5-2017

Investigating Tactile Displays to Support Anesthesia Providers in the Operating Room

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Recommended Citation

Betza, Scott Michael, "Investigating Tactile Displays to Support Anesthesia Providers in the Operating Room" (2017). *All Theses*. 2605.
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INVESTIGATING TACTILE DISPLAYS TO SUPPORT ANESTHESIA PROVIDERS IN THE OPERATING ROOM

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Industrial Engineering

by
Scott Michael Betza
May 2017

Accepted by:
Sara Lu Riggs, PhD, Committee Chair
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ABSTRACT

There has been a growing interest in using the tactile modality to offload the often overburdened visual and auditory channels. Although the promise and merit of using the tactile channel has been demonstrated in various work domains, more work is needed to understand perceptual limitations like change blindness. Change blindness refers to the failure in detecting expected visual changes (both small and large) within a scene or on a display when these changes coincide with a visual "transient" (i.e., a brief disruption in visual continuity). While the majority of work on change blindness has been conducted with vision, there is evidence it affects the tactile modality as well. The goal of this study was to examine how movement and tactile cue complexity affect the ability to detect tactile changes. The findings show that the ability to detect tactile changes is affected by movement as walking resulted in worse change detection rates compared to sitting. The findings also demonstrated that higher complexity cues had worse change detection rates compared to lower complexity cues. Overall, this work adds to the knowledge base of tactile perception and can be applied to multiple work domains such as anesthesiology to inform the design of tactile displays.

DEDICATION

This thesis is dedicated to my family and friends, and especially to my mother and father (Patsy and Scott), who provided support with my decision to pursue an advanced degree after many years of working and encouraged me to continue to challenge myself in not only learning but in all aspects of my life.

ACKNOWLEDGMENTS

I am extremely thankful for all of the support I received during my time at Clemson in my coursework, research, and thesis work. My advisor, Dr. Sara Lu Riggs, has exceeded my expectations in terms of guidance and time dedication from my journey to formulate a valid research question, to shaping my study design, and finally with providing support with developing this thesis document which I hope will be a meaningful contribution to the knowledgebase of tactile perception and tactile change blindness. It has been a pleasure to work with my other committee members, Dr. David Neyens and Dr. Joel Greenstein, and I'd like to thank them for their time and valuable feedback throughout my research. I would also like to acknowledge that their passion lecturing the human factors and system design courses was extremely helpful with providing me a foundation to develop a better research strategy and to produce meaningful insights from the study.

I would also like to thank Alexei Yankovsky for his significant effort in developing and testing the program that allowed me to conduct my study. Thank you Kylie, Shannon, Aakash, Megan, Ebony, Jake, Katie, Myrtede, Ali, Elizabeth, Dan, Michael, and Darlene for all the help, encouragement, and laughs over the past two years. I would like to thank my family and friends for believing in me and supporting me. Finally, I'd like to thank Casey for her amazing support and patience.

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CHAPTER ONE

INTRODUCTION

Anesthesia Work Domain

Anesthesia providers have the challenge of managing the side effects of surgery such as pain and awareness (i.e., depth of anesthesia), as well as sustaining proper oxygenation and ventilation levels, while also considering the patient’s pre-existing conditions (Sanderson, 2006). Specifically, they need to divide their mental resources effectively amongst monitoring equipment status and multiple physiological variables (e.g., electrocardiogram, heart rate, blood pressure, and body temperature) by attending to various displays (primarily visual) such as the patient monitor, anesthesia machine monitor, the electronic health record (EHR), and video laryngoscope (Miller & Pardo, 2011). It is critical that anesthesiologists continuously monitor physiological variables, and that while anesthesia is extremely safe today even as anesthesia equipment has become more complex, incidents can still occur if safety measures are not followed and drugs are given improperly (Miller & Pardo, 2011).

Data overload, especially in the visual and auditory channel, already represents a growing challenge within the operating room. Audition can be used for communicating information and alarms, and to offload information from the visual channel, but excess noise can negatively impact short-term memory, hinder the ability to detect audible alarms, and ultimately distract clinicians (Rostenberg & Barach, 2012). One promising means of addressing challenges associated with visual data overload is the introduction of multimodal interfaces that distribute information across vision, audition, and/or touch (Oviatt, 2002; Sarter, 2002). Multimodal displays output information primarily via visual and auditory cues, but other modalities have been implemented such as touch (Sarter, 2006), with a growing interest in the latter (Ferris, Stringfield, & Sarter, 2010).

Ferris & Sarter (2011) performed a study with multimodal displays (including the tactile modality) that communicated mean arterial pressure (MAP), end-tidal carbon dioxide (EtCO2), and tidal lung volumes (TV). The anesthesiologists who were participants in the study wore two garments with tactors (small piezo-electric devices that provide vibrotactile stimulation). The anesthesiologist monitored the physiological variables (i.e., MAP, EtCO2, and TV) that were conveyed via the tactile displays and adjusted ventilation, infusion pumps, and administered drugs accordingly. The results showed that monitoring performance with the tactile displays resulted in faster response times as well as supported multitasking better than the baseline configuration that consisted of only visual and auditory displays.

Similarly, novel tactile displays on the upper arm have been developed for anesthesia information in multiple studies with messages that were encoded via tactons (i.e., tactile icons; Brewster & Brown, 2004). Heart rate and pulse oxygenation were communicated through separate tactons (i.e., heart rate first then pulse oxygenation) or integrated tactons via spatial and temporal mapping (McLanders, Santomauro, Tran, & Sanderson, 2014; McNulty et al., 2016; Shapiro, Santomauro, Mclanders, Tran, & Sanderson, 2015). Additionally, Fouhy, Santomauro, Mclanders, Tran, & Sanderson (2015) have preliminarily investigated an upper arm tactile display while performing both a pellet moving task with their hands and a simulated laparoscopic task, and found that the arm motion alone did not significantly affect performance.

Multimodal displays utilizing the tactile modality seem to be a viable option to address visual and auditory data overload. However, the effectiveness of these tactile displays may be compromised if their design does not take into consideration the limitations of human perception and cognition. One such limitation is a phenomenon called change blindness – the surprising difficulty humans have in detecting even large changes in a visual scene or on a display when these changes coincide with another visual event (Simons, 2000). To date, the phenomenon has been studied primarily in vision, but there is limited empirical evidence that the tactile modality may also be subject to change blindness (Gallace, Tan, & Spence, 2006), especially in the presence of movements (Gallace, Zeeden, Röder, & Spence, 2010). If confirmed, this raises concerns about the robustness of multimodal displays and their use in the operating room due to possible low accuracy of tactile change detection from change blindness. This thesis will address the following questions:

1. How do various body movements affect tactile detection?
2. Does the complexity of the tactile cue affect the ability to detect tactile changes?
3. Are certain locations on the body more susceptible to tactile change blindness during movement?

Multimodal and Tactile Interfaces

Multimodal interfaces (interfaces that present information via vision, audition, and touch) are a type of human-machine interface that facilitates interaction with complex systems through various display outputs (Sarter, 2002). The benefits of using multimodal displays for information output may enhance the throughput of human information processing capacity (Sarter, 2002).

In recent years, touch has received considerable attention (Hancock et al., 2015; Jones & Sarter, 2008; Lu et al., 2013; MacLean, 2008). It offers a promising means to offload the visual and auditory channels which are increasingly overburdened in several domains (e.g., in the operating room; Ferris & Sarter, 2011). The tactile modality has many clear advantages; it is omnidirectional (which allows for the information receiver to maintain their current head and eye position), transient, not overly invasive (Sarter, 2002), requires a small exposure duration to be detected, has a high spatial acuity (Lu, Wickens, Sarter, & Sebok, 2011), and information has a greater privacy (Erp & Veen, 2001) compared to vision and audition.

