of cue complexity which can be used in the tactile channel (Miller, 1994). Increasing complexity can result in decrements to tactile cue identification, especially when the number of alternatives a stimulus takes increases (Brown, Brewster, & Purchase, 2006; Lu et al., 2013). Alternatively, other studies have shown high identification accuracy with complex tactile icons that incorporate multiple tactile parameters (Dosani et al., 2012; Jones, Kunkel, & Piateski, 2009). Therefore, it is important to determine the level of *cue complexity* that is appropriate to reliably communicate information using the tactile channel. Given that movement is known to affect tactile sensitivity, it is also critical to understand whether the level of cue complexity which can be detected varies when subject to movement demands.

There has been limited work investigating the effects of body movement on tactile change detection despite the evidence of sensory suppression during movement (Chapman et al., 1987; Juravle et al., 2017). Given that body location and cue complexity are also known to affect information processing in the tactile channel, it is important to understand the level of cue complexity and locations that can be used to present information in the tactile channel while subject to movement demands typical of operators in complex domains. The work presented in this dissertation aims to understand the effects of the following variables on tactile perception and change detection: (a) movement (i.e., comparing sitting, standing, and walking), (b) tactile display location (i.e., back versus arm), and (c) tactile cue complexity (i.e., comparing low, medium, and high complexity cues).

Mapping Information in the Tactile Channel to Support Cognition

In order for tactile displays to be effective, their design needs to support the user's cognition—the second step of human information processing in the MRT model. This includes supporting the user's ability to interpret the information communicated which requires considering how well the tactile signal maps to the encoded information. It has been shown that the way information is represented in a display can influence the ease of interpreting the information and may impact performance on tasks which rely on the display (MacLean, 2008). Previous work on auditory displays has shown that the choice of which acoustic parameters are used impacts performance (Walker & Kramer, 2005). One study investigated four different mappings of acoustic parameters (pitch, loudness, tempo, and onset) to convey data concepts (temperature, size, pressure, and rate) during a process monitoring task (Walker & Kramer, 2005). They found that the data-to-acoustic parameter mapping that the experimenters believed to be the most "intuitive" a priori resulted in the worst performance whereas the mapping choice that the experimenters deemed as "random" resulted in the best performance (Walker & Kramer, 2005). Post-hoc explanations for their findings indicate that the effectiveness of auditory displays is determined in part by how well the mapping of data-to-display parameters takes into account the user's expectancies of how a data concept should sound (Ferguson & Brewster, 2017; Walker, 2002). This suggests that the design of auditory displays of information should consider the user's mental model—i.e., a user's representation (in the head) of their understanding of a system (Carroll & Olson, 1988; MacMillan, Getty, Tatum, & Ropp, 1997).

The importance of designing for display compatibility between a user's mental model of a system and how the system actually works has been applied in the design of visual displays and controls and to some extent in auditory display design (McNeer, Bodzin, Bennett, Edworthy, & Dudaryk, 2018; Watson & Sanderson, 2001; Wickens, Hollands, Banbury, & Parasuraman, 2013). It is important to note that mental models can be shaped by a user's knowledge, beliefs, and experience with a system so display design should consider the mental model of the intended end user (Moray, 1999). It may be helpful to adopt an approach which considers the user's mental model in tactile display design to ensure the user's expectancies of how they think a data concept should "feel" matches what it actually feels like (Ferguson, Williamson, & Brewster, 2018). It has also been shown that the ease of interpreting information in a tactile display can depend on how naturally the tactile signal is mapped to the information it represents (MacLean, 2008)—this highlights the importance of data-to-display parameter mapping in tactile display design.

The tactile modality offers several parameters that can be used to encode and communicate information including intensity, temporal characteristics, and location on the body (Brewster &

Brown, 2004). However, it is important to ensure that the tactile parameters used to represent information are intuitive, easy to learn and remember, and carry meaning (Jones & Sarter, 2008; Pasquero, 2006). This requires determining the most effective mapping of tactile parameters to information that needs to be communicated. There is limited work to guide tactile display designers as to what are effective representations of information in the tactile channel. Additionally, effective information to tactile parameter mappings will depend on what information is to be represented in the specific domain that the display will be used in. Currently there is no consensus on how to effectively map tactile parameters—i.e., changes to intensity, temporal aspects, and body location (Arrabito et al., 2009)—especially within the context of anesthesia. This overlooked step is an important consideration in the development of effective tactile displays to support attention management and multitasking in anesthesia (Ferris & Sarter, 2011; Pasquero, 2006).

Tactile parameter mappings in anesthesia. The tactile parameters that have been evaluated in their ability to represent information to support anesthesia monitoring have included:

- *Intensity.* Intensity has been mainly used to convey urgency and severity. Ferris and Sarter (2011) used intensity to represent the severity in changes to a physiological measure. This mapping resulted in improved detection to changes in physiological measures while attending to a secondary intubation task (Ferris & Sarter, 2011).
- *Body Location*. Where tactile devices are located on the body has been used to represent certain physiological measures (Ferris & Sarter, 2011; Ng, Barralon, Schwarz, Dumont, & Ansermino, 2008). For instance, a tactile belt around the waist with four or six tactors was used where each tactor location was assigned to represent a different physiological measure (Barralon, Dumont, Schwarz, Magruder, & Ansermino, 2009; Dosani et al., 2012). The

location of a tactor on the body has also been used to convey the relative value of physiological measures (Ferris & Sarter, 2011; McLanders, Santomauro, Tran, & Sanderson, 2014). With two or three tactors on the upper arm, a vibration presented higher on the arm would correspond with a higher physiological measure value whereas a lower location would correspond with a lower value (Fouhy, Santomauro, Mclanders, Tran, & Sanderson, 2015; McLanders et al., 2014; Shapiro, Santomauro, McLanders, Tran, & Sanderson, 2015).

- *Temporal Changes.* The most commonly used temporal mapping is having the number of vibrations correspond to the degree of severity of changes in a physiological measure. For instance, fewer vibrations represents a less severe change compared to receiving a higher number of vibrations (e.g., 1-2 vs. 3-5 vibrations; Dosani et al., 2012; Fouhy et al., 2015; McLanders et al., 2014; Ng, Man, Fels, Dumont, & Ansermino, 2005; Shapiro et al., 2015). An underutilized temporal mapping is inter-pulse interval (IPI; the time between consecutive tactile pulses; Ng et al., 2005). Shorter IPIs have been found to correspond with more severe or urgent information (Ng et al., 2005; White & Krausman, 2015).
- *Combinations of the Aforementioned*. Many studies have used location with another tactile parameter. Ferris and Sarter (2011) redundantly encoded location and intensity to represent changes in a physiological measure (e.g., location and intensity both indicated an increasing physiological measure). However, location and intensity were also used to encode different information (e.g., location represented the direction of change and intensity represented the severity of the change; Ferris & Sarter, 2011). Location and number of vibrations have also been used to convey information regarding the direction and severity, respectively (e.g., higher location represents an increase in heart rate and more

vibrations means the change is severe; Ng et al., 2005). Alternatively, location and number of vibrations have been used to represent the relative values of different physiological measures (e.g., higher location represents high heart rate and more pulses represent low pulse oximetry; Fouhy et al., 2015; McLanders et al., 2014; Shapiro et al., 2015). Body location, number of pulses, and pulse duration have been used redundantly to encode the physiological variable, level and direction of change in the physiological variable, respectively (Barralon et al., 2009). In general, redundant encodings using two tactile parameters has resulted in faster response times, even in high workload situations (Ferris & Sarter, 2011; McLanders et al., 2014; Shapiro et al., 2015).

The tactile parameters which have been used to represent physiological information vary widely from study to study. This demonstrates that there is a lack of consensus on the most effective use of tactile parameters to represent events and changes during physiological monitoring. Given that information-to-display mappings can influence the ease of interpretation of information in a display, it is important to understand: (a) what information to communicate via the tactile display and (b) how to best represent this information using tactile parameters. It is also important to engage end-users in working towards establishing effective mappings as the user's mental model—which is based on their knowledge and experiences—may influence their perception of effective information-to-display mappings. This work aims to address these challenges by engaging end users to understand which tactile parameters may be effective to represent physiological monitoring information in order to support cognition when interpreting information presented in the tactile channel.

Tactile Displays to Support Physiological Monitoring in Anesthesia

To ensure that tactile displays are effective at supporting data overload challenges, their design needs to support responding to the information in the display—the third step of human information processing in the MRT model—especially in the presence of concurrent task demands. Specifically, in anesthesiology, providers are responsible for supporting a patient's organ systems and hemodynamics while eliminating pain and awareness (Miller & Pardo, 2011). In order to achieve these goals, anesthesia providers must attend to and monitor various sources of visual and auditory information in order to make decisions about a patient's anesthesia management (Miller & Pardo, 2011; Sanderson, 2006). Anesthesia providers also must carry out other ongoing tasks which compete for their visual attention including drug and blood administration, electronic health record entry, and direct observation of the patient (Betza et al., 2016; Sanderson, Watson, & Russell, 2005). A failure to frequently monitor visual displays may result in a failure to detect critical, meaningful changes in a patient's state which can lead to adverse patient outcomes (Zhang et al., 2002). Visual attention is an important but limited resource for anesthesia providers. There is a need to explore ways to alleviate visual data overload and its associated challenges for the anesthesia provider.

This has led to the exploration of other sensory channels to present patient physiological information in anesthesia. Auditory displays which map auditory signal dimensions to represent numerical patient physiological data, known as a sonification display, have gained considerable interest (Paterson, Sanderson, Paterson, & Loeb, 2017; Sanderson et al., 2009). A sonification display that has been universally adopted is the pulse oximetry display which maps pulse rate and pitch of the tones to represent a patient's heartbeat/pulse and blood-oxygen saturation (Deschamps et al., 2016; Paterson et al., 2017). Researchers have proposed and investigated the potential of sonification displays to represent other patient physiological measures such as blood pressure and various respiratory parameters (Seagull, Wickens, & Loeb, 2001; Watson & Sanderson, 2001, 2004).

There are certain challenges associated with the use of auditory displays of patient physiological data. The operating room is a noisy environment—due to communication between surgical staff, operation of surgical equipment, and equipment alarms—so there is concern about the annoyance from the additional sound that auditory displays may introduce. In addition, alarm sounds from auditory displays may be masked by the noise already present in the operating room, which can result in misinterpretation of alarms or missed alarms (Lacherez et al., 2007; Sanderson et al., 2009). Auditory alarm sounds have the potential to result in attention capture and may startle, interrupt, or distract individuals which can negatively affect concentration and performance. Auditory displays are also presented to everyone in the operating room making all individuals subject to interruption and distraction (Kam, Kam, & Thompson, 1994; Stevenson, Schlesinger, & Wallace, 2016). Finally, there is concern that auditory streams of patient monitoring information may contribute to auditory alarm fatigue, which currently represents a major challenge in clinical environments (Kam et al., 1994; Whalen et al., 2014). If auditory displays of patient information contribute to alarm fatigue, they are subject to the same risks as current auditory alarms including that they may be ignored or disabled in the case that too many false alarms are presented (Purbaugh, 2014; Whalen et al., 2014).

In contrast, the tactile modality offers several benefits which make it a promising means to present patient monitoring information. Such benefits include that the tactile channel offers greater privacy than the auditory modality, is obligatory, is omnidirectional, and is able to be perceived concurrently with visual and auditory stimuli (Bitterman, 2006; Sanderson, 2006). The tactile channel has been evaluated as a possible means to communicate patient physiological information to anesthesia providers (Dosani et al., 2012; Ferris & Sarter, 2011; McLanders et al., 2014; Ng et al., 2005). In particular, the tactile channel may be able to direct attention to visual monitoring displays or directly present physiological information with minimal disruption to other ongoing tasks (e.g., medication preparation, electronic health record entry). However, it is critical to evaluate whether tactile display design, which communicates physiological information, supports anesthesia providers in their response to the display when subject to concurrent task demands. Therefore, this body of work aims to evaluate the effectiveness of a tactile display design intended to support the various stages of information processing.

Motivation

In order for tactile displays to be effective at supporting operator performance in any particular domain, it is critical that their design supports the stages of information processing. Therefore, this dissertation aims to better understand how to support perception, cognition, and responding when communicating information in the tactile channel. Chapter 2 will aim to understand the effects of movement on tactile perception (see Figure 1.2, part A). The work presented in Chapter 3 seeks to understand how to effectively represent information in anesthesia using tactile parameters in order to support cognition (see Figure 1.2, part B). In Chapter 4, the findings from previous chapters will be used to inform a tactile display design which will be evaluated for its effectiveness to support responding and concurrent task performance (see Figure 1.2, part C).

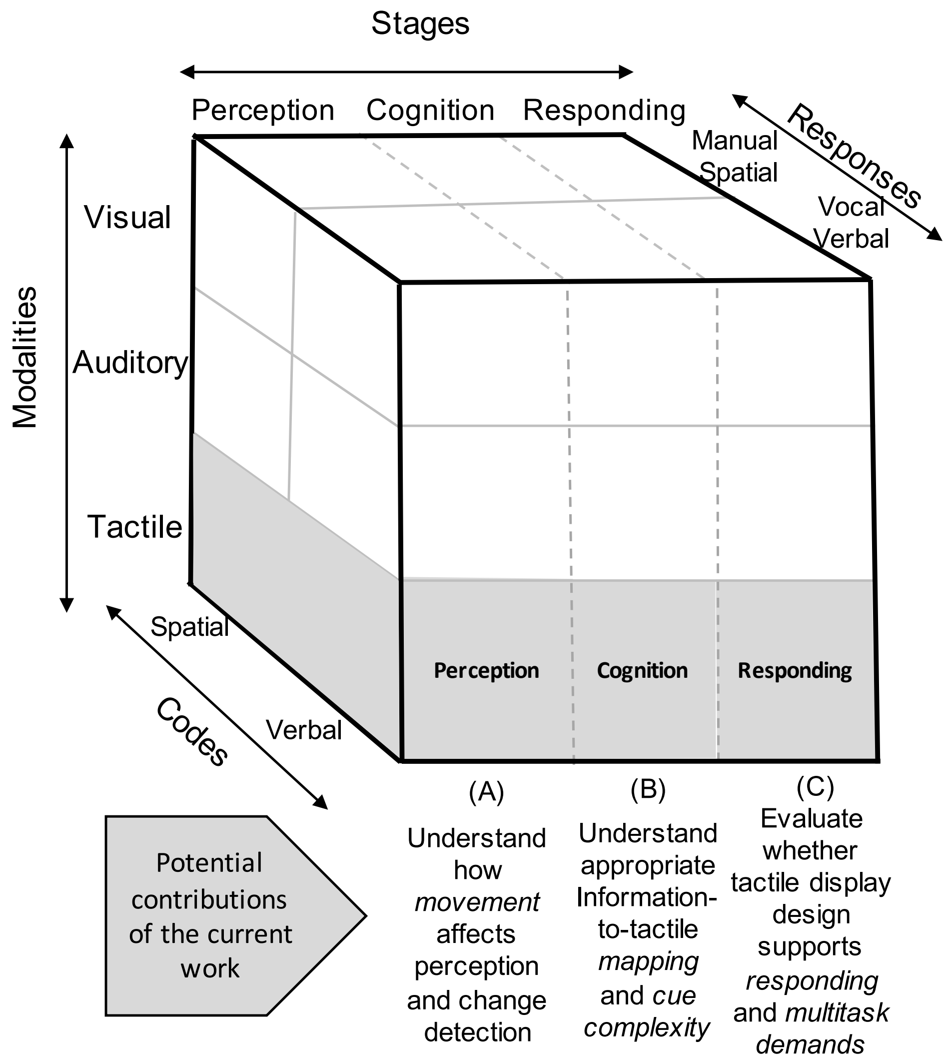

Figure 1.2 Summary of potential contributions of this body of work in relation to the information processing stages within the MRT

It is important that tactile display design considers factors that may affect perception, cognition, and responding to the display within the domain in which the display is intended to be used. Within the context of anesthesia, the following may need to be considered in tactile display design:

(a) Limitations to tactile *perception* that include movement observed by anesthesia providers,

(b) Design that supports *cognition* by considering effective information representation in the tactile channel, and

(c) Whether the design supports accurate *responding* when subject to concurrent tasks demands.

The body of work presented here aims to contribute to a better understanding of tactile display design to support operators in complex domains by understanding how to support perception, cognition, and responding within the context of anesthesia.

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Chapter 2

The Effect of Movement, Cue Complexity, and Body Location on Tactile Change Detection

Introduction

As described in Chapter 1, tactile displays have been shown to be a promising means to support data overload in complex domains (Ferris & Sarter, 2011; Hameed, Ferris, Jayaraman, & Sarter, 2009). However, their effectiveness may be compromised if their design does not consider the limitations of human *perception*—the first step in information processing (see Stages in Figure 2.1). One limitation which has been shown to affect the tactile channel is *change blindness*, i.e., the failure to detect changes in a stimulus when changes coincide with an event or disruption (Gallace, Zeeden, Röder, & Spence, 2010). To date, the majority of tactile change blindness studies have required participants to remain stationary by having them stand or sit. However, this is not representative of the tasks found in most real-world domains where operators may be moving while on the job. There is compelling evidence that movement is known to contribute to *tactile sensory suppression,* i.e., decreased tactile sensitivity in the moving body part during movement (Chapman, Bushnell, Miron, Duncan, & Lund, 1987; Juravle, Binsted, & Spence, 2017). Currently, little is known about the effects that movement may have on tactile change detection.

This raises concerns about the robustness of tactile displays and their use, especially in domains where the operator is subject to task demands which require movement, such as in anesthesia (Betza et al., 2016).

Given there has been limited work investigating the effects of body movement on tactile change detection, this work aims to understand the effects of the following variables on tactile change detection:

(a) **Movement** (i.e., comparing sitting, standing, and walking).

(b) **Tactile display location** (i.e., back versus arm). Given that sensitivity to tactile stimuli is known to vary across different body locations, it is important to understand the extent to which movement-related sensory suppression affects tactile change detection at different body locations (Morioka, Whitehouse, & Griffin, 2008; Wilska, 1954).

(c) **Tactile cue complexity** (i.e., comparing low, medium, and high complexity cues). Increasing cue complexity can result in decrements to tactile cue identification (Brown, Brewster, & Purchase, 2006; Lu et al., 2013). Therefore, it is important to determine the level of complexity that is appropriate, especially when subject to movement demands, to reliably communicate information using the tactile channel.

The expected results were that:

- Sitting will have a higher tactile change detection accuracy compared to standing and walking as movement is shown to adversely affect tactile perceptual sensitivity (Gallace et al., 2010).

- The back will have a higher tactile change detection accuracy compared to the arm when walking as the arm engages in movement during walking and sensory suppression is more pronounced with proximity to moving body parts (Williams, Shenasa, & Chapman, 1998).
- Low complexity tactile cues will have a higher tactile change detection accuracy compared to high complexity cues as increasing cue complexity adversely affects tactile cue identification performance (Lu et al., 2013).

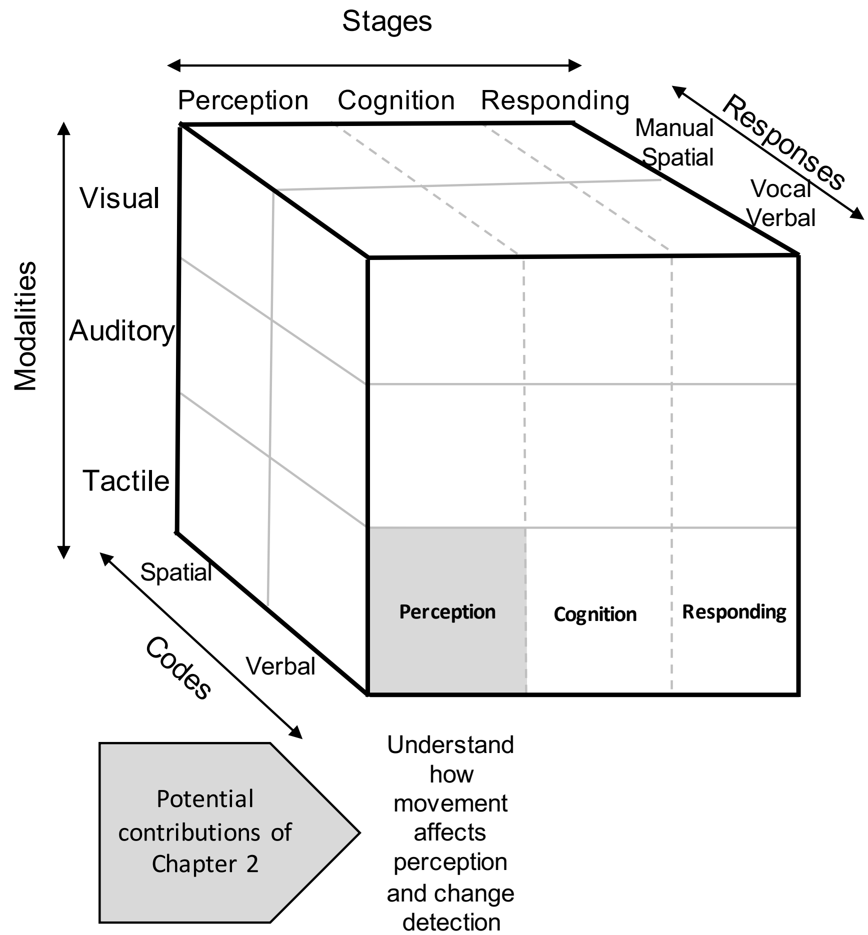


Figure 2.1 Potential contributions of Chapter 2 within the context of the first stage of information processing in the multiple resource theory—perception

The goal of this work is to provide insight on how to effectively present information in the tactile channel under different postural and movement demands typical of various complex domains. This work will add to the knowledge base in tactile perception by providing a better understanding of the effects of movement on change detection as shown in Figure 2.1. The findings from this experiment will be used to inform the design of a tactile display which is described and evaluated in Chapter 4.

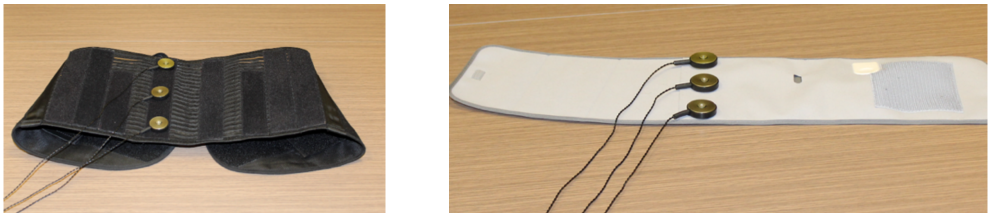
Methods

Participants

Twenty-four Clemson University undergraduate/graduate students participated in this study (13 males, 11 females; *M*=21.9 years, *SD*=2.5). Participants were required to self-report that they had no known impairments to their sense of touch.

Experimental Setup

The participants' task was to verbally indicate whether there was a change in intensity of a presented vibration and the type of change while sitting, standing, or walking. Participants wore a vest around their waist or an arm band (Figures 2.2a-b) over clothing. Each garment had three C-2 tactors (electromagnetic devices; Engineering Acoustics, Inc) attached using Velcro. The tactors on the vest were located on the right side of the participant's spine and the tactors on the arm band were located on the outside of the upper-arm. The spacing between each tactor's center-point was 51 mm for both body locations, which is above the threshold for localizing stimuli on the upper-arm (Cholewiak & Collins, 2003) and back (Eskildsen, Morris, Collins, & Bach-Y-Rita, 1969).



(a) (b)

Figure 2.2 (a) Vest and (b) arm band with tactors

A Dell Precision T3610 workstation sent commands via Bluetooth to a universal control box, which provided the output signal to each tactor, and was placed in a zippered pack worn around the participant's waist. Participants sat in a standard desk chair for the sitting condition and walked on a ProForm Premier 1300 treadmill (model #PFTL13115.0; Figure 2.3) for the walking condition. For the entire study, participants wore Bose QuietComfort 15 noise cancelling headphones, which played pink noise to mask noise emitted from the tactors. Figure 2.3 shows the experimental setup used in the walking condition.

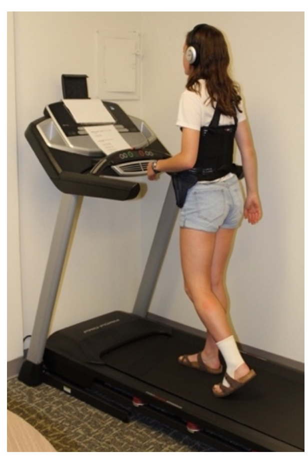


Figure 2.3 Experimental setup for the walking condition. The vest/arm band, zippered pack, and headphones were used across all movement conditions; the treadmill was used only for the walking condition

Tactile Cue Types

For each trial, the starting tactor was randomly selected from the three tactors on the garment and only one tactor emitted vibrations at any given time. The intensity of the presented vibrations was changed by varying the displacement (i.e., gain) of the C-2 tactors with frequency held constant at 250 Hz. The low intensity was set at 4.9 dB (0.9 V_{rms}, 0.096 A_{rms}), medium intensity at 9.3 dB (1.7 V_{rms}, 0.183 A_{rms}), and high intensity at 12.5 dB (2.3 V_{rms}, 0.247 A_{rms}). The intensity always started at the medium level.

Tactile cue complexity was determined based on detection difficulty (e.g., smaller changes in intensity are harder to detect; Brewster & Brown, 2004) and the amount of information embedded in the cue (i.e., number of change alternatives that could be presented; Lu et al., 2013). The four tactile cue conditions used in this study are shown in Table 2.1.

Table 2.1 Tactile cue conditions showing the cue complexity, change description(s), and number of change alternatives for each cue condition

Tactile cue condition	Cue complexity	Change description	Number of change alternatives
Single-step intensity	Low	• Single-step increase or decrease in intensity	2
Graded intensity	Medium	• Graded increase or decrease in intensity	2
Gradual intensity	Medium	• Gradual increase or decrease in intensity	2
Intensity-Location	High	• Single-step, graded, or gradual increase or decrease in intensity • Change in location	7

For intensity changes, the intensity could increase from medium to high or decrease from medium to low. For single-step changes, the intensity change occurred in one step (Figure 2.4a). For graded and gradual changes, the intensity change occurred over the course of four (Figure

2.4b) and eight steps (Figure 2.4c), respectively. In the intensity-location cue condition (high complexity), any of the aforementioned changes in tactile intensity (Figures 2.4a-c) or a change in the location of the vibrating tactor (Figure 2.4d) could occur.

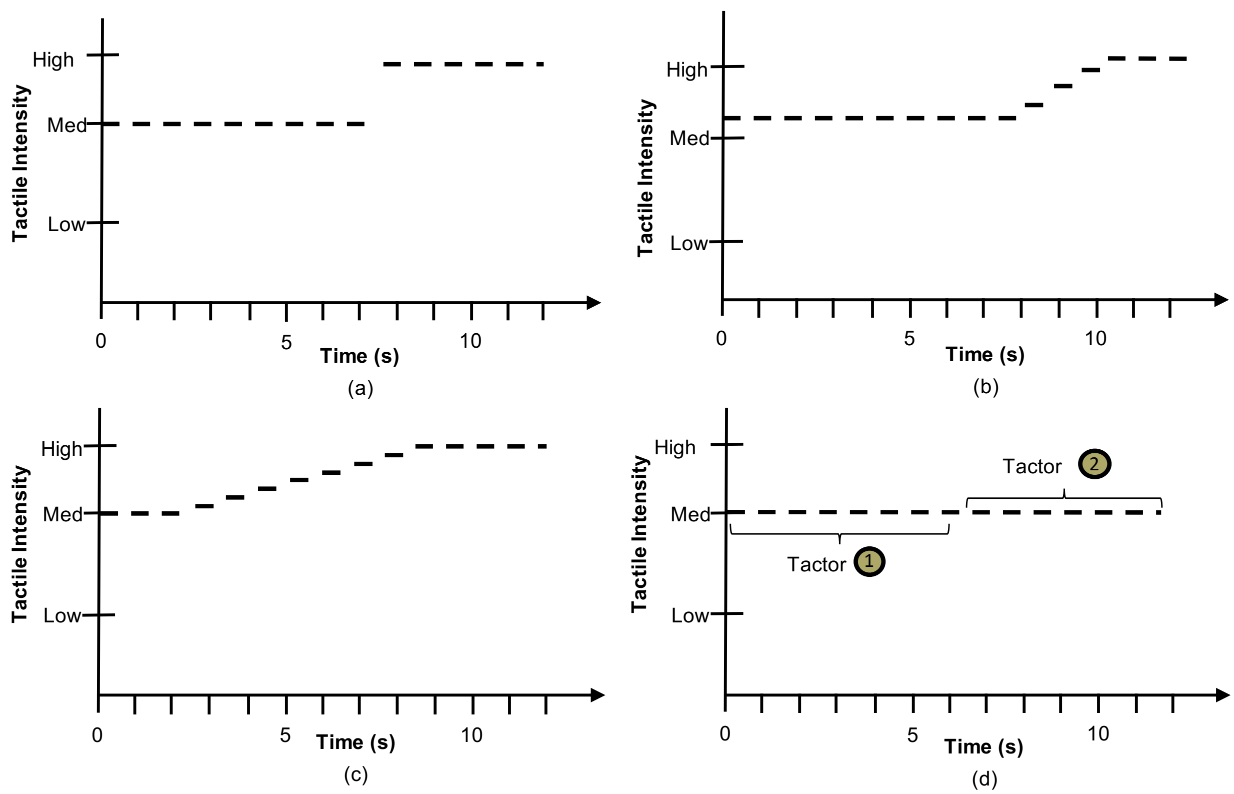


Figure 2.4 Tactile cue types: (a) single-step, (b) graded, (c) gradual, and (d) location change

Movement Type

For the sitting and standing conditions, participants sat in a chair or stood facing a wall. For the walking condition, participants walked at 2 mph on the treadmill with no incline. These movements were selected because they are typical movements expected of operators in various data-rich environments.

Task

Participants advanced through a series of trials where a tactile stimulus was presented and the participants' task was to verbally indicate whether a change occurred and the type of change in vibration intensity or location for each trial. There was a 2-to-1 ratio of trials when a change occurred to when no-change occurred across all conditions. Each tactile stimulus pulsed continuously for 12 s (16 pulses, each was 650 ms duration with an inter-pulse interval of 100 ms) and a change in intensity or location could occur any time between the 4-14th pulse. Figure 2.5 provides an overview of a hypothetical trial where a change occurred. After each trial, participants verbally indicated to the experimenter the change details and the response was recorded. For the low and medium complexity cues, participants were instructed to respond: "no-change," "change-increase," or "change-decrease." For the high complexity cues, participants were required to also indicate what type of intensity change occurred (i.e., "single," "graded," or "gradual") and/or the end location (i.e., tactor "1," "2," or "3").

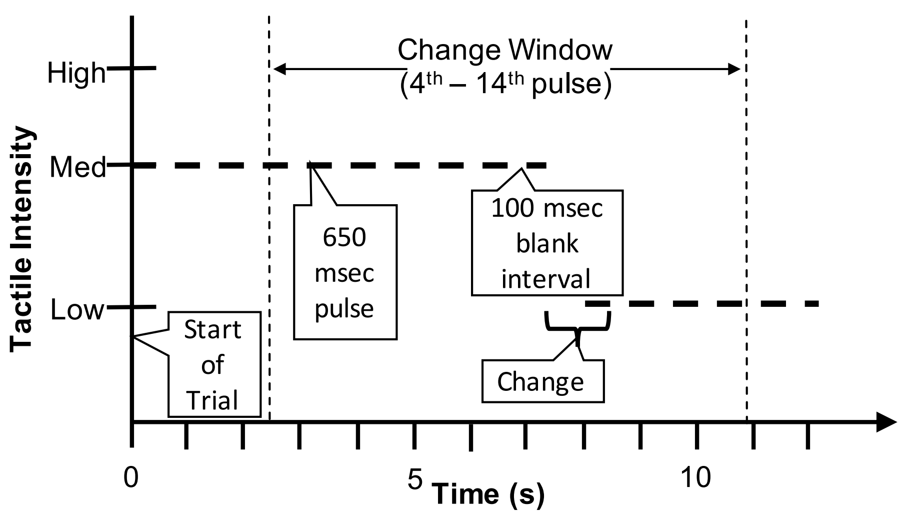


Figure 2.5 Overview for a single-step decrease change trial

Experimental Design

This study employed a 4 (tactile cue: single-step, graded, gradual, intensity-location) × 3 (movement: sitting, standing, walking) × 2 (body location: arm, back) mixed factorial design. The within-subjects factors included tactile cue and movement with body location as the between-subjects factor. Each tactile cue sub-block was completed during each movement block and the order of blocks and sub-blocks was randomized and counter-balanced. The intensity-location sub-block had 36 trials, while the other tactile cue sub-blocks each had 30 trials. Therefore, each movement block had 126 trials for a total of 378 trials across all blocks. There were an equal number of intensity increases and decreases that occurred during each sub-block. For the intensity-location sub-block, an equal number of location and intensity changes occurred, and within the intensity changes, an equal number of each intensity change occurred (i.e., single-step, graded, and gradual).

Procedure

Prior to arrival, participants were instructed to wear close-toed walking shoes. Upon arrival, the participant read and signed an informed consent form. The experimenter then explained the details of the study including the equipment and required tasks. A placard displaying the response options for each tactile cue type was overviewed and was viewable by the participant during the experiment. The participant then performed a training session to become familiar with the expectations of the study during which four single-step change trials were demonstrated. Upon successfully completing a twenty-trial pre-test for single-step intensity changes (i.e., 80% accuracy) while sitting, participants then completed the three movement blocks: (1) sitting, (2) standing, and (3) walking. A demonstration of the graded, gradual, and location changes was given at the beginning of the first block. At the conclusion of the study, each participant completed a debriefing questionnaire (see Appendix 1) and was compensated $10/hour. The study lasted approximately three hours.

Results

The dependent measure was response accuracy (either detection of a change or correct rejection when there was no change). These dependent measures were used to calculate the signal detection measures of sensitivity (*d'*) and response bias (*c;* Tanner & Swets, 1954; Stanislaw & Todorov, 1999). The results were analyzed using 4×3×2 repeated-measures mixed ANOVAs (General Linear Models formulation in SPSS 24.0) to identify main effects on sensitivity, response bias, and hit rate. Post-hoc tests using Bonferroni adjustments were applied to determine differences among means when the omnibus ANOVA indicated statistically significant differences among conditions. Error bars represent standard errors and asterisks represent significant differences among conditions.

Sensitivity (*d'*)

Mauchly's sphericity test indicated that the assumption of sphericity was violated for cue type ($\chi^2(5)=13.03$, $p=.023$) and a Greenhouse-Geisser correction factor was applied ($\varepsilon=.744$). There was a main effect of movement type ($F(2,44)=13.65$, $p<.001$, $\eta_p^2=.383$), cue type ($F(2.23,49.09)=88.72$, $p<.001$, $\eta_p^2=.801$), and body location ($F(1,22)=9.15$, $p<.001$, $\eta_p^2=.294$) on sensitivity. There were no significant interaction effects (all $p>.07$).

Post-hoc tests showed that sensitivity was significantly lower when walking compared to sitting (p<.001) and standing (p=.019; Figure 2.6).

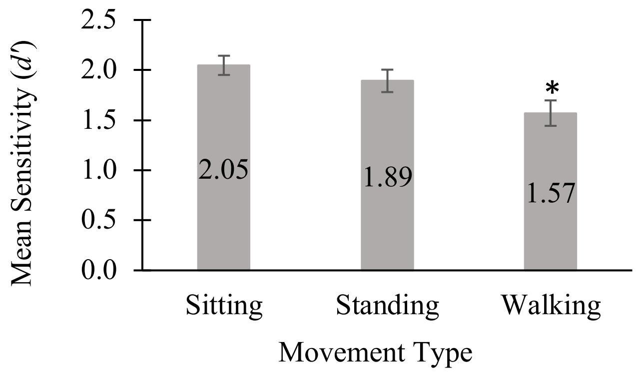


Figure 2.6 Mean sensitivity (*d'*) for each movement type

Mean sensitivity for each cue type were all significantly different from each other, with single-step cues having the highest sensitivity, followed by graded, gradual, and intensity-location cues having the lowest sensitivity (all p<.05; Figure 2.7).

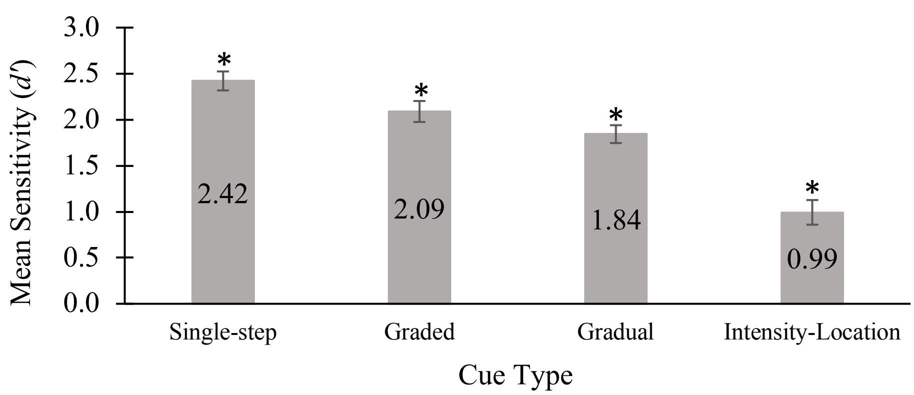


Figure 2.7 Mean sensitivity (*d'*) for each tactile cue type

For body location, post-hoc tests showed that the mean sensitivity was significantly higher for tactile cues presented on the arm (*d'*=2.09) compared to the back (*d'*=1.58; p=.006).

Response Bias (*c*)

There was a main effect of cue type ($F(3,66)=17.58$, $p<.001$, $\eta_p^2=.444$) and body location ($F(1,22)=15.50$, $p=.045$, $\eta_p^2=.170$) on response bias, but not movement type. Post-hoc tests showed that response bias was significantly higher for intensity-location cues compared to all other cue types (all $p<.001$; Figure 2.8).