There have been several anesthesia studies showing the efficacy of tactile displays to communicate anesthesia related physiological variables (McLanders et al., 2014; McNulty et al., 2016; Shapiro et al., 2015). McLanders et al. (2014) investigated pulse oxygenation saturation (SpO2) and heart rate with tactons of up to five alarm threshold levels represented through spatial (i.e., top, middle, and bottom) and temporal mapping (i.e., one, two, or three rapid pulses). SpO2 and heart rate were found to be effectively communicated via tactile displays with an accuracy of greater than 90%. However in a follow-up experiment, Shapiro et al. (2015) found that performance was affected when frequent changes occurred under a high workload condition. In the study of Ferris & Sarter (2011) discussed earlier, standing participants wore tactile displays that communicated MAP, EtCO2, and TV via spatial, intensity, and temporal parameters. It was found that an anesthesiologist's ability to monitor a patient's vitals improves when using tactile displays. Although the tactile modality and its integration into multimodal displays has potential advantages, technology design must account for human limitations including tactile change blindness.

Change Blindness

Change blindness refers to the failure in detecting expected visual changes (both small and large) within a scene or on a display when these changes coincide with a visual "transient" (i.e., a brief disruption in visual continuity; Simons & Levin, 1997). An example of change blindness is the study of Rensink, O'Regan, & Clark (1996), shown in Figure 1.1, where a sequence of images is repeated of a couple having dinner (280 msec), with an 80 msec flicker (i.e., a blank screen transient that briefly occludes a scene), followed by the original with a minor change in the original image, and finally followed by another flicker. The study found that participants took an average of 17.1 (10.9 s) sequence alternations to notice minor changes with the presence of a flicker, compared to 1.4 alternations (0.9 s) when there was no flicker present. In addition to flickers, a mudsplash is another type of transient where small highly contrasting shapes are overlaid on an image (O'Regan, Rensink, & Clark, 1999).

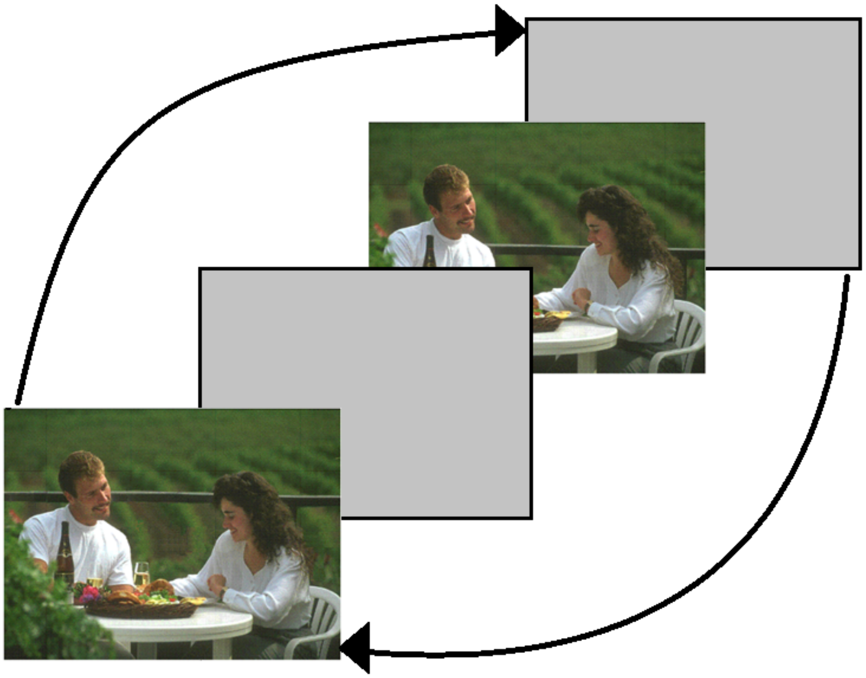


Figure 1.1: General change scene frames with flicker (movement of railing in background; Rensink et al., 1996)

Change blindness has been primarily documented in vision, but there has been evidence of its effect on the tactile modality (sometimes referred to as change numbness; Hayward, 2008). Gallace, Auvray, Tan, & Spence (2006) led one of the earliest studies that confirmed change blindness of a tactile display in the presence of blank intervals between the tactile displays and from visual transients.

Auvray, Gallace, Hartcher-O'Brien, Tan, & Spence (2008) investigated tactile displays on fingertips and also found reduced performance when introducing a blank interval between tactile changes, and further performance decrement when using a tactile mask (i.e., occurrence of another tactile stimulus not related to the tactile display being monitored). Additional studies include that of Ferris, Stringfield, & Sarter (2010) where participants monitored tactile intensity changes across various conditions such as intensity instantly changing, a blank interval between changes, a masked interval (whole display vibrated), a mudsplash interval (portion of the display vibrated), and a linear gradual change. The masked and mudsplash conditions exhibited poor performance, and the gradual condition even worse performance. To date, studies of tactile change blindness have primarily required participants to remain stationary such as standing (e.g., study of Ferris et al., 2010) and sitting (e.g., studies of Gallace et al., 2010; Riggs & Sarter, 2016), rather than having participants engage in movements.

Movement as a Tactile Transient

Gallace et al. (2010) found evidence of tactile change blindness while engaging in a secondary task requiring movement which consisted of monitoring the illumination of two LEDs with various Stimulus Onset Asynchrony (SOA) and pushing a button, turning a steering wheel, and/or verbally responding to indicate the appropriate LED (i.e., to the left or right of participant). The results suggest that performance of a secondary task reduced the ability to detect tactile changes, but performance was even worse with arm movements. In a recent literature review, Juravle, Binsted, & Spence (2016) provide insight into the findings of Gallace et al. (2010) and discuss that tactile suppression (i.e., performance decrement in tactile detection) is maximized on the moving body part and further emphasize that the context of the movement phase is important as performance is enhanced right as one prepares to move.

Karuei et al. (2011) examined tactors worn on the participant’s feet, outer thighs, wrists, stomach, upper arms, chest, and spine in a study where participants were asked to walk and sit. The results indicate that walking reduces the odds of detecting a vibration and increases reaction time, with thighs and feet being the most negatively affected, but found that the arms were less affected. Oakley & Park (2008) also had participants conduct a tacton recognition task involving location and roughness (i.e., frequency with amplitude modulation), while also performing distracter tasks of mouse-based data entry (sitting), typing transcription (also sitting), or walking. The distracter tasks compared to the control resulted in a 5-20% reduction in performance of tacton recognition, with transcription tending towards causing the most impairment.

Some literature has focused on body and limb positioning such as the study of D’Amour & Harris (2016) which investigated tactile masking and found that holding arms parallel and straight to each other enhanced masking when the opposite arm experienced a tactile mask. Additionally it was found that touching arms increased the effects of tactile masking. The effects of hand finger posture were also explored by Riemer, Trojan, Kleinböhl, & Hölzl (2010) where participants wore tactile devices on their index and middle fingers while having the two fingers of one hand vertically on top of the other or while weaving the fingers. Two of the participant’s fingers were stimulated and they had to identify the stimulated finger (index or middle) or hand (right or left). Participants made fewer errors for the finger task when their fingers were interleaved and for the hand task when their hands were in the vertical posture.

However, other work has shown no effect of movement on tactile change detection. Calvo, Finomore, Burnett, & McNitt (2013) had participants use a navigation aide prototype while walking. Their results indicate that the user successfully interpreted tactile directional information while walking, and that a tactile navigation display is as effective as a visual one. At the cognitive level, Bantoft et al. (2015) investigated the effects of working while seated, standing, and walking on short-term memory, working memory, selective and sustained attention, and information processing speed by administering a battery of cognitive tests involving the visual and auditory modalities. The study concluded that cognitive performance is not degraded for all of the investigated movements. This suggests that standing and walking movements often performed by anesthesia providers in the operating room may not impair their cognitive function for vision and audition, but validation is needed to confirm this result for touch.