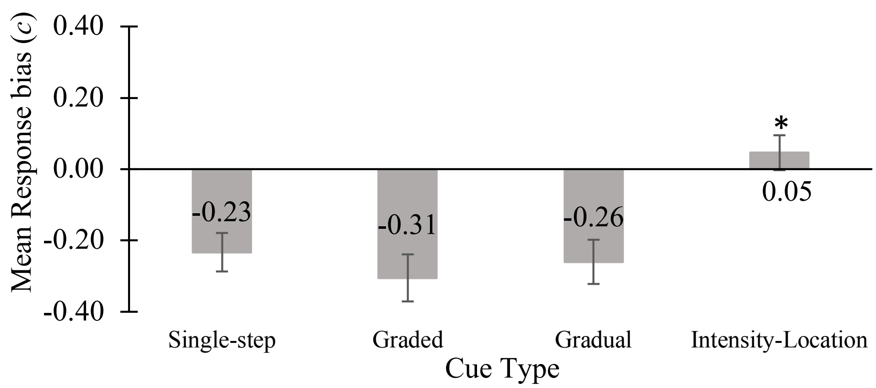
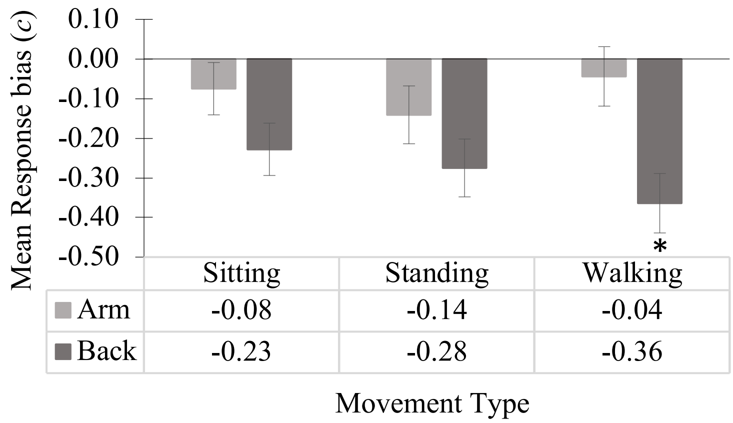


Figure 2.8 Mean response bias (*c*) by cue type (*Note: Negative *c* values signify a bias toward responding 'yes' whereas positive c values a bias toward responding 'no')

With body location, response bias was significantly higher with tactile cues presented on the arm ($c=-0.09$) compared to the back ($c=-0.29$, $p=.045$).

There was a two-way interaction of movement type × body location on response bias ($F(2,44)=5.98$, $p=.005$, $\eta_p^2=.214$; Figure 2.9). Post-hoc tests showed that with walking, response bias was significantly higher on the arm compared to the back ($p=.006$).



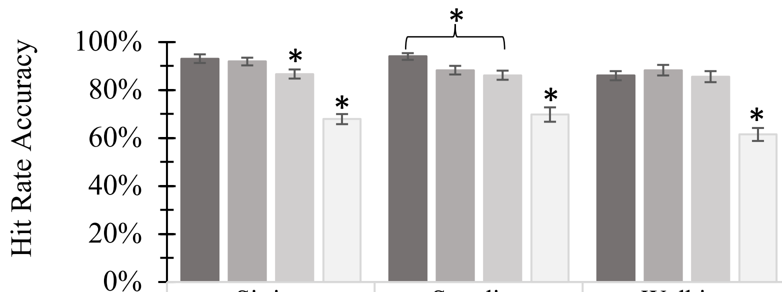
	Sitting	Standing	Walking
Arm	-0.08	-0.14	-0.04
Back	-0.23	-0.28	-0.36

Figure 2.9 Mean response bias (c) between body locations for each movement type

Change Trial Accuracy (Hit Rate)

Mauchly's test indicated that the assumption of sphericity was violated for cue type ($\chi^2(5)=18.26$, $p=.003$) and a Greenhouse-Geisser correction factor was applied ($\varepsilon=.617$). There was a significant effect of movement type ($F(2,44)=7.40$, $p=.002$, $\eta_p^2=.252$), and tactile cue type ($F(1.85,40.72)=88.20$, $p<.001$, $\eta_p^2=.800$) on the hit rate, but not body location. Post-hoc tests showed that the mean hit rates were the worst when participants were walking (hit rate=79%) compared to sitting and standing (both hit rates=84%; both $p<.05$). For cue type, hit rate was significantly worse for the intensity-location (hit rate=66%) cues compared to all other cue types (all $p<.001$). The hit rate for gradual changes (hit rate=86%) was also significantly worse than with the single-step (hit rate=91%) and graded cues (hit rate=90%; both $p<.05$).

There was a two-way interaction between movement type × cue type ($F(6,132)=2.25$, $p=.042$, $\eta_p^2=.093$). For all movement types, hit rates were the worst for the intensity-location cues compared to all other cue types (all $p<.01$; Figure 2.10). When participants were sitting, the hit rate was significantly lower for gradual cues compared to single-step ($p=.017$) and graded cues (*p*=.012). When participants were standing, hit rate was significantly lower for gradual cues compared to single-step cues (*p*=.01).



	Sitting	Standing	Walking
Single-step	93%	94%	86%
Graded	92%	88%	88%
Gradual	87%	86%	86%
Intensity-Location	68%	70%	62%

Movement Type

Figure 2.10 Hit rates for each tactile cue type by movement type

Debriefing Questionnaire Responses

Participants were asked to "rate how difficult it was to monitor the tactile displays while performing the following movements and tasks" on a scale of 1 to 7 (1=very easy; 7=very difficult). Walking was rated the most difficult (mode=6), followed by standing (mode=3) and then sitting (mode=2). One-third of the participants that wore the tactor belt stated that it conformed to their body best when sitting. When looking at movement condition independent of the location of the tactors, one-third of the participants indicated it was easier to focus while sitting and found maintaining their balance in the standing condition distracted them from the change detection task. With walking, 58% of the participants felt that movement distracted them from the change detection task.

Discussion

Although tactile displays are a promising means to support data overload in complex domains (Ferris & Sarter, 2011; Hameed et al., 2009), their effectiveness may be compromised if their design does not consider the limitations of human perception. The goal of this work was to determine the extent to which tactile change detection is affected by movement, tactile cue complexity, and the location of tactile displays on the body.

Effect of Movement

This study confirmed that movement adversely affects tactile change detection and supports our first hypothesis: sitting will have a higher tactile change detection accuracy compared to standing and walking. This contributes to the growing body of work which shows the likelihood of detecting vibrations decreases in the presence of movement (Chapman et al., 1987; Karuei et al., 2011).

The findings support and add to the body of work on sensory suppression – i.e., decreased sensitivity to tactile stimuli during goal-directed movements (Juravle et al., 2017; Juravle & Spence, 2011). First, this study demonstrates that lower-body goal-directed movement, i.e. walking, is also subject to tactile sensory suppression. Second, this study adds to the limited work on sensory suppression using a continuous task and shows that tactile sensory suppression is observed while participants were continuously engaged in executing a movement.

The findings show that tactile change detection may be affected by micro-movements. Given that participants were tasked to stand still for 30 minutes during the standing condition, it is likely that shifts in the center of gravity resulted in unintentional micro-movements (i.e., swaying;

Winter, 1995). The debriefing questionnaire confirmed this notion as one-third of participants mentioned that standing was more difficult as they had to shift their weight due to fatigue over time and/or to keep their balance. The debriefing questionnaire also revealed that one-third of participants who wore the tactor vest cited that it fit best when sitting compared to standing or walking.

The findings also support previous work which has shown that goal-directed movements decrease sensitivity (i.e., *d*'; Juravle & Spence, 2011; Van Hulle et al., 2013). Changes to sensitivity may be due to the fact that tactile perception is affected by the following:

- **Absolute detection thresholds**. This refers to the intensity level that the stimulus needs to be for the observer to just notice it (Ehrenstein & Ehrenstein, 1999). Absolute detection thresholds for tactile stimuli increase for body parts engaged in movement compared to when at rest (Juravle, Deubel, Tan, & Spence, 2010). It is recommended that the intensity of tactile stimuli be increased during movements to ensure the likelihood of detection compared to when the participant is at rest.
- **Just noticeable difference (JND) threshold**. This refers to the difference between the intensity of a reference stimulus that is held constant and the intensity of a comparison stimulus for there to be a perceptible difference. The findings support previous work showing that people have a difficult time detecting gradual changes that occur over time (Ferris, Stringfield, & Sarter, 2010) and this effect is exacerbated when moving. It is recommended that to maximize change detection rates, the minimum intensity change may need to be greater than 45% during movement based on our findings.

It is important to note that unlike previous work, movement did not affect response bias (Gallace et al., 2010); however, this may be attributed to differences in the location and movements used here (i.e., upper-body vs. lower-body; discrete vs. continuous movements).

Effect of Cue Complexity

As tactile cue complexity increased, change detection accuracy and sensitivity decreased. The best performance and highest sensitivity was observed for the low complexity cue (single-step), followed by the medium complexity cues (gradual/graded), and then the high complexity cue (intensity-location). This supports our second hypothesis: lower complexity cues will have a higher change detection accuracy than higher complexity cues. The results can be explained in part by limitations in information transmission, i.e. the amount of information received by a participant that can be attributed to the information presented in the stimulus (Miller, 1994). There is a limit to the amount of information that can be transmitted (i.e., channel capacity), which depends in part on the number of alternatives the stimulus can take. It is recommended that the tactile channel be used for low complexity cues and vision and audition for more complex cues (Lu et al., 2013; Riggs et al., 2017).

The results can be explained in part by limitations to information transmission and channel capacity, i.e. the amount of information received by a participant that can be attributed to the information presented in the stimulus (Miller, 1994). Channel capacity is a function of the number of alternatives the stimulus can take. When the number of stimulus alternatives exceed the channel capacity, this will increase confusion between stimulus alternatives. Tactor spacing may have also adversely affected change detection performance for the intensity-location cues which involved a location change (~33%). Although the inter-tactor spacing was above the threshold to localize stimuli for both locations, this may not be adequate when movements are involved.

The role of attention may be another reason that change detection rates were the lowest with the intensity-location cues. There is evidence that attention is not only necessary to detect visual changes (O'Regan, Rensink, & Clark, 1999), but also to detect tactile changes especially during movement (Van Hulle et al., 2013). The findings support the need to direct attention to the tactile modality to ensure tactile changes are detected. Although participants were prepared for the possibility of a change that could occur this may have been easier for lower complexity cues as participants could focus their attention to detect a certain type of change (e.g., only intensity) compared to higher complexity cues (e.g., intensity or location) where more than one type of change could occur. This supports previous work showing that it is more challenging to attend to two aspects of a tactile signal compared to one (Brown et al., 2006).

For the medium complexity cues (gradual and graded), performance may have been subject to the effects of change blindness. The findings support previous work showing that the absence of transients can adversely affect tactile change detection (Ferris et al., 2010), and the effects may be more pronounced with movement. Although hit rate was highest with single-step changes, for gradual and graded changes hit rates were still high across all movement conditions (>85%). This demonstrates the positive implications of these types of cues for operational use; however, it is advised that they be used with caution. It is important to note that between graded/gradual cues, gradual cues had lower sensitivity and hit rates compared to graded cues. Both cue types were classified as medium complexity according to the meta-analysis conducted by Lu et al. (2013) whereas both would be low complexity according to information theory (i.e., 1 bit of information). However, the performance difference between these two cue types highlight that tactile cue complexity should consider task difficulty—the nature of the discrimination task matters—as this can also influence tactile change detection.

Effect of Body Location

Sensitivity and response bias were higher when the tactile cues were presented on the arm compared to the back across all movement conditions which contradicts our third hypothesis: the back will have better change detection accuracy compared to the arm. Differences in sensitivity and response bias may be due to the fact that tactile sensitivity is a function of body location (Choi & Kuchenbecker, 2013) and proximity to the moving body part (Williams et al., 1998). Although both the arms and legs were engaged while walking, the findings show that change detection was worse for the back than the arm. One possible explanation is that whole-body movements can potentially be further divided into "active" movements (i.e., legs when walking) and "passive" movements (i.e., arms when walking). Also, half of the participants mentioned during the debriefing questionnaire that the tactors moved slightly on the back when walking even though the experimenter took proactive measures to ensure a consistent fit of the tactile garments across participants. The findings show that body location should be considered in light of how movement affects tactile change detection.

Limitations

There are limitations of this work that need to be considered including that this study only evaluated the arm and back locations, whereas other viable body locations should be considered. This is especially important with the increased adoption of wearable devices to present tactile information. It is also important to consider perceptual differences across individuals. For instance, it has been shown that tactile sensitivity varies with age (Verrillo, Bolanowski, & Gescheider, 2002). The context and environment should also be taken into account in the design of tactile displays for real-world domains. It is critical to ensure future work on tactile displays considers the tasks that could interfere with tactile perception. It is recommended that tactile display design considers whether the tactile channel is an appropriate means of presenting information and if so, adopts an approach to identify the limitations in tactile perception and ensure information is conveyed in the manner intended to support operators in complex domains that include aviation, healthcare, and military operations.

Conclusion

The findings from this work can be used to inform the design of tactile displays in a variety of complex domains—namely to account for the effects of movement, cue complexity, and where tactile cues are presented on the body (Gomes, Betza, & Riggs, 2019). First, this work confirms that movement can adversely affect tactile sensitivity and result in decreased tactile change detection performance. As such, tactile display design needs to consider whether an operator will exhibit movements when using the display and should utilize single-step intensity changes to maximize the likelihood of perceiving and detecting tactile changes. This work also sheds light on the importance of considering limitations to information transmission in the tactile channel and the level of cue complexity which is appropriate to ensure effective communication with the display. It is also recommended that cue complexity is minimized, especially during movement.

Specifically applying these findings to anesthesiology, tactile display design should consider the various postures and movements that anesthesia providers engage in, which range from sitting to walking. Although low and medium complexity cues can reliably be detected while moving, the former is recommended in safety-critical domains such as anesthesia to maximize the likelihood that all care providers successfully detect and interpret tactile notifications and alerts. Finally, the location of a tactile display on the body should consider parts of the body that may be engaged in movement and the contexts in which the display will be used. To this end, both the arm and back are viable locations to present tactile information as these locations do not interfere with the tasks and responsibilities of anesthesia providers; however, the arm appears to be a better location as it resulted in higher change detection rates. These recommendations and their application to the design of a tactile display to communicate physiological monitoring information will be discussed in Chapter 4.

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Chapter 3

Understanding Effective Mappings of Physiological Information to Tactile Parameters: A Study with End Users

Introduction

The findings from Chapter 2 showed that tactile change blindness in the presence of movement is a limitation to tactile *perception* and should be accounted for in the design of tactile displays. Another consideration which should be taken into account is whether displays using the tactile channel support *cognition*—the second step in information processing (see Stages in Figure 3.1). The tactile modality offers several parameters that can be varied to encode information including frequency, intensity, temporal characteristics (e.g., pulse duration and inter-pulse interval), waveform, and body location (Brewster & Brown, 2004). Tactile parameters can also be used in isolation or in combination with one another. However, there are limitations associated with some tactile parameters including that the perception of frequency is influenced by changes in intensity and the perception of different waveforms is difficult, limiting the different values that can be encoded using waveforms (Brewster & Brown, 2004). Each tactile parameter can also be changed by increasing or decreasing the level of the parameter, and such changes can be used to convey specific information. An important consideration when designing tactile displays to communicate information is that the way information is represented by the display should be easy to learn and remember, intuitive, and carry meaning (Hoggan, Raisamo, & Brewster, 2009; Jones & Sarter, 2008; Pasquero, 2006). However, one limitation that has yet to be addressed in the tactile literature is understanding which tactile parameters are most effective to represent specific types of information.

To effectively support continuous monitoring, anesthesia providers need to know in real-time the rate at which patient physiological measures are increasing or decreasing. A limitation of previous work that has evaluated tactile displays to support anesthesia monitoring is that there is a lack of consensus on the mapping of tactile parameters to represent physiological information. In addition, the tactile parameters currently used may not be best to represent the information intended to be communicated. Therefore, in order for tactile displays to be effective to support physiological monitoring, there is a need to understand the following:

(a) What information is best to present using the tactile channel and

(b) How to most effectively represent this information using the available tactile parameters

This work aims to address this gap by determining whether and how tactile parameters—i.e., intensity, inter-pulse interval, body location, and combinations thereof—can effectively communicate information about the following physiological measures: Mean Arterial Pressure (MAP), End tidal Carbon Dioxide ($EtCO_2$), and pulse oximetry. These physiological measures were identified as potential candidates to present via the tactile channel by an anesthesia provider and human factors expert at a large academic medical center in the Southeast. This work will add to the knowledge base on tactile display design by providing insight as to the types of information that may be most effectively communicated using certain tactile parameters as summarized in Figure 3.1. The findings from this experiment will inform the mapping of information-to-tactile parameters for a tactile display design which is described and evaluated in Chapter 4.

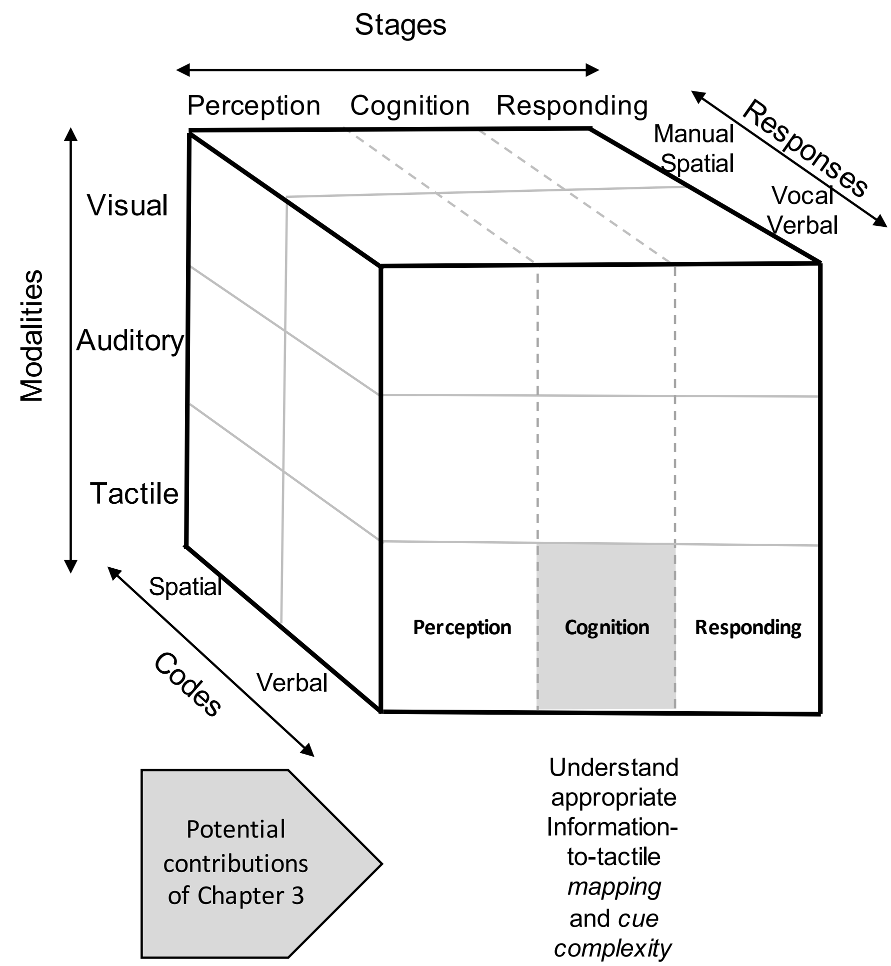

Figure 3.1 Potential contributions of Chapter 3 within the context of the second stage of information processing in the multiple resource theory—cognition

Methods

Participants

Participants included 22 healthcare professionals in the Department of Anesthesia at a large hospital in the Southeastern US (15 male, 7 female; mean age = 36.6 years, SD = 7.1). The participants which took part in this study included nine attendings, seven residents, and six certified registered nurse anesthetists (mean years of experience = 6.7; SD = 5.5). Each of these healthcare providers' roles are representative of those who may benefit from a tactile display of physiological information in the operating room. All participants self-reported that they had no known impairments to their sense of touch.