Terrence, Brill, & Gilson (2005) examined tactile and spatial auditory directional cues while participants were in the supine (i.e., laying on back), kneeling, sitting, standing, and prone positions. It was found that tactile response time was faster than the auditory response time for all body positions, and that the supine position had significantly higher response times across both modalities. The results suggest that the various stationary positions (e.g., sitting and standing) often have similar performance, however dynamic movements such as walking were not investigated. Many studies focus solely on sitting participants such as in the tactile change blindness study of Gallace, Tan, et al. (2006) where participants performed a tactile location change detection task and it was found that accuracy was negatively impacted when a tactile mask was presented between displays. Similarly in the study of Gallace, Auvray, et al. (2006), seated participants performed a tactile change detection task and were near perfect when displays were presented without pause, but failed to detect some changes when an empty interval was introduced, and performance degraded even further with the presence of a visual mask, indicating that visual masking transients can elicit tactile change blindness.

To address the concerns of change blindness, countermeasures to tactile change blindness were investigated by Riggs & Sarter (2016) for sitting participants. Participants performed an intensity change detection task while being subjected to tactile mudsplashes (all tactors vibrate) or flickers (some tactors vibrate). Countermeasures were employed that aimed to mitigate change blindness: proactive alerting, signal gradation for misses, and comparison cue for misses. The authors found all countermeasures improved change detection. Yoshida, Yamaguchi, Tsutsui, & Wake (2015) investigated tactile search for change where participants moved their hand to identify changes on a matrix of tactile stimulator reeds, and found that there is a smaller memory capacity of approximately one item versus the two to ten of visual exploration. The studies of Riggs & Sarter (2016) and Yoshida et al. (2015) underline the importance of considering human limitations when designing tactile systems.

Table 1.1 summarizes literature which includes tactile displays being investigated in an anesthesia context, having coincidently both tactile displays and body movements, or having a specific focus of investigating the effect of body position and body movement on tactile performance and change detection. The motivation for this research is that there has been limited work investigating performance and accuracy of tactile displays where participants were purposefully subjected to multiple body movements and postural demands such as sitting, standing, and walking. Therefore this study aims to further investigate body movements and their relationship to tactile change detection.

Table 1.1: Summary of tactile display literature with movement

Study	Description	Movement	Tactile Location	Findings
Bantoft et al., 2015	Working at a desk.	Sitting, standing, and walking	N/A	No change in short-term memory, working memory, attention, or information processing speed in all conditions.
Calvo et al., 2013	Navigation along a route using auditory or tactile cues.	Walking	8 tactors around torso	Tactile cues as effective as visual map.
D'Amour & Harris, 2016	Identified tactile stimuli under masking effects while varying test and masking arm position.	Sitting	1 tactor on middle left inner forearm, 1 vibrator masking stimulus on right middle right inner forearm or right shoulder	No main effect for test arm position on sensitivity and effectiveness of masking is best when arms are parallel.
Ferris & Sarter, 2011	Monitoring of simulated patient supported with the design of a tactile alarm and two different continuous tactile displays for TV, ETCO2, and MAP.	Standing	18 tactors, with 8 on left and right side of back, 5 on spine, and 5 on upper arm	All three displays improved performance, with hybrid display (more salient as time went on) having the best performance.

Table 1.1: Summary of tactile display literature with movement

Study	Description	Movement	Tactile Location	Findings
Ferris et al., 2010	Monitor simulated patient blood pressure and adjust drug delivery as well as intubate patient.	N/A	4 tactors on non-dominant forearm, dorsal and palmar at wrist and near elbow	Best performance was baseline condition, then blank interval, and worse was gradual change. Masked and mudsplash intervals showed worse performance. Addition of secondary task did not affect performance.
Ford et al., 2008	Monitoring simulated case of anaphylaxis and administering a drug to patient.	Standing	4 tactors on waist	Best reaction time was in multimodal condition versus control (visual display only) condition. No significant difference in situational awareness between the two conditions however.
Fouhy, 2014	Monitored tactons for HR (spatial) and SpO2 (temporal) under low task load (moved pellets with hand) and high task load (move pellets with laparoscopic graspers – less movement than with hand).	Standing	3 tactors on upper right arm	Low task load accuracy higher than 90% and high task load accuracy lower than 90%. High task load HR accuracy higher than low task load HR accuracy, therefore movement shown to not affect performance overall and for one of the two patient variables.

Table 1.1: Summary of tactile display literature with movement

Study	Description	Movement	Tactile Location	Findings
Gallace, Auvray, et al., 2006	Detect tactile stimulus change with various interval types with tactile or visual transients.	Sitting	6 tactors used, with 1 on left forearm near wrist, left bicep, left mid shin, right upper shin, right of belly button, and right upper bicep	Tactile change blindness elicited by visual transient as well as tactile masking.
Gallace, Tan, et al., 2006	Detect tactile stimulus change when 2-3 tactors presented simultaneously during interval.	Sitting	7 tactors on left wrist, below left elbow, mid right forearm, on middle-left back, on right-side waist, above left ankle, and mid right calf	Change detection almost 100% for no interval gap, less for empty interval, and worse when masked.
Gallace et al., 2010	Detect tactile stimulus change when 3 tactors presented simultaneously while performing motor, verbal response, steering, or no secondary task of discriminating 2 LEDs being illuminated.	Sitting	8 tactors on forearms, upper arm, thighs, and shins	Performance affected by motor tasks being performed. Greater onset between movement and change cause worse performance. Movement can elicit tactile change blindness.

Table 1.1: Summary of tactile display literature with movement

Study	Description	Movement	Tactile Location	Findings
Jones, Kunkel, & Piateski, 2009	Display with directional cueing to support navigation in unfamiliar environments.	Sitting	12 tactors (4x4 array) on back and 9 tactors (3x3 array) on forearm	The back display had significantly higher accuracy than the arm display. Both locations however were demonstrated to be effective, but the arm location is constrained by surface area.
Karuei et al., 2011	Detect vibration while performing visual task.	Sitting and walking	13 tactors with 1 on upper spine and 1 on each foot, thigh, stomach, chest, upper arm, and wrist	Walking decreased odds of detection and increased reaction time. The thighs and feet are most affected and chest, arms, and wrists are the least affected.
McLanders et al., 2014	Monitor pulse oximetry using two tactile display designs.	N/A	3 tactors on elbow crease, midshaft of humerus, and deltoid	90% accuracy for both integrated and separated (heart rate first) displays. Heart rate easier to identify in integrated display.
Ng, Man, Fels, Dumont, & Ansermino, 2005	Monitored decreasing and increasing alarms with three severity levels each.	N/A	2 tactors on left forearm	Tactile alarms had better reaction times than auditory alarms. 70% of participants preferred tactile alarms versus auditory. No significant difference between multimodal (auditory + tactile) alarm and tactile only.

Table 1.1: Summary of tactile display literature with movement

Study	Description	Movement	Tactile Location	Findings
Oakley & Park, 2008	Identify tacton while entering data with a mouse, walking, and transcribing.	Sitting and walking	3 tactors on wrist	Distractor tasks can mask tactile cues and cause 5-20% reduction in performance.
Riemer et al., 2010	Discriminate and identify hand and finger where tactile stimulus is applied while fingers are interleaved or vertical.	Sitting	4 solenoids attached to fingertips (2 for each hand)	Hand and finger identification influenced by hand (vertical or woven) posture.
Riggs & Sarter, 2016	Detect tactile changes with countermeasure methods (proactive, miss with gradual increased intensity, miss with low to high intensity).	Sitting	12 tactors on back in 3x3 array (with middle having 2 tactors on each side of spine)	All countermeasures improved tactile change detection. Increasing intensity after missed change had best detection rate.
Terrence et al., 2005	Detect auditory and tactile directional cues in various body positions.	Sitting, standing, kneeling, prone, and supine	8 tactors placed around abdomen and back about 1 inch above naval	Tactile display outperformed auditory display with response time being shorter for tactile signal for all positions.
Yoshida et al., 2015	Detect differences in stimuli for visual and tactile search tasks.	N/A	40 x 56 matrix of reeds on palm of hand	Tactile search for change has smaller memory than visual search for change. Haptic system almost memoryless outside fingertips.