Experimental Setup

Figure 3.2 shows the experimental set up that included a 21" Dell S2240Tb computer monitor displaying the experimental interface used to present each tactile cue, control box to transmit the tactile cues, and C-2 tactors to present the tactile cues (electromagnetic devices developed by Engineering Acoustics, Inc.; solenoid-based actuators with up to 1 mm displacement; diameter = 3.05 cm, height = 0.79 cm).

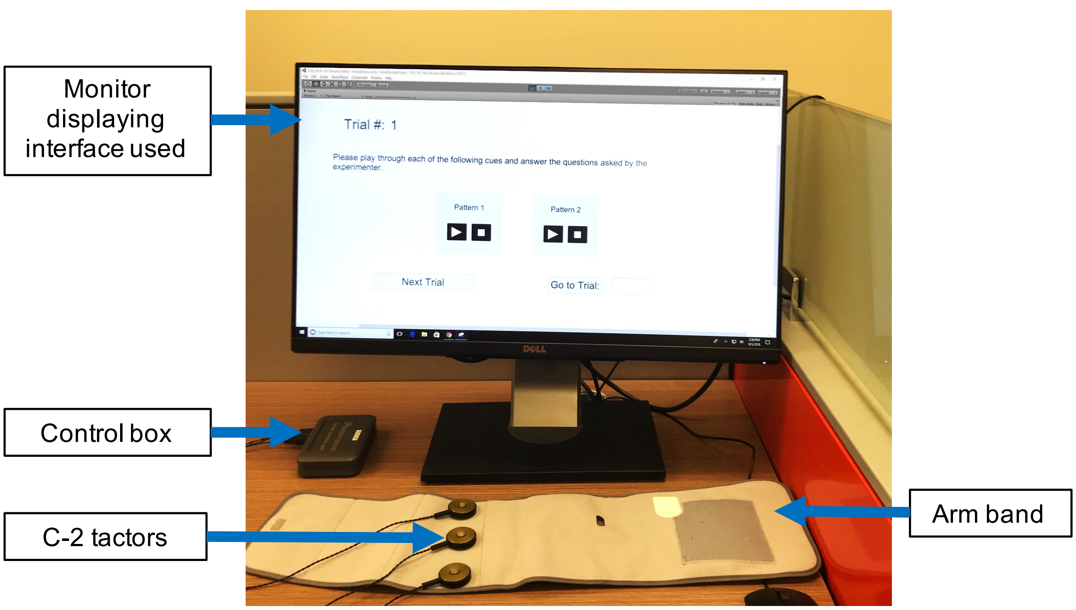

Figure 3.2 Tactile cue response task experimental setup including the interface participants used to play the tactile cues

Three C-2 tactors were secured to the left arm using a Velcro arm band and arranged as shown in Figure 3.3. The arm was selected to present the tactile cues as the accuracy of tactile cue detection on the arm has been shown to be higher than at other body locations (Gomes et al., 2019; Karuei et al., 2011). This three tactor configuration has also been successfully adopted in other studies (e.g., McLanders, Santomauro, Tran, & Sanderson, 2014; Shapiro, Santomauro, McLanders, Tran, & Sanderson, 2015) and is a practical location to minimize interference with the clinical work required of anesthesia providers.

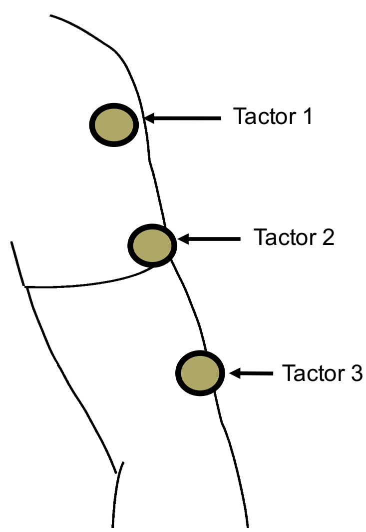

Figure 3.3 Locations of tactors on the upper left arm

Task

For each trial, participants evaluated a set of two tactile cues. During each trial, participants had the opportunity to play both tactile cues in the trial at their own pace and as many times as they wanted. Following this, the experimenter asked participants to answer a series of questions about the pair of tactile cues. This process was repeated for 12 trials.

Tactile cue description. The three tactile parameters in addition to all two-way combinations of the parameters, resulted in the following six tactile parameter combinations that were used in this study: Intensity, Temporal, Location, Intensity+Temporal, Intensity+Location, and Location+Temporal. The temporal tactile parameter used in this study is inter-pulse interval (IPI). Each tactile parameter had three severity levels: low, medium, and high (Table 3.1). Each of the 24 tactile cues in this study included the following three components:

- One of the six possible tactile parameter combinations,
- One of two possible directions of change (i.e., increase or decrease in severity level), and
- One of two different magnitudes of change [i.e., small/moderate change (e.g., change from low to medium severity level) or large/critical change (e.g., change from low to high severity level)]

Table 3.1 Tactile parameters and associated properties for each severity level

Tactile Parameters	Severity Level		
	Low	Medium	High
Intensity	4.9 dB	10.4 dB	15.9 dB
Temporal	750 ms	500 ms	250 ms
Location	Tactor 3	Tactor 2	Tactor 1

Each tactile cue consisted of eight consecutive vibrations of 500 ms each with an IPI of 500 ms each (except for when the temporal parameter was varied) and included a change to one or two of the tactile parameters after the third vibration. The intensity of the presented tactile cues was changed by varying the displacement (i.e., gain) of the C-2 tactors with frequency held constant at 250 Hz. It is important to note that a three-way combination of the tactile parameters was not included as previous work has shown performance decrements in tactile cue idenfication when multiple tactile parameters are used to encode information (Brown, Brewster, & Purchase, 2006).

Each of the 12 trials included two tactile cues. Both tactile cues in a single trial involved the same tactile parameter combination and direction of change but each had a different magnitude of change.

- *Intensity change trials*. Two trials involved changes in intensity. One trial included only increases in intensity changing from low to medium severity for a small magnitude of change and low to high for a large magnitude of change (Figure 3.4a). The other trial included decreases in intensity changing from high to medium and high to low respectively for small and large magnitudes of change (Figure 3.4b). All intensity changes were presented using the middle tactor (i.e., tactor 2).

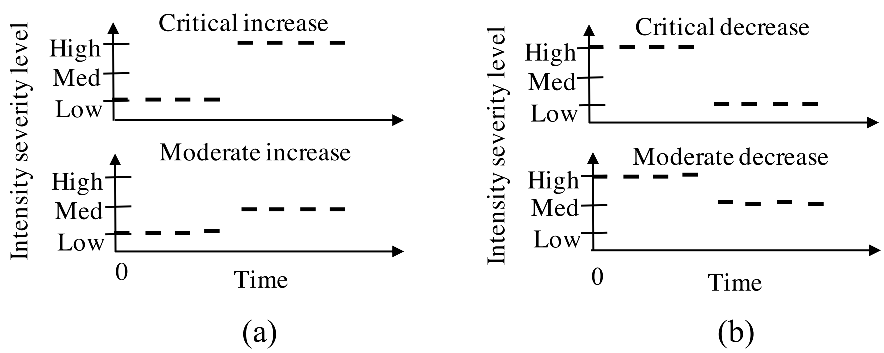

Figure 3.4 Schematic showing (a) intensity increases and (b) intensity decreases

- *Temporal change trials.* One trial involved temporal increases where the IPI changed from 750 to 500 ms for a small magnitude of change and 750 to 250 ms for a large magnitude of change (Figure 3.5a). Another trial involved temporal decreases with a change in IPI from 250 to 500 ms and 250 to 750 ms respectively for small and large magnitudes of change (Figure 3.5b).

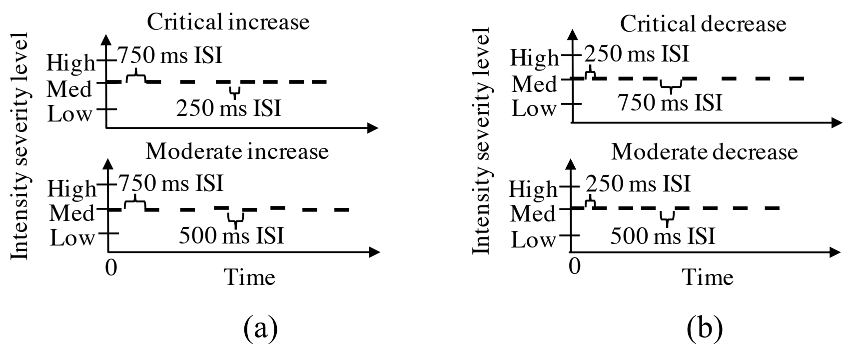

Figure 3.5 Schematic showing (a) temporal increases and (b) temporal decreases

- *Location change trials.* One trial involved location increases where the presentation of vibrations changed from a lower to higher location on the arm, changing from tactor 2 to 1 for a small magnitude of change and from tactor 3 to 1 for a large magnitude of change (Figure 3.6a). Another trial involved location decreases where the presentation of vibrations changed from a higher to lower location, changing from tactor 1 to 2 and tactor 1 to 3 respectively for small and large magnitudes of change (Figure 3.6b).

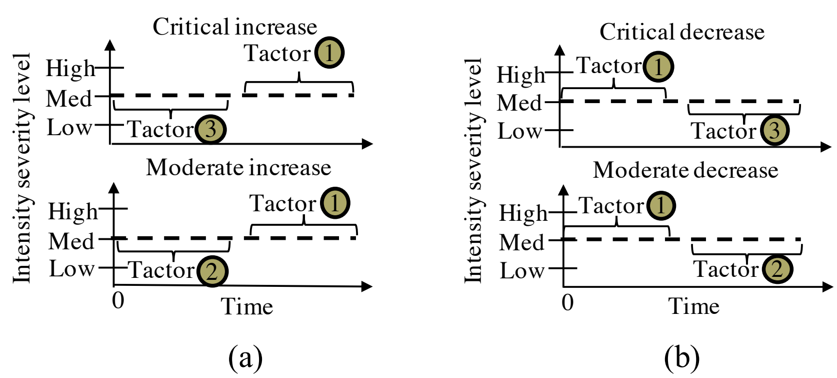

Figure 3.6 Schematic showing (a) spatial increases and (b) spatial decreases

- *Parameter combination trials*. For the combination tactile cues – i.e., Intensity+Temporal, Intensity+Location, and Location+Temporal – the changes were redundant in nature. For example, an Intensity+Temporal tactile cue would involve both a change in intensity and IPI. The changes for the six combination trials were the same as the six single parameter trials except, the changes involved two tactile parameters, merging the same direction and magnitude of change of each tactile parameter.

Experimental Design

This study was a within-subjects 6×2 full factorial design with tactile cues that included all of the tactile parameters and their combinations (i.e., intensity, temporal, location, intensity+location, intensity+temporal, and location+temporal) and two directions of change (i.e., increase, decrease in magnitude). The order of presentation of cue types was randomized for all participants. The dependent variables included participants' responses to the questions about each tactile cue.

Procedure

After obtaining informed consent from the participant, they were explained the details of the study. The tactors were then affixed to the participant's left arm using the Velcro arm band over clothing. A demo of the various tactile cues was presented prior to beginning any data collection. Participants were then presented the first trial of tactile cues and were required to play all the tactile cues presented in that trial. After playing the cues, participants were prompted to verbally respond to the following questions about the cues:

- Rate, on a scale of 1-7, how difficult it was to differentiate between these tactile cues (1 = very easy, 7 = very difficult)?
- Rate, on a scale of 1-7 for each tactile cue, how urgent you perceive each tactile cue to be (1 = least urgent, 7 = most urgent)?

- What could the tactile cues tell you about any of the following physiological measures and state any assumptions:
    - Mean arterial pressure (MAP)?
    - End-tidal Carbon Dioxide ($EtCO_2$)?
    - Pulse oximetry?

This process was repeated for each trial. After the last trial, participants were asked to verbally respond to debriefing questions (see Appendix 2) and their responses were recorded using Audacity 2.1.3 and transcribed. At the conclusion of the study participants were compensated $30 for their time. The experiment lasted approximately 30 minutes for each participant.

Results

Quantitative Data Analysis

Repeated measures linear models (GLM formulation in SPSS 23.0) were used to identify main and interaction effects of tactile parameter combination, direction of change, and magnitude of change on the ratings for the ease of differentiating between small (moderate) and large (critical) magnitude changes and the perceived urgency ratings. All post-hoc tests employed Bonferroni corrections to account for multiple pairwise comparisons.

Ratings for ease of differentiating between moderate and critical changes. There was a significant effect of the direction of change ($F(1, 21) = 12.39$; $p = .002$; $\eta_p^2 = 0.37$) and tactile parameter combination ($F(5, 105) = 11.04$; $p < .001$; $\eta_p^2 = 0.35$; Figure 3.7) on the participant's ability to differentiate between cues of different magnitudes of change (i.e., moderate vs. critical changes). Differences in magnitude were easier to perceive for increases in severity (mean rating = 3.53) compared to decreases (mean rating = 4.21; $p = .002$). With tactile parameter combinations, location+temporal cues (mean rating = 5.48) were rated as more difficult to perceive differences in magnitude compared to all other parameter combinations (all $p < .01$).

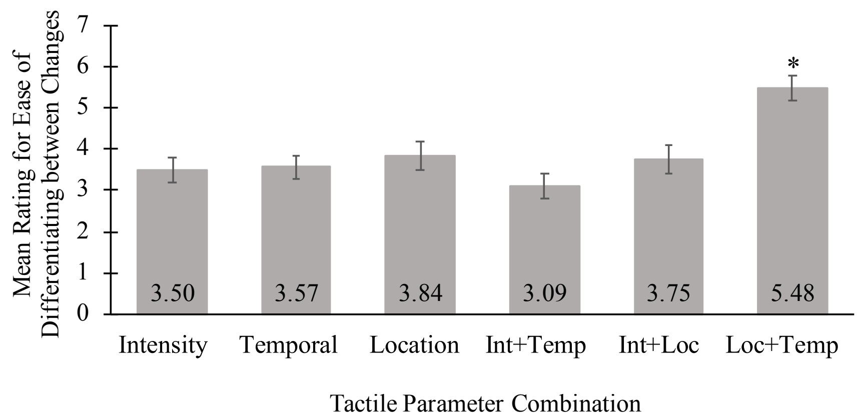

Figure 3.7 Mean ratings for differentiating between cues with different magnitudes of change in each trial for each tactile parameter combination (1 = very easy, 7 = very difficult; * represents significant differences between conditions)

There was an interaction effect between tactile parameter combination × direction of change on the participants ability to differentiate between small and large magnitudes of change ($F(5, 105) = 2.63$; $p = .03$; $\eta_p^2 = 0.11$; Figure 3.8). Post-hoc tests showed that aside from intensity and intensity+location, tactile parameter combinations that increased in severity were rated as easier to perceive differences in the magnitude of change (i.e., small vs. large) compared to ones that decreased in severity (all $p < .05$).

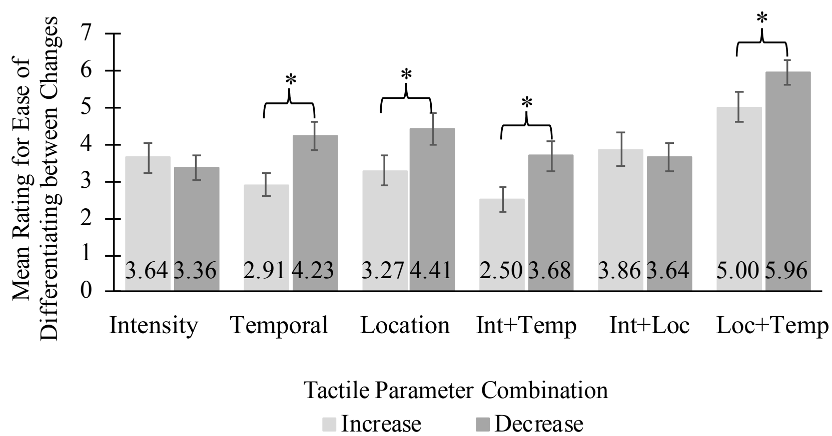

Figure 3.8 Mean ratings for differentiating between cues with different magnitudes of change comparing direction of change for each tactile parameter combination (1 = very easy, 7 = very difficult; * represents significant differences between conditions)

Perceived Urgency Ratings. There was a significant effect of the direction of change ($F(1, 21) = 12.53$; $p = .002$; $\eta_p^2 = 0.37$), magnitude of change ($F(1, 21) = 31.11$; $p < .001$; $\eta_p^2 = 0.60$), and tactile parameter combination ($F(5, 105) = 8.37$; $p < .001$; $\eta_p^2 = 0.29$; Figure 3.9) on the perceived urgency. Participants rated increases in severity (mean rating = 4.52) as more urgent than decreases (mean rating = 3.97; $p = .002$). Participants also rated tactile cues with larger magnitudes of change (i.e., critical changes; mean rating = 4.52) as more urgent than cues with smaller magnitudes of change (i.e., moderate changes; mean rating = 3.97; $p < .001$). With regards to tactile parameter combinations, participants rated location cues (mean rating = 3.36) to be significantly less urgent compared to all other parameter combinations except location+temporal cues (all $p < .01$).