Research Objective

This work aimed to develop novel tactile displays which would support anesthesia provider monitoring tasks in the operating room. In particular, the focus was to understand how body movement impacts the detection and interpretation of tactile information. The experiment evaluated the tactile displays in the context of the three types of movements that have been identified to be typical of anesthesiologists in the operating room: *sitting*, *standing*, and *walking*. The tactile displays on the arm and back varied in complexity which allowed further insight to determine whether tactile displays are feasible to introduce into operating rooms and what level of cue complexity is appropriate for anesthesia providers. The expected results were as follows:

1. Sitting will have a higher tactile change detection accuracy compared to standing and walking,
2. Low complexity tactile cues will have a higher tactile change detection accuracy compared to high complexity tactile cues, and
3. The back location will have a higher tactile change detection accuracy compared to the arm location when walking.

CHAPTER TWO

METHODOLOGY

Participants

Eighteen English-speaking participants participated in this study (12 males and six females; M = 22.4, SD = 2.6). Participants were required to have no impairments to their sense of touch (verified during pre-test).

Experimental Setup

Each participant wore a belt (Figure 2.1) or arm band (Figure 2.2) garment over their clothing and each garment had three C-2 tactors (diameter = 3.05 cm and height = 0.79 cm) affixed with Velcro. The tactors were developed by Engineering Acoustics, Inc. A universal controller box, which provided the output signal to each tactor, was powered by a lithium ion battery pack (2600 mAh, Li-18650-2S1P-7.4V) and placed on the participant in a zippered pack worn around the waist. A Dell Precision T3610 workstation sent commands via Bluetooth to the universal controller box. Experimenters used a Dell UltraSharp U2717Dt 27” monitor to progress through each block and record responses. A ProForm Premier 1300 treadmill model no. PFTL13115.0 was used for the walking condition. Pink noise (i.e., less hissing and more soothing than white noise) was played over Bose QuietComfort 15 acoustic noise cancelling headphones to mask noise emitted from the tactors.

Figure 2.1: Back garment with tactors affixed

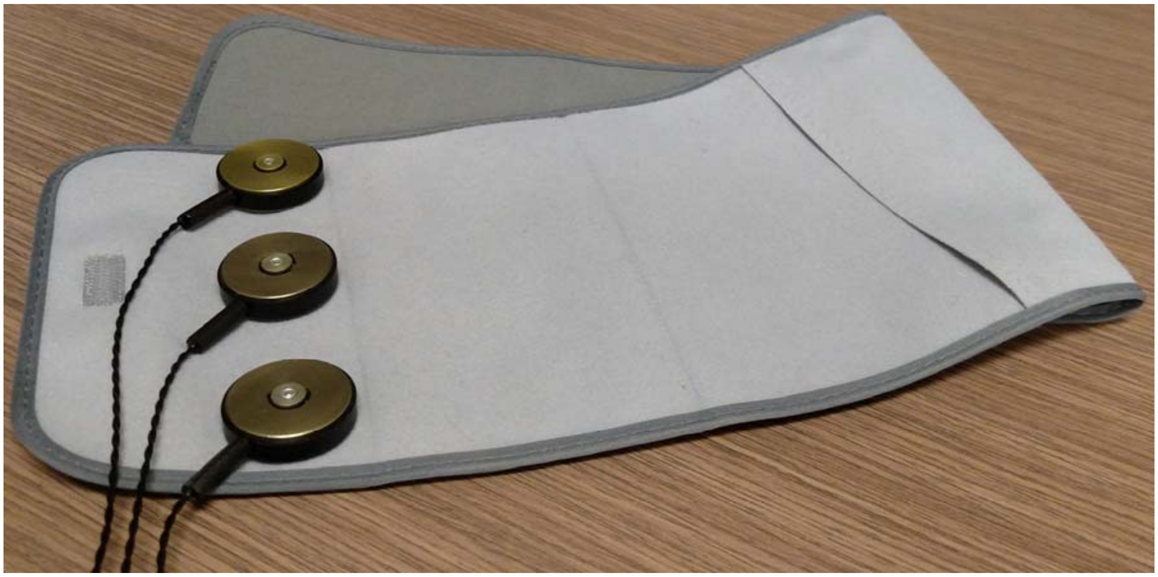


Figure 2.2: Arm garment with tactors affixed

Task and Trial Description

The participants' task was to verbally indicate the type of changes in vibration intensity and/or location for each trial. An auditory tone signified the start for each trial that would include a tactile signal that continuously pulsed for 12 s (16 vibrations with

650 ms duration and an inter-stimulus interval of 100 ms). A change in intensity and/or location could randomly occur any time between the fourth and 14th vibration. Figure 2.3 provides a summary of a hypothetical trial where there is a change. After each trial, participants verbally indicated to the experimenter the change details and the experimenter recorded the response. For the low and medium complexity cues, participants were instructed to respond “no change”, “increase”, or “decrease”. For the high complexity cue changes, participants were required to also indicate what type of intensity change occurred (i.e., “single”, “graded”, or “gradual”) or the ending location (i.e., “location 1”, “location 2”, or “location 3”).

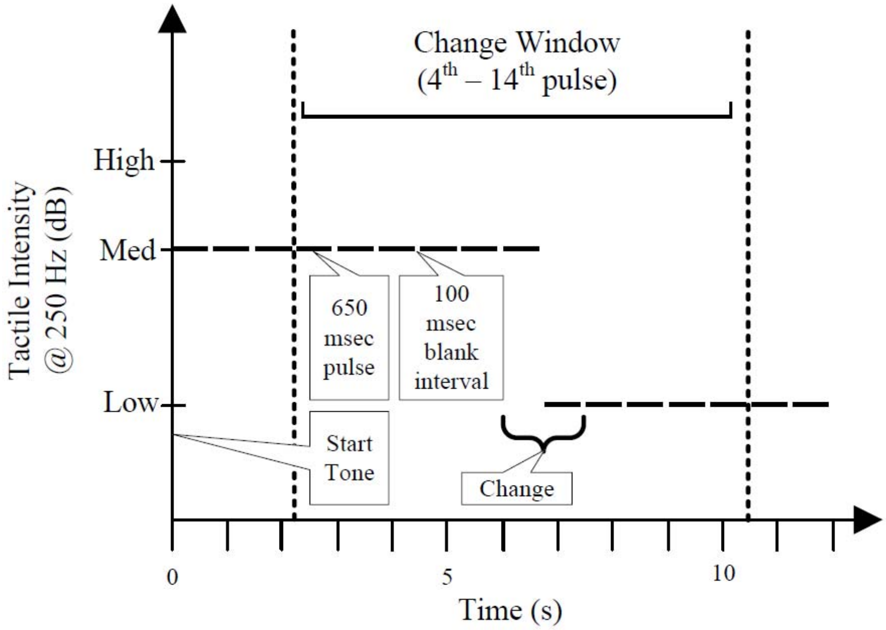


Figure 2.3: Overview for one single-step decrease change trial (longer dashed lines represent duration of tactile vibration pulses)

Tactile Cues

For each trial, the starting tactor was randomly selected from the three tactors on the garment. Vibrations were only emitted from one tactor at any given time. The universal controller used pulse width modulation to set the output voltage and current drive levels for each tactor. The low intensity was set at 0.9 V_{rms} (0.096 A_{rms}; 4.9 dB), medium intensity at 1.7 V_{rms} (0.183 A_{rms}; 9.3 dB), and high intensity at 2.3 V_{rms} (0.247 A_{rms}; 12.5 dB). A trial always started at the medium intensity level and if there was a change, it started between the fourth and 14th pulse.

Tactile cue complexity was determined based on detection difficulty (i.e., smaller changes in intensity are harder to detect due to Weber's Law of just noticeable difference; Brewster & Brown, 2004) and the amount of information embedded in the cue (i.e., intensity steps and location changes). The four tactile cue types that were used in the study included the following:

1. Single-step change (low complexity),
2. Graded change (medium complexity)
3. Gradual change (medium complexity)
4. Intensity or location change (high complexity)

In the single-step (low complexity) tactile cue the intensity change occurred in one step (Figure 2.4). The intensity change could increase from medium to high or decrease from medium to low. For the graded and gradual (medium complexity) tactile cues, the change occurred over the course of four (Figure 2.5) and eight steps (Figure 2.6) respectively. In the location-intensity (high complexity) cue, there could be a change in intensity (i.e., single-step, graded, or gradual) or a location change (Figure 2.7).

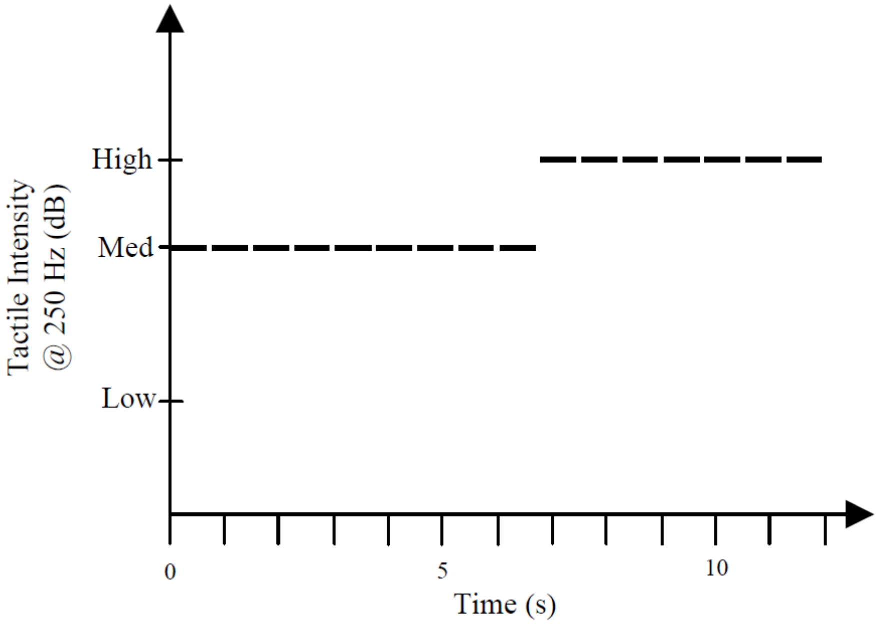


Figure 2.4: Single-step increase in intensity (low complexity)

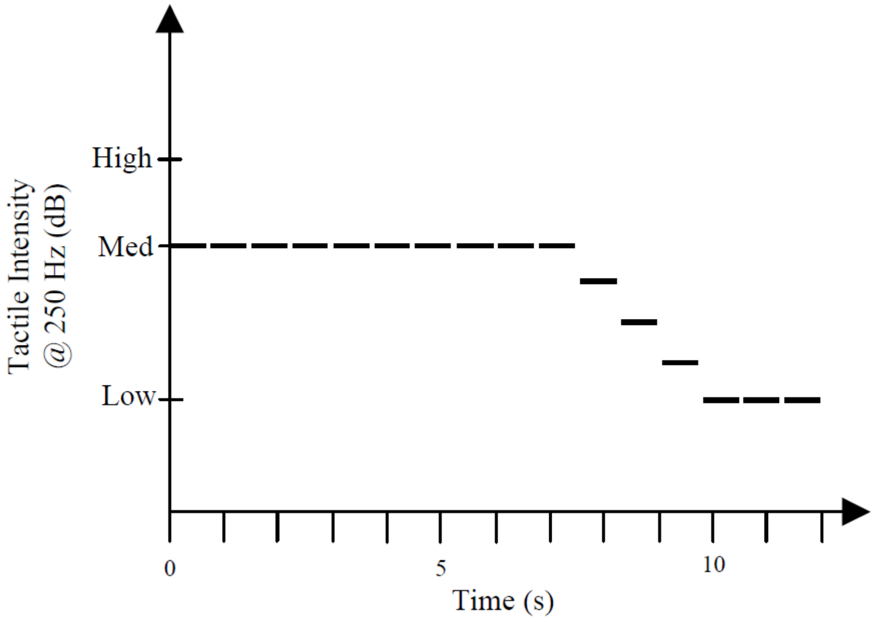


Figure 2.5: Graded decrease in intensity over 4 steps (medium complexity)

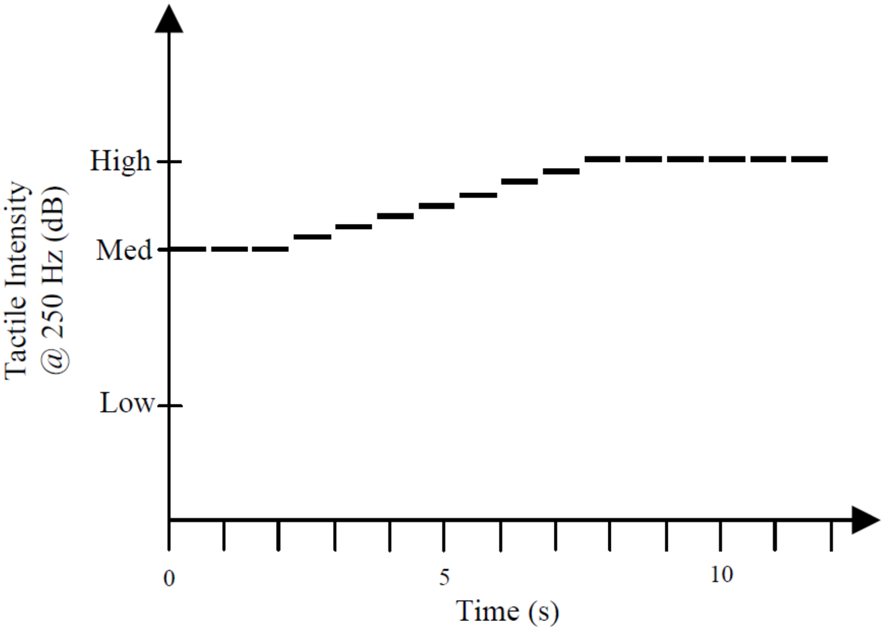


Figure 2.6: Gradual increase in intensity over 8 steps (medium complexity)