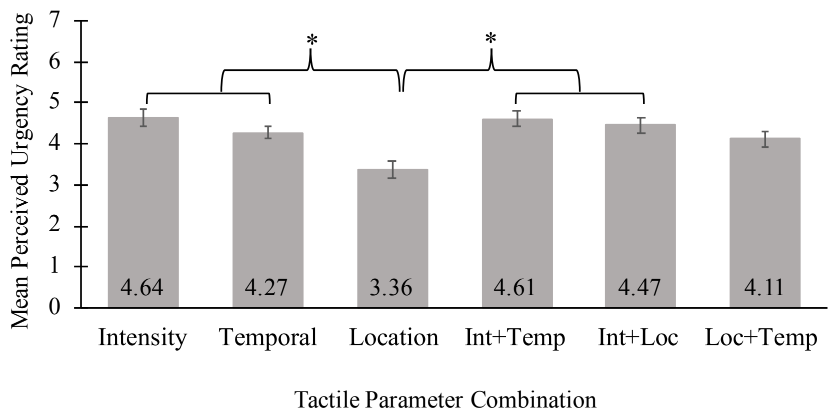

Figure 3.9 Mean perceived urgency ratings for each tactile parameter combination (1 = least urgent, 7 = most urgent; * represents significant differences between conditions)

There was a significant two-way interaction between tactile parameter combination × direction of change on the perceived urgency ($F(5, 105) = 2.51$; $p = .035$; $\eta_p^2 = 0.11$). Post-hoc tests showed that with intensity and intensity+location cues, increases in severity (mean rating = 4.98 and 5.16, respectively) were rated significantly more urgent than decreases (mean rating = 4.11 and 3.96, respectively; both $p < .02$). There was also a significant two-way interaction between tactile parameter combination × magnitude of change on the perceived urgency ($F(5, 105) = 7.33$; $p < .001$; $\eta_p^2 = 0.26$). Post-hoc tests showed that for intensity, temporal, and intensity+temporal cues, large changes in magnitude (mean rating = 5.21, 4.71, and 5.11, respectively) were rated as more urgent than small changes (mean rating = 4.07, 3.84, and 4.11, respectively; all $p < .01$). Finally, there was a significant three-way interaction between tactile parameter combination × direction of change × magnitude of change on the perceived urgency ($F(5, 105) = 8.03$; $p < .001$; $\eta_p^2 = 0.28$). Post-hoc tests revealed that with large magnitudes of change in intensity, temporal, and intensity+temporal cues, increases in severity (mean rating = 6.23, 5.36, and 5.86, respectively) were rated significantly more urgent than decreases (mean rating = 4.18, 4.05, and 4.36, respectively; all $p < .01$).

Qualitative Data Analysis

Using tactile cues to represent specific physiological measures. From the responses given as to what each tactile cue could represent, the percentage of participants that indicated a specific tactile parameter combination could correspond to a specific physiological measure was calculated for MAP, $EtCO_2$, and pulse oximetry (Table 3.2). Intensity (90.9%), temporal (81.8%), and parameter combinations with intensity (>77%) had a strong mapping to MAP. Intensity cues also had a relatively strong mapping to $EtCO_2$ (81.8%). Temporal (81.8%) and intensity+temporal cues (77.3%) also mapped well to pulse oximetry. Location cues had the weakest mapping to represent any of the physiological measures (all <55%). Additionally, 45.5% of participants felt that location cues were, "N/A or not specific to any physiological measure."

Table 3.2 Response percentages for tactile parameters in representing physiological measures

Tactile Parameter Combination	Physiological Measures		
	MAP	$EtCO_2$	Pulse Oximetry
Intensity	90.9%	81.8%	72.7%
Temporal	81.8%	68.2%	81.8%
Location	50.0%	54.5%	40.9%
Intensity+Temporal	95.5%	68.2%	77.3%
Intensity+Location	77.3%	63.6%	68.2%
Location+Temporal	68.2%	68.2%	68.2%

Using tactile cues to convey information about physiological measures. The open-ended responses to the prompt, "What could the tactile cues represent about any of the physiological measures" were coded into six information categories (Table 3.3).

Table 3.3 Information categories and descriptions

Information Category	Description
1.Low	Physiological measure is decreasing or low
2.High	Physiological measure is increasing or high
3.Changed	Physiological measure has changed (increase or decrease)
4.Outside normal range	Physiological measure is outside of the normal range (too high or too low)
5.Normalizing	Physiological measure is normalizing or returning back to the normal range
6.Look at vitals	Need to look at monitor and address something

For increases in magnitude, intensity (31.8%; Table 3.4) and temporal parameters (36.4%) were found to have the strongest mapping to represent a low physiological measure and also showed the best mapping to represent a physiological measure outside of the normal range (27.3%). Compared to all other parameters, intensity+location had the strongest mapping to a high physiological measure (31.8%) and intensity+temporal had the best mapping to a physiological measure that has changed (27.3%). All increasing parameter types were found to have a weak mapping to represent a normalizing physiological measure (≤ 9.1%).

Table 3.4 Response percentages for tactile parameter combinations which increase in magnitude to represent information about physiological measures

Tactile Parameter Combination (↑ Increase in magnitude)	Information Category					
	Low	*High*	*Changed*	*Outside normal range*	*Normalizing*	*Look at vitals*
Intensity	31.8%	9.1%	13.6%	27.3%	4.5%	13.6%
Temporal	36.4%	13.6%	13.6%	27.3%	0.0%	4.5%
Location	4.5%	13.6%	18.2%	4.5%	0.0%	4.5%
Intensity+Temporal	18.2%	9.1%	27.3%	13.6%	0.0%	9.1%
Intensity+Location	13.6%	31.8%	13.6%	18.2%	0.0%	13.6%
Location+Temporal	9.1%	13.6%	9.1%	13.6%	9.1%	4.5%

For decreases in magnitude, intensity and temporal parameters (40.9%; Table 3.5) as well as combinations with intensity (≥ 31.8%) were shown to have the strongest mappings to represent a low physiological measure. Across all decreasing parameter types, intensity (27.3%) and combinations with intensity (≥ 27.3%) were found to have the best mapping to represent a physiological measure that is normalizing. All decreasing parameters showed a very weak mapping to represent a high physiological measure (≤ 4.5%). All decreasing tactile parameters, except temporal and intensity+temporal, had a very weak mapping to represent a variable outside the normal range (4.5%).

Table 3.5 Response percentages for tactile parameter combinations which decrease in magnitude to represent information about physiological measures

Tactile Parameter Combination (↓ Decrease in magnitude)	Information Category					
	Low	*High*	*Changed*	*Outside normal range*	*Normalizing*	*Look at vitals*
Intensity	40.9%	0.0%	9.1%	4.5%	27.3%	0.0%
Temporal	40.9%	4.5%	9.1%	4.5%	13.6%	9.1%
Location	18.2%	4.5%	9.1%	9.1%	0.0%	4.5%
Intensity+Temporal	31.8%	4.5%	0.0%	9.1%	27.3%	4.5%
Intensity+Location	36.4%	0.0%	0.0%	4.5%	36.4%	4.5%
Location+Temporal	18.2%	4.5%	9.1%	4.5%	9.1%	13.6%

Debriefing Questionnaire

Participants' responses to the debriefing questionnaire were thematically categorized. Responses to the questions regarding whether any tactile cue was best and best to represent specific physiological measures were categorized into three overarching themes: (1) tactile cue quality, (2) representation of physiological measures, and (3) representation of physiological events with associated sub-themes (Table 3.6). When evaluating tactile cues, participants felt that intensity (31.8%) and intensity+temporal cues (40.9%) were the best at capturing attention whereas location (36.4%) was the least noticeable. With regards to representation of specific physiological measures, most participants (63.6%; Table 2.6) did not have strong feelings as to specific tactile parameters representing specific physiological measures. However, some participants did feel that temporal (27.3%) or intensity (13.6%) could map to pulse oximetry whereas others suggested that intensity (18.2%) could represent MAP. A number of participants (22.7%) brought up that locations could be assigned to represent specific physiological measures (e.g., top tactor for MAP). When considering the types of events or information tactile cues could represent, participants tended to suggest that increasing the severity for intensity (27.3%) and/or temporal cues (22.7%) could alert that a physiological measure is deviating from the normal range or needs attention.

Table 3.6 Themes from debriefing questionnaire responses

Theme	Sub-theme	Percentage of participants
Tactile Cue Quality	Intensity+Temporal changes were most noticeable	40.9%
	Location changes were not meaningful or noticeable	36.4%
	Intensity changes were most noticeable	31.8%
	Location changes got my attention	22.7%
Representation of Physiological Measures	No response as to whether specific cue types better represent certain physiological measures	63.6%
	Temporal changes could represent pulse oximetry	27.3%
	Could use specific locations to represent different physiological measures	22.7%
	Intensity could represent MAP	18.2%
	Intensity could represent pulse oximetry	13.6%
Representation of Physiological Events	Increasing intensity can alert that physiological measure is deviating and/or needs attention	27.3%
	Increasing Intensity and Temporal can alert that a physiological measure is deviating and/or needs attention	22.7%
	Intensity can map to the relative value of a physiological measure	18.2%
	Location could represent the relative value of a physiological measure	18.2%

Discussion

To date, studies which have evaluated tactile displays to support physiological monitoring have not established effective mappings of tactile parameters to represent physiological information—an important step to ensure the effectiveness of tactile displays to communicate information. The goal of this work is to understand how changes in various tactile parameters (i.e., intensity, IPI, and body location) can be used to convey physiological information to support patient monitoring in anesthesia. The findings of this work confirm that of previous work which has shown the tactile modality may be able to communicate more detailed information beyond simple alerts (Brewster & Brown, 2004). Table 3.7 provides an overview of the tactile parameters which have been used in previous work to communicate physiological information along with a summary of the design recommendations based on the findings of the current study.

The literature to date and the findings here demonstrate the potential of tactile displays to support physiological monitoring. Foremost, participants rated that it was easy to differentiate critical changes (i.e., large magnitude changes) from moderate changes (i.e., small magnitude changes) for most tactile parameter combinations (exception: location+temporal). This supports previous work where participants could discern with almost 100% accuracy between different magnitudes of change for tactile cues which use a single tactile parameter (e.g., McLanders et al., 2014; White & Krausman, 2015). The ease of differentiating between magnitudes of change for tactile cues that redundantly used intensity with another parameter was no different than single parameter combinations. In particular, the intensity+location parameter combination was cited as an effective means to represent changes in physiological measures. This supports previous work which showed that intensity+location cues result in improved detection and correction times for physiological events and improved maintenance of a patient's state (Ferris & Sarter, 2011).

Table 3.7 Summary of tactile parameters used in previous tactile display literature

Tactile Parameter(s)	Reference	Tactile mappings	Contributions of current work
Location (on the body)	Ford *et al.* (2008)	Right & left side of torso mapped to different physiological measures Front & back of torso mapped to increases & decreases in variables, respectively	Body location may be effective to represent different physiological measures. Body location may not be effective to represent specific changes in physiological measures.
	Ferris and Sarter (2011)	Body location (arm & back) mapped to different physiological measures	
	McLanders *et al.* (2014)	Body location mapped to value of heart rate (HR) High location = high HR Low location = low HR	
Temporal	McLanders *et al.* (2014)	Number of pulses per cue mapped to value of oxygen saturation (SpO_2) 1 pulse = normal SpO_2 2 or 3 pulses = low SpO_2	IPI should be considered to communicate urgency of physiological changes.
Intensity & Location	Ferris and Sarter (2011)	**Location** (arm & back) mapped to different physiological measures and location at each body part mapped to direction of change High location = increasing value Low location = decreasing value **Intensity** mapped to direction of change High intensity = increasing value Low intensity = decreasing value	Support for using intensity to communicate information during physiological monitoring. Intensity may be effective to convey severity/urgency of physiological monitoring changes. Decreasing intensity may be effective to represent improved vital status (i.e., normalizing).
	Ferris and Sarter (2011)	**Location** (arm & back) mapped to different physiological measures and location at each body part mapped to direction of change **Intensity** mapped to severity of change High intensity = more severe Low intensity = less severe	
Location & Temporal	Dosani *et al.* (2012) Ng *et al.* (2008)	**Location** mapped to different physiological measures **Temporal:** number of pulses per cue mapped to the level of a change in a physiological measure 1-2 pulses = moderate change 3-5 pulses = severe change	When used with location, temporal aspects (i.e., IPI) can communicate information to support continuous physiological monitoring in anesthesia. Temporal aspects (i.e., IPI) can be effectively mapped to the severity/urgency of physiological changes.
	Fouhy *et al.* (2015) McLanders *et al.* (2014) Shapiro *et al.* (2015)	**Location** mapped to value of HR High location = high HR Low location = low HR **Temporal:** number of pulses per cue mapped to value of SpO_2 1 pulse = normal SpO_2 2 or 3 pulses = low SpO_2	
	Ng *et al.* (2005)	**Location** mapped to direction of change High location = increasing HR Low location = decreasing HR **Temporal:** number of pulses per cue & IPI mapped to severity of change Less pulses & long IPI = less severe More pulses & short IPI = more severe	

The findings also show that although location and temporal cues were easily discernable when presented in isolation, participants had more difficulty detecting differences between moderate and critical changes with the redundant location+temporal cues. Our findings differ from previous work which has shown location+temporal to be an effective cue combination in anesthesia. For example, previous work showed that using the location+temporal to encode direction (location) and severity (IPI and number of pulses per cue) of a change in heart rate resulted in almost 100% cue identification accuracy (Ng et al., 2005). It is important to note that many of the studies which utilized the location+temporal cue used the number of pulses per cue as the temporal parameter (see Dosani et al., 2012; Fouhy et al., 2015; McLanders et al., 2014; Ng et al., 2008; Shapiro et al., 2015) rather than IPI, the temporal element used in this study.

The diverging results highlight two important considerations with regards to developing tactile cues. First, the findings reveal that the Just Noticeable Difference (JND) guidelines—i.e., the minimum amount that a comparison stimulus must differ from a reference stimulus for there to be a noticeable difference that is perceptible (Ehrenstein & Ehrenstein, 1999)—for a single tactile parameter cannot be considered in isolation when combining parameters. Previous recommendations had suggested that IPI be at least 10 ms to achieve the JND thresholds (Gescheider, 1974), but this was not sufficient for the tactile cues evaluated as part of this study. The findings also highlight that effective tactile displays need to consider the effects of sensory overload and/or "tactile clutter", i.e., the reduced comprehension due to simultaneous or sequential presentation of multiple tactile messages/parameters on the same display (Van Erp, Veltman, Van Veen, & Oving, 2003). Although tactile cues have been effective in conveying information, it is critical to balance the amount of information presented with a person's perceptual capabilities and limitations as demonstrated in Chapter 2.

Application in the Anesthesia Domain

With regards to physiological monitoring, the findings reveal several potentially effective mappings between tactile parameters and physiological measures and events with respect to: (1) perceived urgency, (2) mapping to a specific physiological measure, and (3) ability to support continuous physiological monitoring.

Perceived urgency. Overall, the findings support previous work showing that the tactile modality is effective in presenting information regarding urgency (Lewis, Eisert, & Baldwin, 2014; Lu et al., 2013). Intensity and the combination of intensity+temporal received the highest perceived urgency ratings which is in line with previous work demonstrating the effectiveness these parameters to communicate perceived urgency (Van Erp, Toet, & Janssen, 2015; White & Krausman, 2015). Although intensity and IPI have rarely been used to communicate physiological information, the findings here support the limited work which has evaluated the use of both parameters in the context of anesthesia (Ferris & Sarter, 2011; Ng et al., 2005). Larger magnitudes of change (i.e., critical changes) were perceived to have a higher sense of urgency compared to smaller ones (i.e., moderate changes) and increases were perceived to be more urgent than decreases, particularly for intensity, temporal, and intensity+temporal cues. This supports the notion of the principle of the moving part—i.e., the elements move in a pattern and direction compatible with the user's mental model of how it actually moves in the system (Wickens, Hollands, Banbury, & Parasuraman, 2013)—as increases in magnitude corresponded with higher urgency levels and vice versa. Ideally, magnitude and direction of change should be considered in tandem when developing tactile cues using intensity or IPI to effectively convey different levels of urgency regarding a patient’s state.

Mapping to a physiological measure. Intensity and temporal tactile cues were found to better represent physiological measures and events compared to location tactile cues. Intensity, temporal, and intensity+temporal cues were all cited as possible candidates to represent the physiological measures of MAP, $EtCO_2$, and pulse oximetry. Participants indicated location changes were, "N/A to any specific parameter;" however, 23% of participants suggested that designating specific locations to represent specific physiological measures would be an effective means to incorporate body location. For example, a participant noted that with a two tactor display, the top tactor could be used to present changes to MAP whereas the bottom tactor could be used to present changes to $EtCO_2$.This arrangement has been shown to be effective with anesthesiologists in a simulated clinical scenario when discerning between four locations around the waist with each location corresponding to one of the following: blood pressure, ventilation, airway pressure, or $EtCO_2$ (response accuracy > 89%; Dosani et al., 2012).

Supporting Continuous Physiological Monitoring. Currently, anesthesia providers must direct their visual attention to monitor for changes in MAP and $EtCO_2$ and use visual and auditory attention to monitor for changes in pulse oximetry (Watson & Sanderson, 2004). Incorporating tactile cues to communicate information about physiological changes can continuously inform anesthesia providers of important changes without requiring the anesthesia provider to look at the patient or ventilator monitor. In general, intensity, temporal, and parameter combinations with intensity can effectively convey different levels of urgency, especially when paired with varying direction and/or magnitudes of change. This has the potential to support attention and interruption management. Specifically, providing operators with informative alerts about the status or urgency of events can support them in more effectively timesharing their attention between tasks by allowing them to attend to the high priority information (Hameed, Ferris, Jayaraman, & Sarter, 2009; Ho, Nikolic, & Sarter, 2001). This in turn can minimize the number of task interruptions and/or task switching. Previous work has shown that anesthesia providers switch between tasks as often as once every nine seconds (Betza et al., 2016). Specifically, task switching can lead to a reduction in physiological monitoring activity (Gaba, Herndon, Zornow, Weinger, & Dallen, 1991; Loeb, 1993). It is important for anesthesia providers to be aware of changes in the patient's vitals because not directing attention to time-critical events could lead to severe and detrimental complications for patients if not treated in time (Sanderson, 2006).

When participants were asked what specific information each tactile cue could represent, increases and decreases for each individual tactile parameter in isolation were interpreted differently. Many participants indicated that increases in intensity and temporal IPI could represent physiological measures outside the normal range. Participants also noted that decreases in intensity and temporal cues could correspond with a low (i.e., decreasing) or normalizing physiological measure. Tactile cues that included intensity and combinations of intensity—i.e., intensity+location and intensity+temporal—were also cited as candidates to represent a low or normalizing physiological measure. In general, intensity and combinations using intensity may be able to provide detailed information on the severity and rate of change of physiological measures to support continuous physiological monitoring.

Information Communication using Tactile Parameters

Considering the broader knowledgebase of how intensity, IPI, and location parameters have been used outside of the anesthesia domain can provide insight as to the specific types of information each tactile parameter may be a good candidate to represent. As such, we consider the findings from the current work in relation to the broader literature on tactile displays in terms of how intensity, IPI, and location have been used successfully to communicate information in various contexts.

Body location. The location of tactile stimulation on the body has been widely used to encode information about the spatial location of a target in the environment (Ho, Tan, & Spence, 2005; McDaniel, Krishna, Colbry, & Panchanathan, 2009). Several studies have successfully used the locations of tactile stimuli on the body to support navigation, for instance, by providing left and right turn information to the left and right sides of the body, respectively (Calvo, Finomore, McNitt, & Burnett, 2014; Jones, Kunkel, & Piateski, 2009; Piateski & Jones, 2005; Van Erp & Van Veen, 2001). Several studies have also confirmed that there are crossmodal links between visual and tactile spatial attention such that providing information about where a target is located in space in the tactile channel facilitates visual search and target detection (Ferris & Sarter, 2008; Hameed, Jayaraman, Ballard, & Sarter, 2007; Ho et al., 2005). Therefore, the use of body location in the tactile channel may be most effective to represent spatial information in the environment, such as the location of a target. This could serve as one explanation as to why spatial changes were not shown to have a strong mapping to any specific physiological events. In addition, it may explain why some participants recommended assigning each body location to represent a different physiological measure—each physiological measure has a specific location where it is shown on a visual display.

Temporal inter-pulse interval. One way in which IPI has been used to encode information includes conveying distance to a target with shorter IPIs used for closer targets (McDaniel et al., 2009; Van Erp & Van Veen, 2001). There is also compelling evidence which has shown a consistent relationship between IPI and perceived urgency. Several studies have shown that perceived urgency increases with shorter IPIs and decreases with longer IPIs (Baldwin & Lewis, 2014; Van Erp et al., 2015; White & Krausman, 2015). The findings here confirm this association as participants rated temporal cues where the IPI became shorter with a higher perceived urgency and associated them with more urgent physiological events. Alternatively, temporal cues where the IPI became longer were cited by several participants to be able to represent less urgent physiological information (e.g., that a physiological measure is normalizing).

Intensity. Tactile intensity has been used less often, compared to IPI and location, as a means to encode information in a tactile display. Increases in intensity have been utilized and evaluated as a countermeasure to tactile change blindness in order to improve tactile cue detection (Riggs & Sarter, 2016). Ferris and Sarter (2011) used intensity to communicate direction and severity of change in a physiological measure, with increasing intensity representing increases in and more severe changes in a physiological measure. Some previous work has also shown an association between intensity and perceived urgency, with increases in intensity being perceived as more urgent (White & Krausman, 2015). The findings here also support this association as intensity increases received higher ratings of perceived urgency. The findings from the current study also show that participants most often associated intensity increases and decreases with the relative value of a physiological measure. Specifically, participants cited that increases to a higher intensity could represent a physiological measure that is increasing or too high and decreases to a lower intensity could represent a physiological measure that is decreasing or too low. These findings provide support that one potential use of intensity in the tactile channel is that it may be able to convey information about the magnitude or relative value of a data concept.

Limitations

There are limitations of this work that should be considered. One shortcoming of the current findings is that the accuracy of detecting differences between small and large magnitudes of change may not be sufficient for use in the domain of anesthesia. Although the findings of this work provide a starting point in terms of mapping tactile parameters to physiological information, it is important to develop tactile cues which can be reliably detected and identified if they are to be used in anesthesia to communicate information (Jones et al., 2009). As such, it may be important to tradeoff the amount of information that can be presented by minimizing cue complexity which is in line with the findings presented in Chapter 2. It will also be important to investigate individual differences in reliably perceiving and identifying tactile cues as there is inter-subject variability due to age, gender, etc. (Fisk, Rogers, Charness, Czaja, & Sharit, 2009; Verrillo, Bolanowski, & Gescheider, 2002).

Conclusion

Overall, this work emphasizes the importance of considering the mapping of tactile parameters to information in the design of tactile displays, especially as increases and decreases in tactile parameter magnitude and the various tactile parameters can be interpreted differently (Gomes, Reeves, & Riggs, 2018). This work not only demonstrates the potential for the tactile channel to represent detailed information beyond simple alerts, but also provides insight as to the types of information that the tactile parameters (i.e., intensity, temporal IPI, and location) may be able to represent. First, changes in body location may not be very informative, however, individual body locations may be more effective when used to represent separate elements which may have a spatial relation in the physical environment. This work is in line with previous work in showing that changes in IPI and intensity may be effective to convey different levels of perceived urgency. Finally, this work shows the potential for intensity to be incorporated in tactile displays as it may be effective to communicate the relative magnitude of a data concept.

This study supports evidence showing the potential use of the tactile modality to present physiological information and support continuous physiological monitoring (Gomes, Reeves, & Riggs, 2019). Specifically, the findings from this work contribute towards an understanding of how changes in intensity, temporal IPI, and separate body locations can be used to represent changes in physiological measures to support anesthesia monitoring. Some recommendations include the following:

- Intensity and combinations with intensity can potentially convey information about increases and decreases in physiological measures
- Increases in intensity and temporal IPI can convey urgent information while decreases in these tactile parameters can convey less urgent information
- Body location may be most effective to represent different physiological measures

The findings and recommendations are considered and used to inform the design of a tactile display to communicate physiological monitoring information to anesthesia providers which is described and evaluated in the next chapter.

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Chapter 4

The Evaluation of a Prototype Tactile Display to Support Physiological Monitoring and Multitasking for Anesthesia Providers

Introduction

The work presented in this chapter centers around the development and evaluation of a tactile display prototype which is informed by the findings from Chapters 2 and 3. In order to ensure that tactile displays support operator performance and maximize the likelihood of accurate *responding* (i.e., the third step in information processing) their design needs to support the initial stages of information processing—i.e., *perception* and *cognition* (see Stages in Figure 4.1). Chapters 2 and 3 provide a better understanding of how to support perception and cognition during information presentation in the tactile channel. Specifically, Chapter 2 demonstrates the importance of considering movement demands to ensure the perception of tactile stimuli. Chapter 3 provides insight as to what tactile parameters may be effective to represent specific types of physiological information. To ensure the robustness of tactile displays in anesthesia, their design should also support multitasking given the various concurrent task demands required of anesthesia providers (Betza et al., 2016). Therefore, the work presented in this chapter will evaluate whether a tactile display design—which considers how to support perception and cognition—is able to support responding when subject to concurrent task demands as shown in Figure 4.1.

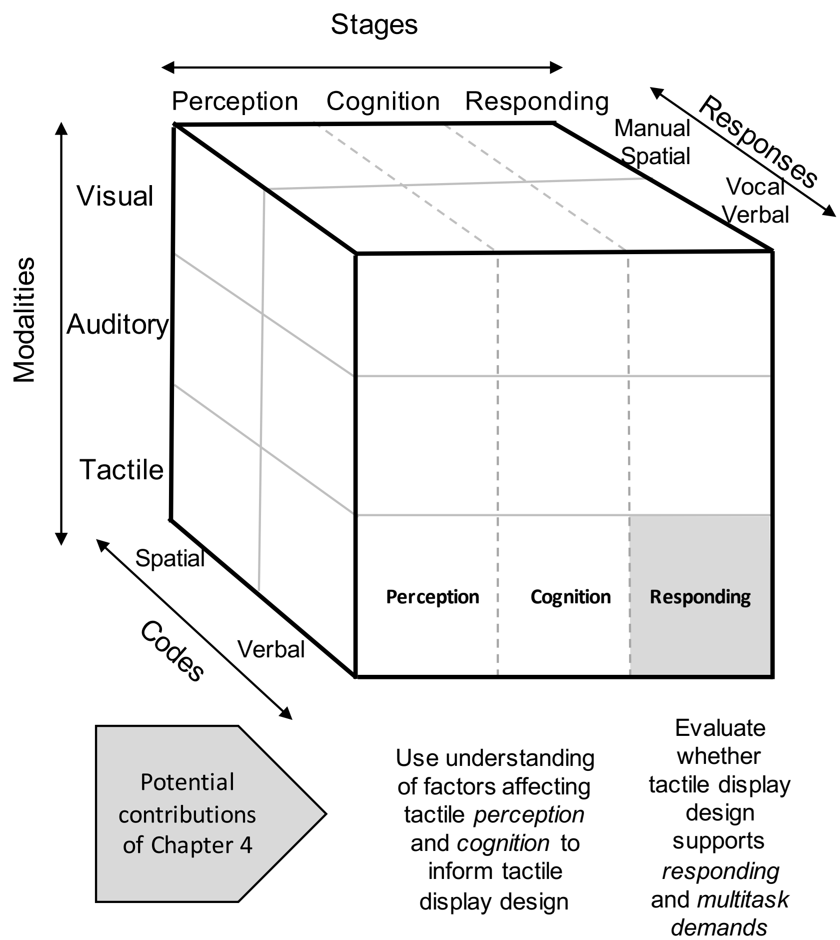

Figure 4.1 Potential contributions of Chapter 4 within the context of the third stage of information processing in the multiple resource theory—responding

The first part of this chapter describes the details of the tactile display design including an overview of the findings which were considered in the design phase. The expected outcomes in terms of performance with the display are then presented. Finally, an empirical study to evaluate the display prototype and test the hypotheses is described and the findings are discussed.

Proposed Tactile Display Design

An important step in display design includes determining what type of information needs to be communicated using the display. It was determined that the current prototype display would communicate information about specific changes in the physiological measures: EtCO_2, MAP, and pulse oximetry. These specific physiological measures have been identified as important to attend to when monitoring and maintaining the health of a patient undergoing anesthesia and were recommended by an experienced anesthesia provider (Ferris & Sarter, 2011). Previous studies have also investigated communicating some of the same physiological measures using tactile displays (Dosani et al., 2012; Ferris & Sarter, 2009, 2011; McLanders, Santomauro, Tran, & Sanderson, 2014). With all of these physiological measures, the information that ideally needs to be communicated includes whether the value is: *increasing*, *decreasing,* or *normalizing*.

There are several considerations from the work conducted as a part of Chapters 2 and 3 as well as findings from previous work on tactile perception and tactile displays which informed the design of the prototype tactile display used in this study.

Deciding how to present physiological measures. The decision of how to encode physiological measures considered participants interpretation of location changes and preferences in Chapter 3. It was determined that separate locations on the upper arms would each be assigned to represent a different physiological measure (see Figure 4.2). Chapter 3 showed that several participants cited a preference for using different locations to represent a different physiological measure—a mapping which has also been used successfully in previous work by assigning separate locations in a tactile belt around the waist to represent a different physiological measure (Dosani et al., 2012; Ng, Barralon, Schwarz, Dumont, & Ansermino, 2008). Previous work has shown that locations of tactile stimuli on the body can be effective to indicate “where” a target is located in the environment. The fact that physiological measures have a specific location where they are shown on a visual display provides an opportunity to associate body locations with a spatial element. As such, the assignment of which locations represent a physiological measure were based on the spatial arrangement of where each physiological measure is shown on the visual display. The physiological measures of MAP and pulse oximetry are on the same display and were assigned to locations on the left arm. $EtCO_2$ is presented on a separate display to the right on anesthesia work station and was assigned to the right arm (see Figure 4.2). The use of locations on separate arms allows for increased physical separation of tactors on the body, which can support spatial localization during perception (Cholewiak & Collins, 2003). The arms were chosen to present the tactile display as the arm has shown good tactile sensitivity and better perception during walking movements compared to other locations on the body (Karuei et al., 2011).

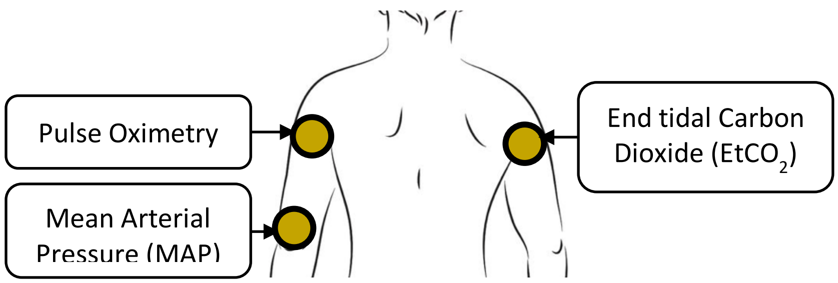

Figure 4.2 Arrangement of the tactors on the arms and the correspondence between physiological measure and body location

Deciding how to present changes in physiological measures. Specific tactile parameter changes were used to represent specific changes in a physiological measure (i.e., increases, decreases, and normalizing) and were based on participant's preferences in Chapter 3. Intensity increases and decreases were used to represent increases and decreases in a physiological measure. This was based on the finding from Chapter 3 that intensity was consistently cited as being able to represent the relative magnitude of a physiological measure. A change from short to long inter-pulse interval (IPI) was used to represent a normalizing physiological measure in this study. This is based on the finding that changes to a longer IPI were perceived as less urgent and cited to be able to represent physiological changes which are informative of an improved patient state. This mapping is also based on evidence that longer IPIs are shown to have an association with lower perceived urgency (Baldwin & Lewis, 2014; Lewis & Baldwin, 2012; White & Krausman, 2015).

Tradeoffs are also an important part of the design process and should be carefully considered. One tradeoff for the current prototype display was adopting low complexity cues which limits the amount of information which can be communicated. Higher complexity cues were considered which would entail using small and large magnitudes of change in intensity to communicate moderate and critical changes in a physiological measure as has been done in previous work (Ferris & Sarter, 2009; McLanders et al., 2014; Shapiro, Santomauro, McLanders, Tran, & Sanderson, 2015). Although participants were able to differentiate between two magnitudes of change with relative ease in Chapter 3, lower complexity cues were used as previous work shows that increasing cue complexity can adversely affect tactile cue identification performance (Brown, Brewster, & Purchase, 2006; Lu et al., 2013). In addition, due to the effects of movement on tactile perception shown in Chapter 2, single-step changes were used (as opposed to gradual changes) in order to maximize change detection performance in the case of movement.

Objectives and Expected Outcomes

The current study aims to evaluate the effectiveness of the prototype tactile display design to communicate physiological monitoring information. Given the importance of ensuring the display is able to communicate information during multitasking performance, this study evaluates performance with the prototype display while simultaneously performing a secondary task. We hypothesize the following outcomes in terms of participants' performance and preferences when using the prototype tactile display:

- The following tactile cue mappings will be easily learned and result in at least 95% accuracy of identifying the encoded information:
    - Intensity increases and decreases to represent increases and decreases in a physiological measure, respectively
    - Change to a longer IPI to represent a normalizing physiological measure
    - Separate locations on the body to represent each physiological measure
- Accuracy and response times to identify tactile cues will be adversely affected by the performance of a secondary task compared to when no secondary task is performed

Methods

Participants

Nineteen healthcare professionals from the Department of Anesthesia at a large hospital in the Southeast participated in this study (11 male, 8 female; mean age=36.4 years, SD=6.2) including nine attendings, seven residents, and three certified registered nurse anesthetists. All participants self-reported that they had no known disorders which affect their sense of touch.

Experimental Setup

Figure 4.3 shows the experimental setup used for this study. The simulations used for this study were run on a Dell Precision 5820 computer. Two 24" Dell P2418HT touch screen monitors were used to display each task. The monitor on the left presented a simulated patient monitoring display modeled after the patient displays used in the operating room. This display was used to respond to the tactile cues. The monitor on the right presented a virtual syringe task, which participants used to perform the secondary task. Both monitors were placed on a 30" AboveTEK adjustable standing desk and the center of each display was raised to a height of 47" from the floor for all participants.

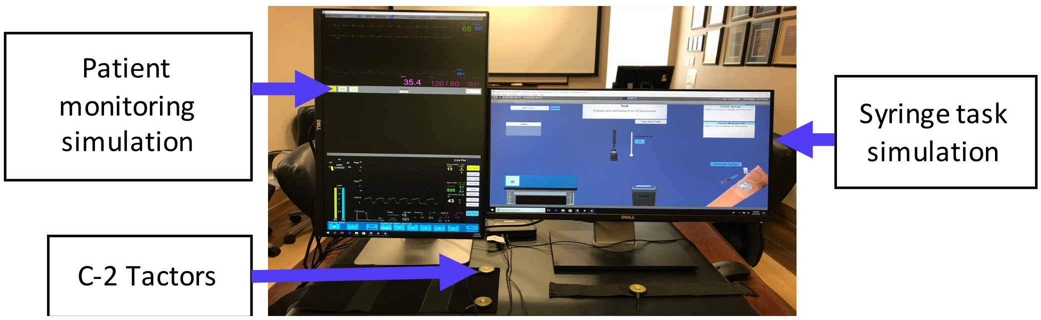

Figure 4.3 Experimental setup showing the two touch screens and simulations used in this study and the C-2 tactor devices

The tactile display included three C-2 tactors (electromagnetic devices developed by Engineering Acoustics, Inc.; diameter = 3.05 cm, height = 0.79 cm; Figure 4.3) which were used to present tactile cues. Each tactor was secured on the outside of one of the participant's upper arms with a velcro arm garment; one tactor was placed on the right arm and two tactors on the left arm. A universal control box sent tactile cue commands from the computer to the tactors. An auditory pulse oximeter display was played throughout the duration of the study at 50 dB using two ORB Audio Mod1 speakers.

Tactile Display

The prototype tactile display was evaluated to communicate information about changes in physiological measures. Two pieces of information were encoded in each tactile cue: (a) the *physiological measure* that changed, encoded using tactor location and (b) the *type of change* that occurred, encoded using unique tactile parameter changes.

Physiological measure. Each tactor location corresponded to a different physiological measure. On the left arm, the top tactor represented pulse oximetry, the bottom tactor represented MAP, and the tactor on the right arm represented $EtCO_2$ as shown in Figure 4.2.

Type of change in physiological measure. Three unique tactile parameter changes were used to each represent a different type of change – that a physiological measure increased, decreased, or normalized. Each tactile stimulus included a series of eight consecutive vibration pulses and included a change in intensity or IPI between the 3^{rd} and 5^{th} pulse. Two tactile parameter changes included a change in intensity with IPI held constant at 500 ms. An intensity increase represented an increase in a physiological measure and an intensity decrease represented a decrease in a physiological measure (Table 4.1). One tactile parameter change included a change in IPI with intensity held constant at 10.4 dB and represented a normalizing physiological measure.

Table 4.1 Description of how intensity or IPI changed and the type of physiological change each represented

Tactile parameter changes	Type of change *The physiological measure…*
Intensity increase low (4.9 dB) → high (15.9 dB) intensity	Increased
Intensity decrease high (15.9 dB) → low (4.9 dB) intensity	Decreased
Change in IPI 200 ms → 800 ms IPI	Normalized

Tasks

Participants completed a tactile cue response task under two different conditions: (1) a *single task* condition, where their only task was to respond to the tactile cues and (2) a *dual task* condition, where they responded to tactile cues while simultaneously performing a secondary task.

Tactile cue response task. Participants were tasked to respond to each tactile cue that was presented as quickly and accurately as possible by identifying the two elements encoded in the cue (i.e., physiological measure and type of change). Participants selected their responses for the physiological measure and type of change that each tactile cue represented on the patient monitor touch screen (Figure 4.4). Participants were instructed not to rely on the physiological data shown on the patient monitor when selecting their responses as the data was not related to the meaning of the tactile cues. After inputting their response for each tactile cue, participants were asked to rate on a scale of 1-10, how confident they were in their response to each cue (1 = least confident, 10 = most confident).