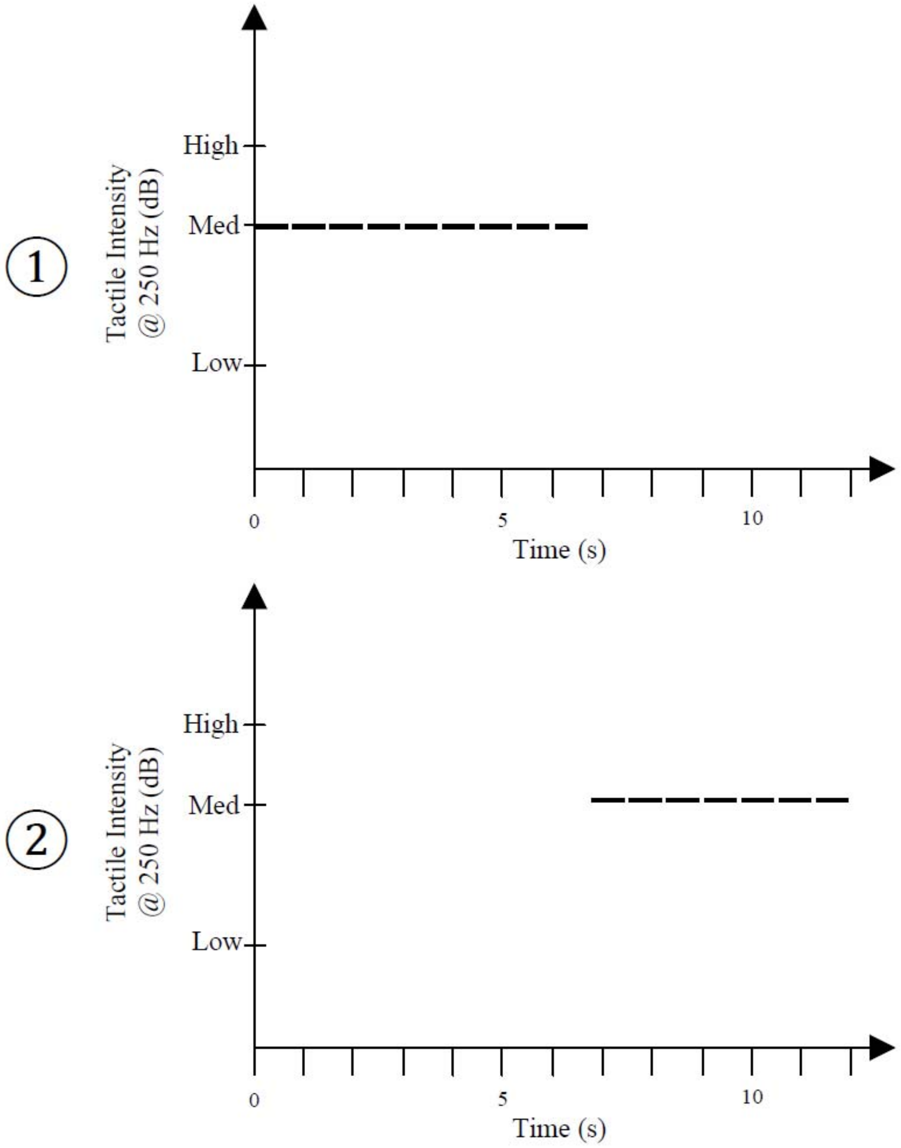


Figure 2.7: Location change from tactor #1 to tactor #2 (high complexity)

Movement Type

For the sitting condition, participants were seated in a stationary chair. For the standing condition, participants were instructed to stand in the same location and to minimize movements. For the walking condition, participants walked on a treadmill with no incline, at a speed of 2.0 miles per hour, and were not permitted to not adjust the speed. These movements were selected because they are typical movements expected of anesthesiologists in the operating room, but also people working in other complex domains.

Procedure

Prior to arrival, participants were instructed to wear adequate walking shoes with laces, not to wear any loose clothing, and to wear a thin base layer such as a t-shirt. Upon arrival, the participant read and signed an informed consent form approved by Clemson University Institutional Review Board (#IRB2016-360). The experimenters then provided an overview of the study goals, equipment, tasks, and required responses. For the required responses, a placard was overviewed that would be viewable during the experiment and explained the response options for each tactile cue type. The participant then performed a training session to become familiar with the expectations of the study where four single-step (low complexity) trials were demonstrated. Upon successfully completing a twenty trial pre-test for single-step changes in intensity (i.e., 80% accuracy) while sitting, participants then completed three blocks: 1) sitting, 2) standing, and 3) walking. During the first block, but immediately prior to the respective tested section, a demonstration of the graded, gradual, and location change trials was given. At the conclusion of the study, each participant completed a debriefing questionnaire (Appendix A). In total, the study lasted approximately three hours and participants were compensated at a rate of $10/hour in gift cards.

Experimental Design

This study employed a 4 (tactile cue – single-step, graded, gradual, and location-intensity) x 3 (movement – sitting, standing, and walking) x 2 (body area – arm and back) mixed factorial design with body area as the only between-groups factor. The order of the movement blocks were randomized and balanced between subjects, and within the three movement blocks, the order of the four tactile cue sub-blocks were randomized. The location-intensity (high complexity) tactile cue sub-block had 36 trials, while the other tactile cue sub-blocks had 30 trials. The difference in the number of trials was due to balancing the requirements of ensuring the location-intensity sub-block had an equal number of intensity change types while also minimizing the duration of the experiment. Therefore, each movement block had 126 trials and the experiment had a total of 378 trials. No-change trials occurred one-third of the time – rather than half of the time which decreased the duration of the experiment. An equal number of intensity increases and decreases occurred during each sub-block. For the location-intensity (high complexity) tactile cue, an equal number of location and intensity changes occurred, and within the intensity changes, an equal number of each cue type occurred (i.e., single-step, graded, and gradual intensity).

CHAPTER THREE

RESULTS

Separate repeated measures ANOVAs (General Linear Models formulation in SPSS 24.0.0.0; Appendix B) were used to identify main effects on the binary response accuracy types (i.e., overall, change, and no-change) and Fisher's LSD post-hoc tests were used to determine differences between means for significant effects. A paired-samples t-test was used to determine whether there was a statistically significant mean difference for increases in intensity compared to decreases.

Overall Response Accuracy

Mauchly's test of sphericity indicated that the assumption of sphericity was violated for cue type ($\chi^2(2) = 15.66$, $p = .008$) and a Greenhouse-Geisser correction factor was used ($\varepsilon = .602$). There was a main effect of movement type ($F(2, 32) = 7.18$, $p = .003$; Figure 3.1), cue type ($F(1.81, 28.91) = 73.56$, $p < .001$; Figure 3.2), and body location ($F(1, 16) = 6.62$, $p = .020$; Figure 3.3) on overall accuracy. Change detection accuracy was significantly lower with walking (accuracy = 76%) compared to sitting (accuracy = 82%, $p = .002$). There was no difference in change detection between sitting and standing. With cue type, all four conditions were significantly different from one another. For body location, participants responded more accurately with tactile cues on the arm (accuracy = 83%) compared to the back (accuracy = 76%). There were no two-way or three-way interactions that were significant.

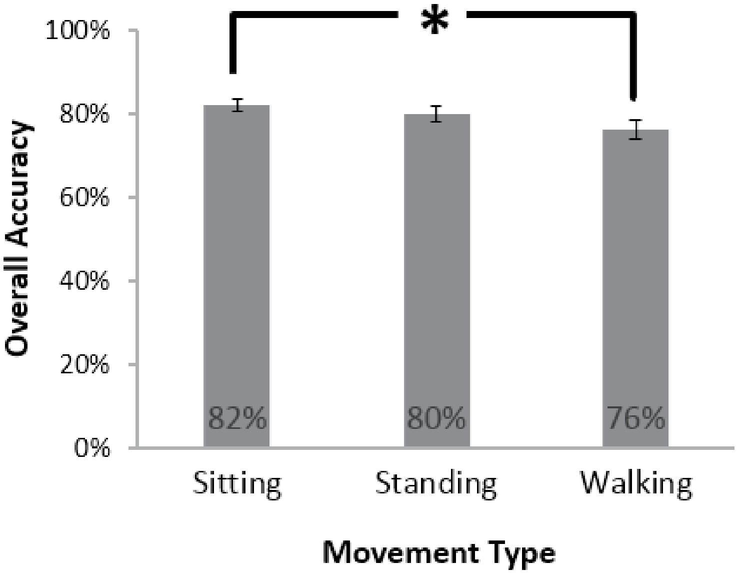


Figure 3.1: Overall accuracy for each movement type (error bars represent standard error; asterisk represents significance between types)