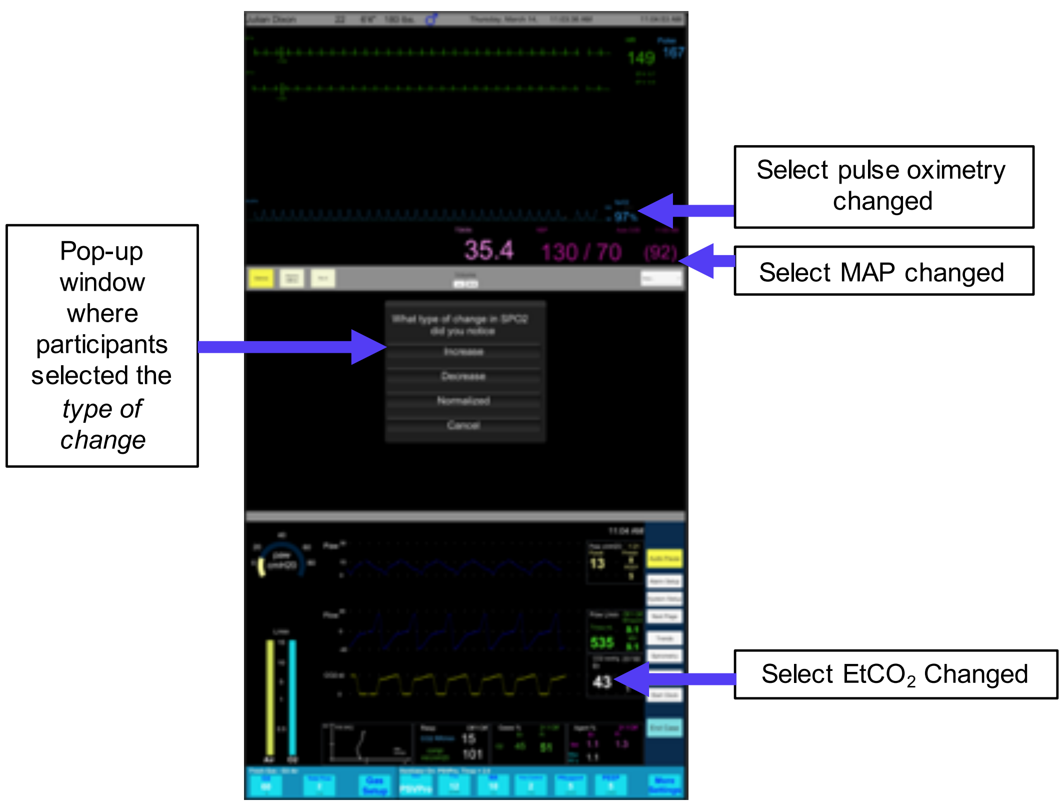

Figure 4.4 Simulated patient monitor touch screen display used to select responses for the physiological measure and type of change each tactile cue represented

Secondary task. This involved preparing and administering virtual syringes using the syringe task simulation touch screen (Figure 4.5). Participants needed to complete the following steps in order by interacting with the touch screen to correctly prepare and administer a syringe:

- *Step 1.* Select correct medication from drop-down menu. Press "Add Vial" button and the vial appears in the **Medication prep area**.
- *Step 2.* Select and move a new syringe to the **Medication prep area**.
- *Step 3.* Select the correct amount of the medication using the sliding scale. Press "Fill" button.
- *Step 4.* Move the label that is automatically generated in the **Syringe label area** to the syringe.
- *Step 5.* Move the syringe to the patient's IV. Press "Administer Syringe" button.
- *Step 6.* Move administered syringe to the trash.
- *Step 7.* Press "View Next Task" and go back to Step 1.

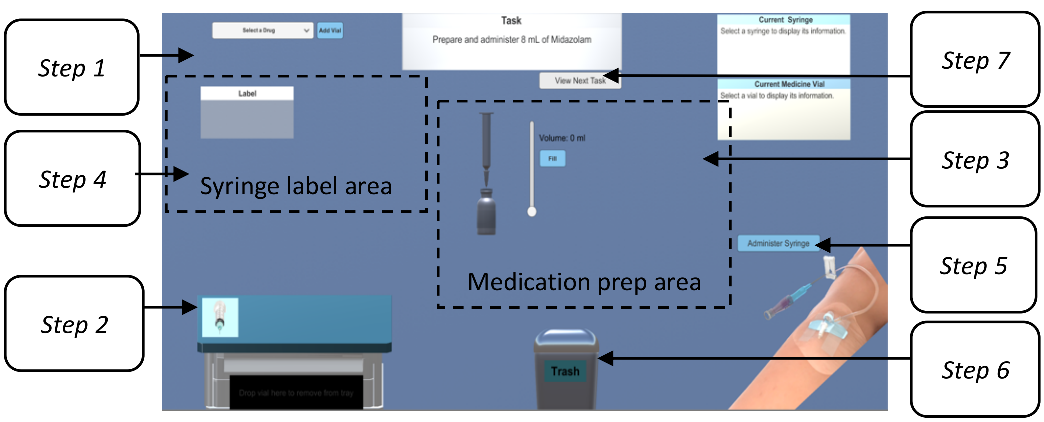

Figure 4.5 Syringe task display showing the location where a participant interacted with the display to complete each step

Figure 4.5 shows where the participant needed to touch the display to complete each step. Instructions on the medication and amount to be filled in each syringe were shown at the top of the display. Participants were instructed to complete as many syringes as possible while maintaining accuracy (i.e., fill the correct medication and amount) and carrying out all steps in the correct order.

Experimental Design

This study included a 3 (tactor location) × 3 (tactile pattern) × 2 (task condition: single, dual) within-subjects full factorial design. Each tactile pattern was presented at each location three times during both task conditions, resulting in a total of 54 tactile cues during the experiment. The order of presentation of each cue was randomized for all participants. The dependent measures were response time and accuracy of responses to the tactile cues (i.e., identifying physiological measure and type of change) and accuracy of completing the syringe task.

Procedure

Participants first read and signed the informed consent form and completed a demographic questionnaire. The experimenter then provided an overview of the study and secured the tactile display to the participant's arms. The participant completed a training session where the meaning of each tactile cue was explained and they were allowed to feel each of the tactile parameter changes. Once they felt comfortable with the meaning of each cue, they completed a pre-test and needed to obtain 100% accuracy identifying each tactile cue one time. The participant then completed the single task condition and then the dual task condition. Directly prior to the dual task condition, participants were trained on how to complete one syringe in the syringe task and were allowed to practice this task until they felt comfortable. Participants were told to respond to the tactile cues as quickly and accurately as possible in both conditions and in the dual task condition to return to the syringe task as much as possible in between responding to tactile cues. Upon the completion of both task conditions, participants completed a debriefing questionnaire and provided open-ended feedback and rated the tactile display on the following six items using a 7-point Likert-type scale (1= very difficult, 7 = very easy):

1. Ease of identifying increases in a physiological measure.
2. Ease of identifying decreases in a physiological measure.
3. Ease of identifying a normalizing physiological measure.
4. Ease of identifying which physiological measure changed.
5. Ease of detecting changes in intensity.
6. Ease of detecting changes in IPI.

The experiment lasted 40 minutes and each participant was compensated $60 for their participation in the study.

Results

The results were analyzed using 3×3×2 repeated-measures mixed ANOVAs (General Linear Models formulation in SPSS 24.0) to identify main and interaction effects on accuracy and response times. Post-hoc tests using Bonferroni adjustments were applied to determine differences among means when the omnibus ANOVA indicated statistically significant differences among conditions.

Accuracy

There was a significant effect of physiological measure ($F(2,34) = 6.49$, p=.004) and type of change ($F(1.39,23.68) = 11.26$, p=.001) on the response accuracy of identifying cues, but not task condition ($F(1,17) = 3.54$, p=.08). Mauchly's test indicated that the assumption of sphericity was violated for type of change ($\chi^2(2) = 9.17$, p=.01) and a Greenhouse-Geisser correction factor was applied (ε=.70). Post-hoc tests showed that response accuracy was the highest when identifying $EtCO_2$ (mean = 99.7%) compared to pulse oximetry (mean = 95.7%) and MAP (mean = 95.1%; both $p<.05$). For type of change, response accuracy was significantly higher for increases (mean = 99.4%) and decreases (mean = 98.1%) compared to normalizing ones (mean = 92.9%; both $p<.05$).

There was a two-way interaction between physiological measure × type of change ($F(2.12,36.10) = 3.38$, p=.043; Figure 4.6). Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(9)$ =3 5.43, $p<.001$) and a Greenhouse-Geisser correction factor was applied (ε=.53). Post-hoc tests showed that response accuracy was significantly higher when identifying cues representing increases in MAP (mean = 100%) compared to normalizing MAP (mean = 89.8%; p=.012).

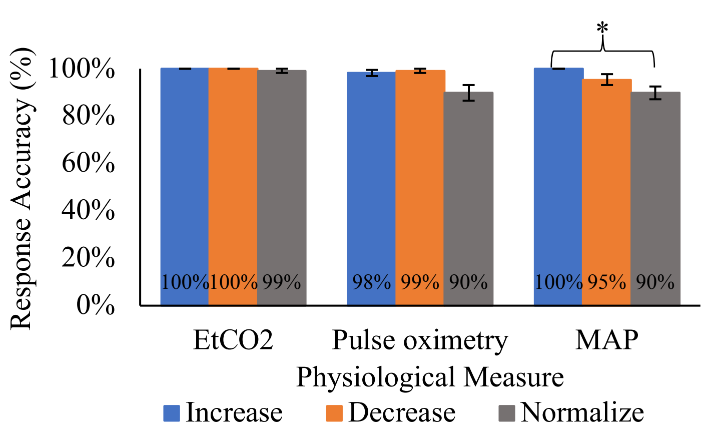

Figure 4.6 Response accuracy for each physiological measure and type of change

Response time

There was a significant effect of physiological measure ($F(2,34) = 10.98$, $p<.001$) and type of change ($F(1.18,20.01) = 5.226$, $p=.029$) on the response time to identify cues, but not task condition ($F(1,17) = 3.78$, $p=.07$). Mauchly's test indicated that the assumption of sphericity was violated for type of change ($\chi^2(2) = 19.22$, $p<.001$) and a Greenhouse-Geisser correction factor was applied ($\varepsilon=.61$). Post-hoc tests showed that response time was significantly faster for responses to $EtCO_2$ (mean = 6.73 sec) compared to pulse oximetry (mean = 7.37 sec) and MAP (mean = 7.04 sec; both $p<.05$). For type of change, response times were significantly faster for cues representing a normalizing change (mean = 6.76 sec) compared to a decreasing change (mean = 7.20 sec; both $p=.033$).

There was a two-way interaction between physiological measure × type of change ($F(4,68) = 3.90$, $p<.001$; Figure 4.7). Post-hoc tests showed that response times were significantly faster to cues representing increasing and normalizing $EtCO_2$ (means = 6.58 and 6.29 sec, respectively) compared to decreasing $EtCO_2$ (mean = 7.32 sec; both $p<.001$).

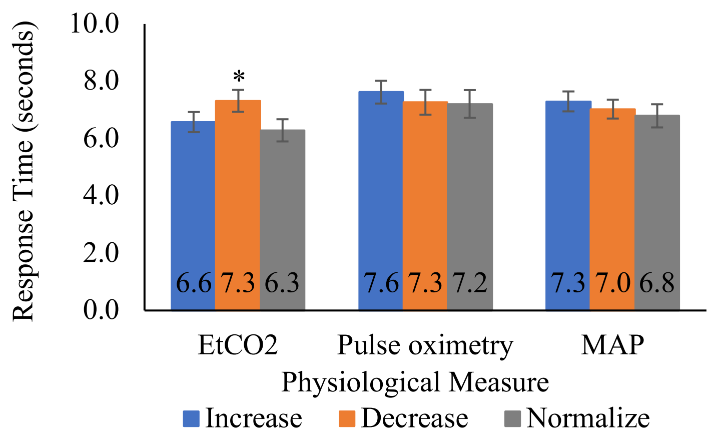

Figure 4.7 Response times for each physiological measure and type of change

Secondary Task

For the secondary task, we report the following measures of performance: the total number of syringes that were prepared, fill accuracy (i.e., whether the correct amount and correct medication was filled in a syringe), and procedural accuracy (i.e., whether all steps were carried out and in the correct order for a syringe). The number of syringes prepared by each participant ranged from 18-30 syringes (mean = 24.5 syringes, *SD* = 3.6).

The number of fill errors were determined by counting the number of times an incorrect medication was selected or incorrect amount of a medication was filled in a syringe. This number was used to calculate fill accuracy as shown in (1).

$$\text{Fill Accuracy (\%)} = \frac{(\text{\# syringes prepared} - \text{\# fill errors})}{\text{\# syringes prepared}} \qquad (1)$$

The number of procedural errors was determined by counting the number of times any of the following occurred: a required step to prepare a syringe was skipped, a step was unnecessarily repeated, or an additional step that was not required was carried out. This number was used to calculate procedural accuracy as shown in (2).

$$\text{Procedural Accuracy (\%)} = \frac{(\text{\# syringes prepared} - \text{\# procedural errors})}{\text{\# syringes prepared}} \qquad (2)$$

The mean fill accuracy for this experiment was 97.0% (*SD* = 4.1%) and the mean procedural accuracy was 96.6% (*SD* = 5.3%).

Debriefing Questionnaire

To analyze participant's subjective ratings of the ease of identifying the physiological information (i.e., type of change and physiological measure) encoded in each tactile cue, a

Freidman test was used to compare ratings for each of the mappings. There were significant differences in the ratings for the ease of identifying the meanings for certain tactile cue mappings ($\chi^2(3) = 24.59$, $p < .001$). Post-hoc pairwise comparisons using Bonferroni corrections showed that participants rated identifying increases in a physiological measure to be easier than identifying a normalizing physiological measure (p = .005) and identifying which physiological measure changed (p = .015; see Table 4.2 for mean ratings).

Table 4.2 Participant's responses rating how easy it is to identify each of the following on a scale of 1-7 (1 = very difficult, 7 = very easy)

	Increases in a physiological measure	*Decreases* in a physiological measure	*Normalizing* physiological measure	*Which physiological measure* changed (i.e., location)
Mean Ratings	6.84 (SD = .37)	6.63 (.60)	5.79 (1.08)	5.7 (1.08)

For the subjective ratings of the ease of detecting tactile changes, participants rated changes in intensity as easier to detect (mean rating = 6.63) compared to changes in IPI (mean rating = 5.84).

The mean of the participants' rating of how confident they were in their response to each tactile cue was also calculated. All tactile cues had a mean confidence rating greater than nine (on a scale of 1-10, where 10 was most confident) in both task conditions with the exception of three cues in the dual-task condition: normalizing pulse oximetry (mean = 8.91), decrease in MAP (mean = 8.93), and normalizing MAP (mean = 8.61).

Discussion

The aim of this experiment was to evaluate the effectiveness of a prototype tactile display which was informed by findings from Chapters 2 and 3. The findings showed after a short training session, anesthesia providers were able to reliably identify all the cues in the prototype tactile display as response accuracy was at least 90% across all cues. While this does not fully support our first hypothesis, i.e., that all cues would be identified with at least 95% accuracy, most of the cues in this study were identified with close to 100% accuracy with the exception of normalizing for pulse oximetry and MAP.

To compare our tactile cues to those from previous work, we report the accuracy and response times from previous studies which have presented physiological monitoring information using the tactile channel in Tables 4.3 and 4.4. It is important to note that comparing response times and accuracy across studies is not as reliable as within study comparisons due to differences in study goals, experimental design, and analysis. One shortcoming of previous work is that they do not evaluate and report performance metrics for the individual elements of the tactile cues used (e.g., for each tactile parameter and the respective physiological information it represents). This makes it difficult to determine what aspects of tactile cues are most effective to use to represent specific physiological information. In terms of reporting performance metrics, some studies report one overall measure of accuracy and response time for all the cues in the study where others report these metrics by certain conditions (e.g., low workload vs. high workload). As such, there is a lack of consistency in how performance metrics (i.e., accuracy and response times) are reported which contributes to the difficulty of comparing tactile cues and the elements that work well within each tactile cue across studies.

Table 4.3 Response accuracy to tactile cues used in previous work

Reference	All tactile cues in the study	All tactile cues in a low workload condition	All tactile cues in a high workload condition	Identification of each physiological measure when mapped to different locations
Barralon *et al.* (2009)	Not reported (n.r.)	79.9%	n.r.	91%
Dosani et al. (2012)	89.5%	N/a	N/a	97.7%
Ng *et al.* (2008)	n.r.	97.1%	93.2%	n.r.
Shapiro *et al.* (2015)	n.r.	83.5%	79.8%	N/a
Current study	93.3%	97.9%	95.7%	96.8%

Table 4.4 Response times to tactile cues used in previous work

Reference	All tactile cues in the study	All tactile cues in a low workload condition	All tactile cues in a high workload condition
Barralon *et al.* (2009)	Not reported (n.r.)	9.3 sec	n.r.
Ng et al. (2008)	n.r.	9.1 sec	9.5 sec
Shapiro *et al.* (2015)	n.r.	7.47 sec	10.82 sec
Current study	7.04 sec	7.23 sec	6.86 sec

Effects of Tactile Display Representation

In particular, the intensity and temporal parameter (i.e., IPI) mappings resulted in fast and accurate responses as anesthesia providers were able to reliably identify all tactile cues used in this study with at least 90% accuracy. These findings support the limited work using these two parameters in the context of anesthesiology and demonstrate the potential of using these two tactile parameters to represent physiological monitoring information (Ferris & Sarter, 2011; Ng, Man, Fels, Dumont, & Ansermino, 2005). The mapping of intensity increases and decreases to increases and decreases in a physiological measure value, respectively, was especially effective. This notion is supported by the debriefing questionnaire as these were consistently rated by the anesthesia providers as the easiest to identify. Using IPI to represent a normalizing physiological measure resulted in the lowest response accuracy in this study; however, it still may be a promising means of presenting patient monitoring information as it resulted in high response accuracy (~93%) and fast response times. Although the use of IPI may not be as effective compared to intensity to communicate physiological information, it still offers a reliable alternative means to present information when used appropriately and may be especially effective when mapped to convey the urgency of information as has been done in previous work (White & Krausman, 2015).

Assigning a specific location to correspond with a physiological measure was also an effective means to communicate information as response accuracy was greater than 95% across participants. To date, there has been no standard on how to best use location to communicate physiological information in anesthesia. Some studies have used location to represent a physiological measure's relative value (McLanders et al., 2014; Shapiro et al., 2015) whereas others have used location to represent a different physiological measure (Barralon et al., 2009; Dosani et al., 2012; Ng et al., 2008). The findings here support the use of separate locations to represent each physiological measure as accuracy levels are comparable to the high accuracy levels of previous work (~90-97%; Barralon et al., 2009; Ng et al., 2008). When comparing the accuracy of identifying each physiological measure, responses to $EtCO_2$ resulted in higher accuracy and faster response times compared to MAP and pulse oximetry. This may be because the tactors representing MAP and pulse oximetry were both on the left arm while $EtCO_2$ was located on the right arm. Challenges associated with spatial localization have been shown to affect tactile perception and can add to cue complexity (Cholewiak & Collins, 2003; Lu et al., 2013). Even though the spacing between the tactors on the left arm for MAP and pulse oximetry was well above the minimum threshold for spatial localization on the upper-arm, it may be that more spatial separation between tactor locations is required to achieve higher accuracy (Cholewiak & Collins, 2003). Several participants cited during the debrief that the placement of two tactors on the same arm presented minor difficulty in distinguishing between MAP and pulse oximetry cues.

Effects of Multitasking

The findings contradict our second hypothesis and showed that multitasking did not degrade task performance when responding to tactile cues as accuracy and response times were comparable in the single and dual task condition. Anesthesia providers were able to reliably and quickly identify the meaning of the tactile cues while preparing and administering virtual syringes—a simulated task that was similar to a task expected to be performed by anesthesia providers. In fact, any effects of a speed-accuracy tradeoff appear to be limited as participants maintained high accuracy on the secondary task (> 90%) while also maintaining accuracy and quick responses to identify tactile cues. This contradicts previous work which showed response times were adversely affected while performing a secondary task. This may be due to the differences in the nature of the secondary task as Ng et al. (2008) used a visual display monitoring task and Shapiro et al. (2015) used a physical task that involved moving pellets with laparoscopic graspers. Alternatively, our secondary task included aspects of more than one task in the operating room (i.e., interacting with technology and performing a physical task).