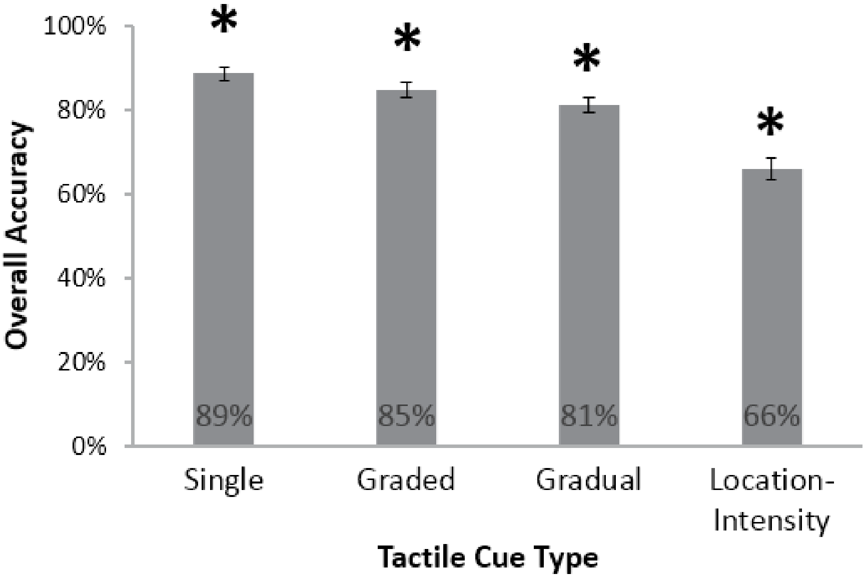


Figure 3.2: Overall accuracy for each tactile cue type (error bars represent standard error; asterisks represent significance)

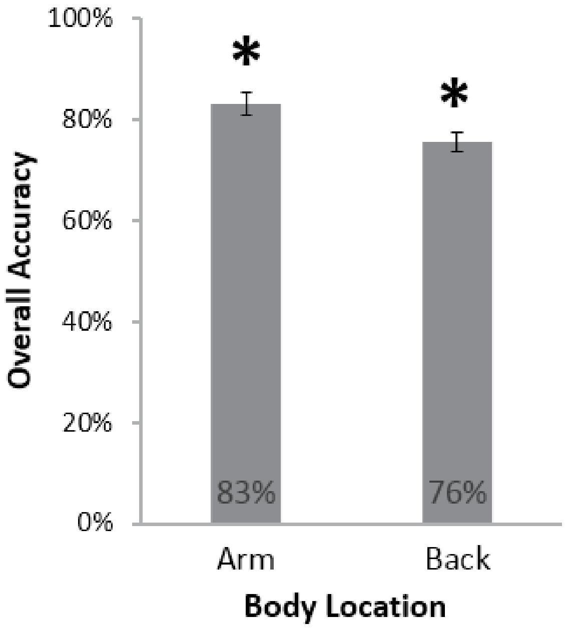


Figure 3.3: Overall accuracy for each body location (error bars represent standard error; asterisks represent significance)

Change Trial Response Accuracy (Hits)

Change trial accuracy took into account trials when there was either a change in intensity or location. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for cue type ($\chi^2(2) = 18.96$, $p = .002$) and a Greenhouse-Geisser correction factor was used ($\varepsilon = .540$). There was a significant effect of tactile cue type on change detection accuracy ($F(1.62, 25.91) = 61.24$, $p < .001$; Figure 3.5), but not movement type ($F(2, 32) = 2.90$, $p = .069$; Figure 3.4) or body location ($F(1, 16) = .80$, $p = .385$; Figure 3.6). Accuracy was significantly lower for location-intensity changes compared to all other cue types (accuracy = 65%; $p < .017$ for all pairwise comparisons).

Gradual changes (accuracy = 86%) were also significantly lower than single-step and graded (p < .017 for both pairwise comparisons). Single and graded were not significantly different from one another. Across all cue types, accuracy was higher for decreases in intensity (accuracy = 90%) compared to increases (accuracy = 75%; t(17) = 7.05, p < .001, d = 1.66). There were no significant two-way or three-way interactions present.

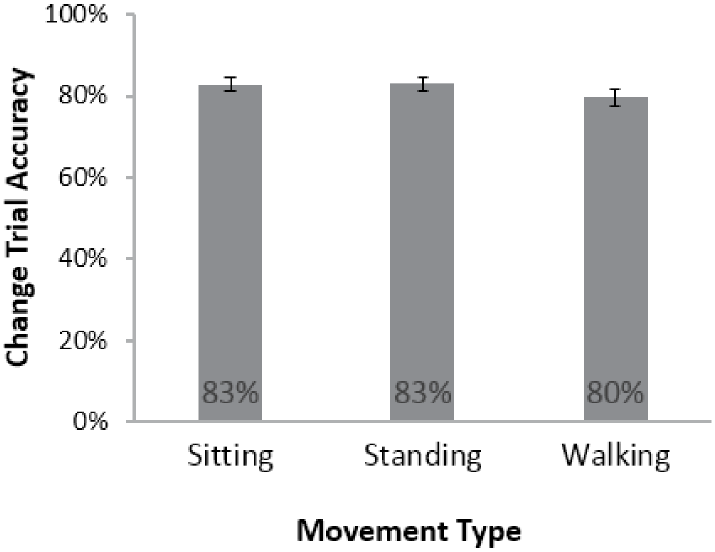


Figure 3.4: Change trial accuracy for each movement type (error bars represent standard error)

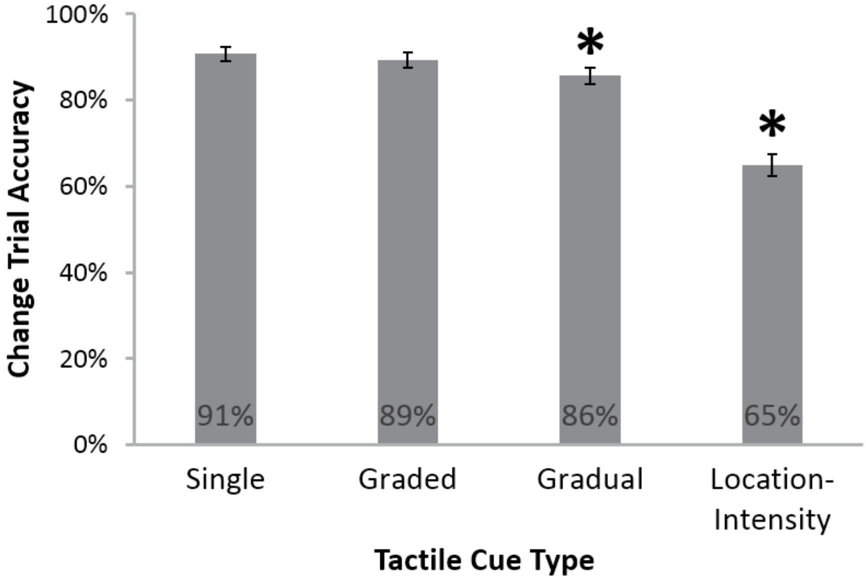


Figure 3.5: Change trial accuracy for each tactile cue type (error bars represent standard error; asterisks represent significance)

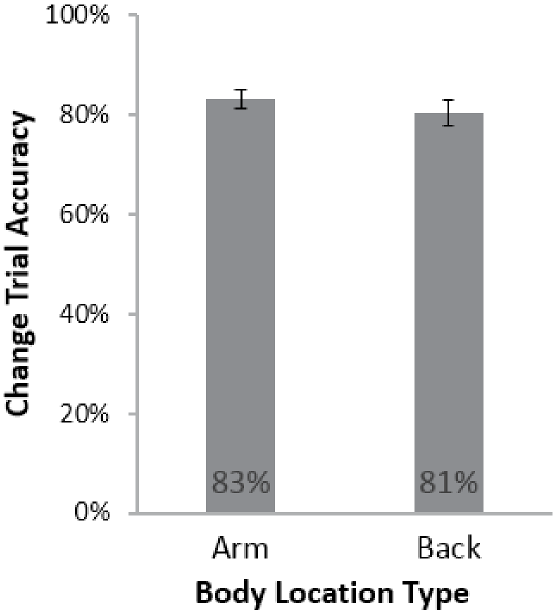


Figure 3.6: Change trial accuracy for each body location (error bars represent standard error)

Location-Intensity: Change Trial Accuracy

Response accuracy for the location-intensity cue was investigated to determine the frequency of hits and misses for change trials. Figure 3.7 shows the percentage of participant responses (i.e., no change, single, graded, gradual, and location) based on the different forms the location-intensity cue could take (i.e., single, graded, gradual, or location) for change trials. When the location-intensity cue took the form of a single-step change, participants incorrectly identified it as a graded cue 17% of the time. When the location-intensity was a graded cue, the majority of the participants responded it was either a single-step (22%) or gradual change (33%). When the location-intensity change was gradual, participants mistook it to be a graded cue 25% of the time. Participants accurately identified location changes 90% of the time.