Another reason the secondary task did not affect the tactile cue task, may be due to learning effects. In this study, participants always completed the single task condition first followed by the dual task condition where they were tasked to simultaneously respond to tactile cues and complete the secondary task. Regardless of the condition order, the findings demonstrate the learnability and effectiveness of the mappings used in our tactile display to communicate physiological monitoring information to anesthesia providers while they are engaged in another ongoing task.

Limitations

There are some limitations of this work which are important to note. First, the virtual syringe preparation task used as the secondary task in this study was not entirely realistic as it required participants to fill a virtual syringe using a touchscreen rather than a physical syringe and was not representative of proper drug dosage and order of administrating the drugs. Participants were informed of this fact prior to the start of the condition with the secondary task. Despite these limitations, the virtual syringe task required the participants to interact with a computer system similar to how an anesthesia provider may interact with an electronic health record system during patient monitoring. Another limitation is the fact that although response accuracy was high, not all the cues reached 100% accuracy. This may be of concern as the tactile display is intended to be used in a work environment where accuracy as well as time to respond to information is critical for patient safety; however, some of the cues, i.e. increase/decrease $EtCO_2$ and increase MAP, did reach 100% across all participants.

It is important to note that the tactile display evaluated here is not intended to replace current displays, but rather to supplement the information that is presented visually and auditorily. We recommend that the tactile channel be used to support attention management by redundantly presenting information that can be found in other modalities to minimize the need to switch between tasks. For example, tactile displays can inform anesthesia providers about the direction and severity of changes and allow anesthesia providers to decide whether switching tasks is necessary without diverting their attention from an ongoing task. However, it is important that future work takes into account whether the introduction of additional alerts in the tactile channel contributes to alarm fatigue, which would be of concern as this is a challenge currently faced by providers (Purbaugh, 2014).

One important consideration for future work is that there is a need to evaluate whether tactile displays can support aspects of performance which have a direct impact on patient outcomes, such as improved response time to notice and address alarming trends in physiological data. In addition, ideally the display should be evaluated in a more realistic setting which accounts for factors which could influence performance with the tactile display in the real world (e.g., movement, noise, cognitive and physical workload). This is a limitation of the current work and one which has yet to be addressed in the literature on tactile displays in anesthesia

Conclusion

Overall, this work provides a better understanding of effective mappings between tactile parameters and physiological monitoring information in anesthesia. This work contributes to the goal of working towards a robust and effective tactile display design to support anesthesia providers during patient monitoring (Gomes, Reeves, & Riggs, 2019). However, design should be an iterative process. Therefore, the findings presented in this dissertation offer several design recommendations which can be built upon through iterative evaluation and refinement moving forward in the efforts to design an effective tactile display.

This study demonstrates that considering human perception limitations and incorporating feedback from anesthesia providers in the design of a tactile display to communicate physiological information was effective in designing tactile alerts that were easily learned, interpreted, and which maximized performance. In addition, the considerations during the design process led to a display design that supported multitasking as the participants were able to accurately respond to tactile cues while completing a secondary task which demanded their visual attention. The findings demonstrate the importance of accounting for factors such as cue complexity and tactile change blindness in the design of a robust tactile display to ensure proper perception and cognition and to support responding to the information communicated. This work sheds light on the importance of incorporating feedback from the end user in the display design process to ensure the way information is represented in the display is intuitive and is effectively communicated to the user. This is especially important for displays that will be used in safety-critical domains, such as in healthcare where inaccurate or delayed responses to events may result in adverse patient outcomes.

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Chapter 5

Conclusion

Tactile displays are a promising means to support operators in complex domains by offloading information presentation from the overloaded visual and auditory channels. In order to ensure the robustness and effectiveness of tactile displays, their design needs to support three critical steps during information processing: perception, cognition, and responding. Therefore, this dissertation seeks to examine the following within the context of anesthesia:

(a) The extent to which movement affects tactile change detection to support *perception*,

(b) Effective information-to-tactile parameter mappings which support *cognition* to ensure the information in the display is interpreted correctly, and

(c) Whether a tactile display design, informed by a better understanding of perception and cognition, supports accurate *responding* in the presence of concurrent task demands.

The anesthesia domain was selected as it represents a complex, data overload environment which may benefit from offloading information presentation in the tactile channel (Ferris & Sarter, 2011).

Intellectual Merit: Contributions to the Tactile Design Knowledgebase

One of the first major findings of this work is that it confirms the phenomenon of change blindness in the tactile channel (Ferris, Stringfield, & Sarter, 2010; Gallace, Tan, & Spence, 2006; Riggs & Sarter, 2016); however, more importantly, it demonstrates that movement may contribute to change blindness in the tactile channel. The findings in Chapter 2 show that tactile change blindness was observed to a greater extent in the presence of movements such as standing and walking compared to sitting across all tactile cue complexities. However, low complexity single-step intensity changes resulted in the best change detection performance during movement. This adds to the growing body of work on change blindness as the current work shows that movement may exacerbate tactile change blindness. The effects of movement on tactile change detection may be attributed to tactile sensory suppression—i.e., decreased sensitivity to tactile stimuli during movement (Juravle, Binsted, & Spence, 2017; Juravle & Spence, 2011). The findings here add to the body of work on sensory suppression and demonstrate that lower body continuous movement, such as walking, may also be subject to tactile sensory suppression. This work demonstrates the importance of considering whether and the extent to which movement may be observed by users in the design of a tactile display. Specifically, single-step intensity changes should be considered in the presence of movement to increase the likelihood that tactile alerts are successfully detected and interpreted even during movement.

This body of work shows that cue complexity is also important to consider to ensure proper perception in the presence of movement as well as to facilitate interpretation of the encoded information. Chapter 2 showed that tactile change detection was worse with high complexity cues (compared to low and medium complexity cues). The performance decrement with high complexity cues may have been due to the increase in the number of cue alternatives that the participant was required to detect. This points to the importance of considering limits to information transmission in tactile display design—i.e. low complexity cues may be most effective to ensure information transmission and communication using tactile displays. This is in line with previous work showing the tactile channel is well suited for presenting low complexity cues by using fewer tactile cue alternatives which can decrease the likelihood of confusing alternatives (Brown, Brewster, & Purchase, 2006; Lu et al., 2013). It is recommended that low complexity cues (i.e., fewer tactile cue alternatives) be used in the tactile channel when possible to maximize the likelihood of correctly interpreting the encoded information.

The findings of this work reveal another important perceptual limitation to consider when designing tactile cues—the just noticeable difference threshold (JND) which is the minimum difference between a reference stimulus and a comparison stimulus that is needed for there to be a perceptible difference (Ehrenstein & Ehrenstein, 1999). The findings of Chapter 2 showed that the ability to detect a change in tactile intensity was best with single-step intensity changes and worse for graded and gradual changes, which entailed smaller magnitude step-wise changes in intensity. The findings show an even greater performance decrement for graded and gradual change detection in the presence of movement. One possible explanation for this is that the smaller changes in intensity may not have been sufficiently above JND threshold to detect a change in intensity. It is important to note that tactile sensitivity decreases during movement, therefore, the magnitude of change may need to be even larger during movement to detect changes. Chapter 3 also showed that participants experienced some difficulty differentiating between smaller and larger magnitudes of change in a tactile parameter, especially for temporal and location changes. This finding emphasizes the importance of considering JND thresholds across all tactile parameters used in display design. It is recommended when tactile parameter changes are used to encode information that the magnitude of change in the tactile parameter is well above the JND threshold in order to maximize the likelihood of perception. The tactile display should also consider whether the operator is moving as the magnitude of change may need to be increased in the presence of movement in order to ensure proper perception and interpretation of the encoded information.

Another contribution of this body of work is that it shows the tactile channel may be able to communicate more detailed information beyond simple alerts to direct attention (Brewster & Brown, 2004). The findings in Chapter 3 suggest that intensity and inter-stimulus interval (ISI) may be useful to communicate specific information about physiological measures and particularly to convey the relative urgency of physiological changes. The findings in Chapter 4 confirm this as the prototype tactile display was able to effectively communicate more detailed information about types of changes that occurred in specific physiological measures. The findings of Chapter 3 are in line with previous work which has shown that the tactile parameters of intensity and IPI may be able to convey the urgency of information and this may be effective to support interruption management. For instance, communicating urgency via a tactile alert can support an operator in prioritizing the importance of the information in the tactile display with minimal disruption to ongoing tasks requiring visual and auditory attention (Hameed, Ferris, Jayaraman, & Sarter, 2009). Overall, the findings from this body of work are line with previous work showing the tactile channel provides an effective way to alert and capture an individual's attention (Ho, Tan, & Spence, 2005). However, the use of the tactile channel to encode and communicate more detailed information should also be considered.

Broader Impact: Implications for Design and Application

This body of work provides insight as to some effective uses of specific tactile parameters to encode information and ensure that information is easily interpreted by the user. First, this work demonstrates the potential effectiveness of two tactile parameters which have been underutilized in previous work to communicate information about physiological measures—intensity and inter-pulse interval (IPI; Ferris & Sarter, 2011; Ng, Man, Fels, Dumont, & Ansermino, 2005). Chapter 2 showed that participants had a preference to use intensity changes to represent the relative magnitude of physiological measures (i.e., increases or decreases in physiological measures). The effectiveness of this mapping was confirmed by the findings in Chapter 4 as the use of intensity to communicate increases and decreases in physiological measures was found to result in greater than 95% accuracy. Intensity has been underutilized to communicate information in the tactile literature and this work provides evidence for a potential use of intensity to represent the relative magnitude of a data concept, such as a patient physiological measure. Chapter 2 showed that changes in IPI were cited as being able to convey the urgency of changes in physiological measures, which is in line with previous work which has shown an association between IPI and perceived urgency (Lewis & Baldwin, 2012; Ng et al., 2005; White & Krausman, 2015). Specifically, changes to a longer IPI were shown to best represent less urgent information—i.e., a physiological measure is normalizing—and this mapping was shown to result in greater than 90% accuracy in Chapter 4. It is recommended that the tactile parameters of intensity and IPI be considered as a means to encode and communicate information such as relative magnitude of a data concept and urgency, respectively.

Another major finding is with respect to the effective use of body location to represent information. Chapter 2 findings revealed that changes in the location of stimulation on the body were not very informative in terms of being able to communicate information about a specific physiological measure. However, several participants expressed the potential for using each location on the body to correspond to a different physiological measure—a mapping which has been used in previous work (Barralon, Dumont, Schwarz, Magruder, & Ansermino, 2009; Dosani et al., 2012; Ng, Barralon, Schwarz, Dumont, & Ansermino, 2008). Previous work has shown that body location is effective when used to encode information which is associated with spatial elements in the environment (e.g., location of a visual target; Hameed, Jayaraman, Ballard, & Sarter, 2007; Ho et al., 2005). Physiological measures have a spatial element associated with them in that each has a corresponding location where it is displayed on a patient monitor. This was considered in the design of the tactile display evaluated in Chapter 4 as separate arm locations were assigned to represent different physiological measures based on their arrangement on the visual patient monitoring displays. The findings of Chapter 4 confirmed the effectiveness of using different locations on the body to correspond to spatial elements as this mapping resulted in close to 100% accuracy of identifying each physiological measure. It is recommended that when considering the use of location in tactile displays that body location is mapped to a spatial element in the environment when possible.

This body of work resulted in a tactile display design that may be a viable candidate to support multitasking and concurrent performance of tasks requiring visual attention in anesthesia. Chapter 4 showed that the performance of a secondary task which required arm movement and visual attention did not interfere with performance (i.e., accuracy or response times) when responding to the tactile cues. The information-to-tactile parameter mappings used and design of the tactile display in Chapter 4 were also shown to result in very high accuracy of responses and greater accuracy compared to previous work (Barralon et al., 2009; Shapiro, Santomauro, McLanders, Tran, & Sanderson, 2015). However, it is important to note that the tactile display should be evaluated in a more realistic setting which takes into account factors that may affect performance with the display. In addition, there are other factors which are important to better understand related to tactile perception as well as systems factors which should be considered in the design of tactile displays. Ideally, display design should be iterative, therefore, this body of work provides a starting point in working towards a tactile display to support anesthesia monitoring which can be built upon while exploring other important systems factors in future work.

This work sheds light on the importance of engaging end users in the display design process, especially to better understand how to map information onto a display in a way that facilities communication of the encoded information. Chapter 3 aimed to understand effective information-to-tactile parameter mappings which may be effective to represent physiological monitoring information. This was achieved through engaging representative end users (i.e., anesthesia providers) and gathering targeted and open-ended feedback about specific tactile parameters and their combinations. While participants did vary in their responses as to the types of information certain tactile parameters could represent, there were some common themes that emerged for specific tactile parameter changes. This demonstrates that the user, in this case anesthesia providers, may have some idea about what a particular data concept or information type should "feel like" which may be based on their mental model. This idea should be investigated in a more objective manner in future work. The findings from Chapter 3 along with findings from previous work on tactile displays were used to inform the design of a prototype tactile display which was evaluated in Chapter 4. The evaluation of the prototype tactile display showed that engaging end users to guide the design of information-to-tactile parameter mappings was effective in designing tactile alerts which were easily learned and interpreted by representative end users.

The findings from this work provide several design recommendations which can be considered in tactile display design to account for the effects of movement on perception as well as information representation to support cognition (see Table 5.1). Specifically, this work provides insight into potentially effective mappings of the tactile parameters of intensity, IPI, and location to represent types of information, which can be generalized, as well as to represent changes in physiological measures. This work also demonstrates important considerations that should be adopted during the tactile display design process to ensure the display can support effective interpretation of information and accurate responses when using the display. First, it is important to engage end users to understand what information should be presented and how to effectively represent the information in the tactile channel. In addition, it is important to incorporate task demands which may be present in the domain where the display will be used during the evaluation process to ensure the display can alleviate data overload and support multitasking.

Table 5.1 Design recommendations and considerations for tactile displays based on the findings of the current body of work

Information processing stage	Step 1: Perception	Step 2: Cognition	Step 3: Responding
Design recommendations	*To account for movement:* • Use single-step tactile changes • Maximize tactile change magnitude	• Minimize cue complexity *Tactile parameter-to-information mapping:* • Body location → spatial elements • Intensity and IPI → urgency • Intensity → magnitude or value of data	• Engage end-users to understand information needs • Evaluate using task demands representative of setting that the display will be used in

Future Work

This dissertation contributes a better understanding of factors which affect perception and information processing in the tactile channel which can be used to inform the design of tactile displays to support operators in complex domains. However, it also highlights several additional questions which need to be understood to support the design of tactile displays of information for use in complex domains.

While the current work engaged end users to understand effective mappings of physiological monitoring information in the tactile channel, it is also important to understand in a more general sense what types of data concepts are most effectively mapped to various tactile parameters (Ferguson, Williamson, & Brewster, 2018). This should be investigated in a more objective manner by adopting the method of magnitude estimation which has been used to understand optimal mappings of acoustic parameters to data concepts for auditory displays (Ferguson & Brewster, 2017, 2018; Walker, 2007). Specifically, magnitude estimation has been used to quantify user's perceptions of a relationship between acoustic parameters (e.g., pitch, loudness) and data concepts (e.g., size, error, urgency; Ferguson & Brewster, 2018; Walker, 2007). Applying this method to quantify perceived relationships between tactile parameters and data concepts can provide a better understanding of optimal mappings in the tactile channel and lead to generalizable design recommendations as to which tactile parameters are suitable to represent specific types of information. In addition, more complex tactile parameters which have been underutilized in tactile display design, such as amplitude modulation and apparent motion, should be explored for their potential to represent data concepts (Brown et al., 2006; Kohli et al., 2006; Roady & Ferris, 2012).

One important consideration guiding future work is that a user's mental model, which is driven by their knowledge and experiences, may dictate preferences for optimal mappings between data concepts and tactile parameters. Therefore, it is not only important to investigate mappings between data concepts and tactile parameters which are generalizable, but this should also be done with representative end users and using data concepts specific to the domain in which the display will be used. This is important to ensure that any mental models specific to the end users are considered in the design of information-to-tactile parameter mappings.

In order to ensure that tactile displays can support anesthesia providers, future work needs to evaluate more direct measures of performance when using tactile displays. Specifically, future work should investigate whether tactile displays of physiological monitoring information leads to improved accuracy or response times in identifying and responding to critical patient events. This requires evaluating tactile displays in a more realistic setting and using higher fidelity clinical scenarios. This points to an important need in this research area—future work needs to evaluate proposed tactile display designs in settings more representative of the environment in which they will be used. In anesthesia, this should include evaluating tactile displays in settings which incorporate the physical and cognitive demands that are present in the operating room. This type of evaluation can reveal whether the display is robust to the effects that other factors in the socio-technical system may have on performance with the display (e.g., movement, verbal communication, multitasking).

Tactile display design research, such as that presented in this work, should also be explored in other contexts where tactile displays may be able to support provider performance and workflow in healthcare including non-operating room anesthesia (NORA), intensive care, and the emergency department. Specifically, in NORA the data overload challenge of patient monitoring is amplified as one anesthesia provider is responsible to monitor multiple patients simultaneously who are not co-located and in settings which are atypical of the normal operating room environment. The presentation of information in the tactile channel can support keeping anesthesia providers informed of critical patient changes when they are attending to another patient. It is important that future work continues investigating the use of the tactile channel to communicate information in new environments as this can provide insights as to how the tactile channel can be used in new and novel ways to communicate information.

Overall, this body of work and future work will add to the knowledgebase of information processing in the tactile channel. This work can be used to inform the design of tactile displays of information which are effective at communicating information and support challenges associated with data overload in various complex domains such as aviation, UAV command and control, and various contexts within healthcare.

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Appendices

Appendix 1: Debrief questions for Chapter 2

1. What is your gender?

   ___ Male ___ Female ___ Other / Prefer Not to Answer

2. What is your age? _____

3. On a scale of 1-10, please rate how alert or sleepy you feel right now (1 = extremely alert, 10 = about to fall asleep) _____

4. Rate how difficult it was to monitor the tactile displays while performing the following movements and tasks (place one "X" for each row):

	Very Easy	Easy	Somewhat Easy	Neutral	Somewhat Difficult	Difficult	Very Difficult
Sitting	___	___	___	___	___	___	___
Standing	___	___	___	___	___	___	___
Walking	___	___	___	___	___	___	___

5. Why did you rate *sitting* how you did in question #4?

6. Why did you rate *standing* how you did in question #4?

7. Why did you rate *walking* how you did in question #4?

8. Describe any strategy you adopted while monitoring the tactile displays.

9. Do you have any general comments for the study? Thank you again for participating in our study!

Appendix 2: Debrief questions for Chapter 3

10. What is your gender?

    ___ Male ___ Female ___ Other / Prefer Not to Answer

11. What is your age? _____

12. What is your current role and years of experience in this role? (check one of the following and fill in the years of experience)

    - ☐ Attending anesthesiologist
    - ☐ Anesthesia Resident
    - ☐ CRNA
    - ☐ Other:________________

    a. Years of experience in current role: _________________

13. Which tactile pattern do you feel is best? *Please state and explain any reasons for your preference(s).*

14. Are there any specific tactile patterns that you believe to be best to represent MAP, $ETCO_2$, and pulse oximetry? *Please state and explain any reasons for your preference(s).*

15. Any other observations, problems, or general comments are appreciated!