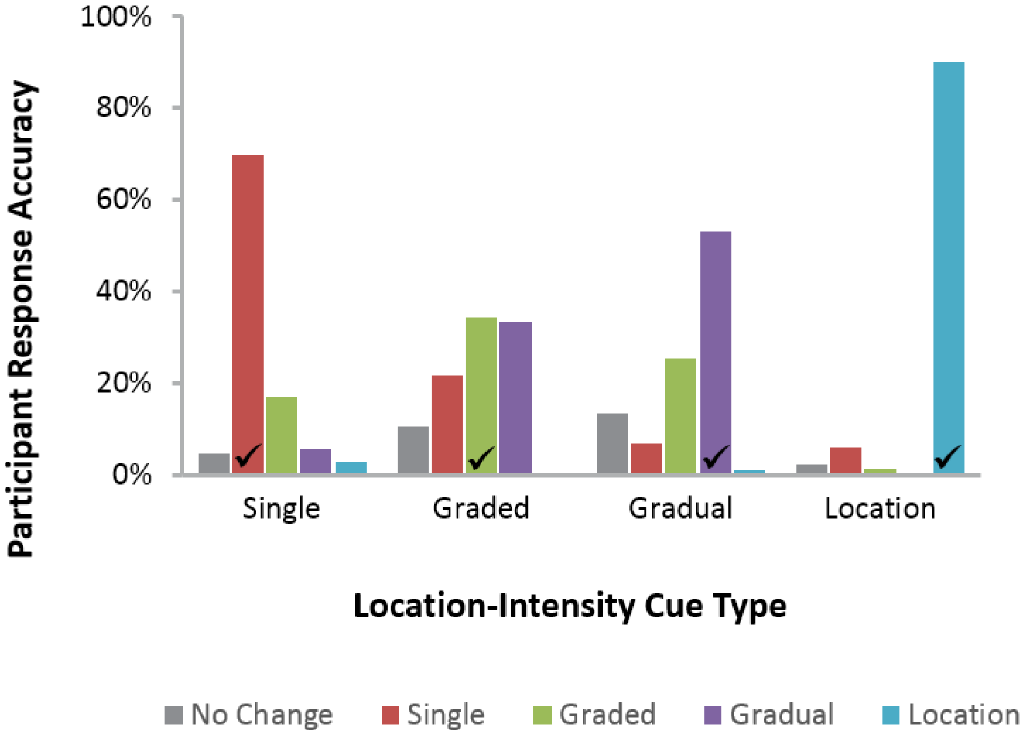


Figure 3.7: Location-intensity tactile cue type frequency for participant responses for change trials (check marks represent correct cue type response)

Figure 3.8 shows the participant response frequency for each correct response for the location-intensity tactile cue type for change trials. Overall accuracy for change increases were 46% and decreases were 59%. Thirty-five percent of the time, participants correctly recognized there was an intensity increase, but identified the wrong tactile cue type, and similarly 39% of the time for intensity decreases.

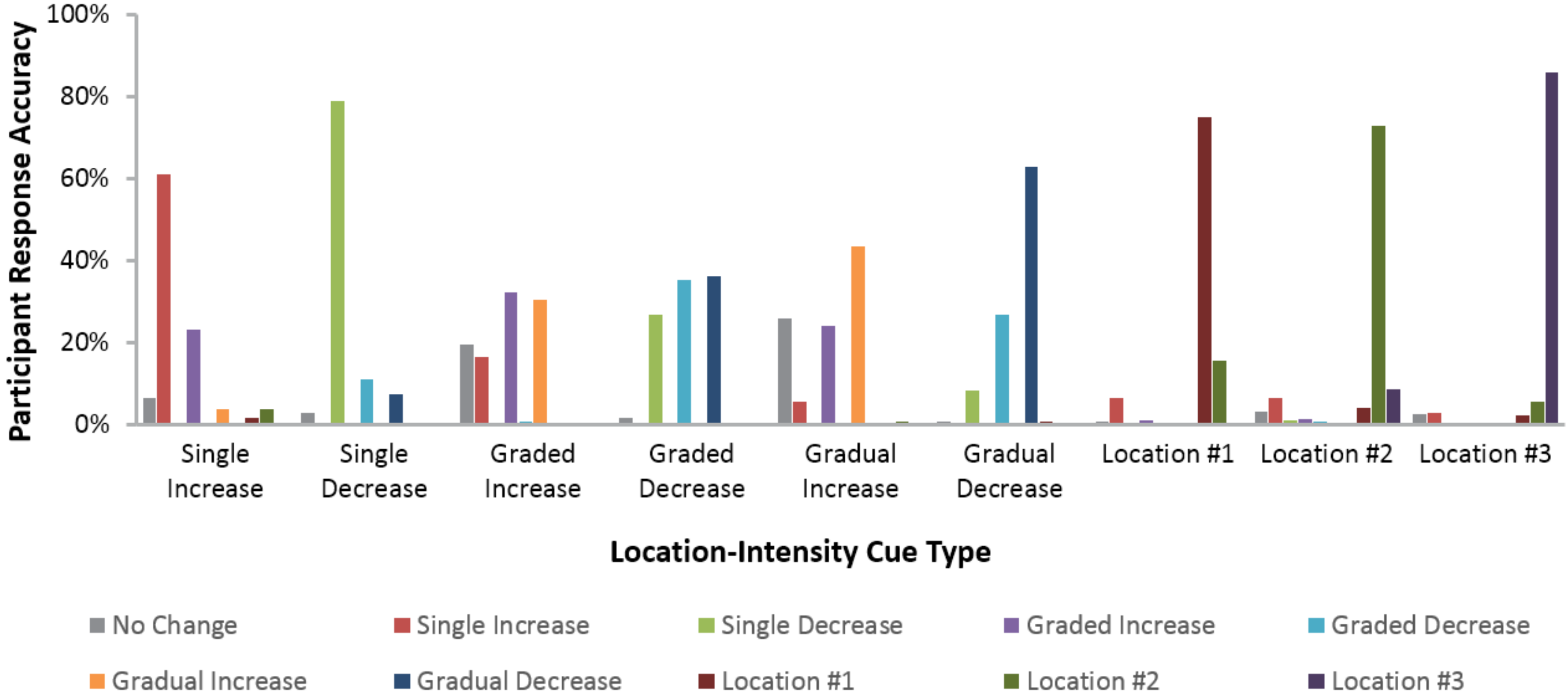


Figure 3.8: Location-intensity tactile cue frequency for participant responses for change trials

No-Change Trial Response Accuracy (Correct Rejections)

No-change trial accuracy took into account trials where there were no changes. There was a main effect of movement type (*F*(2, 32) = 10.18, *p* < .001; Figure 3.9), tactile cue type (*F*(3, 48) = 10.73, *p* < .001; Figure 3.10), and body location type (*F*(1, 16) = 6.85, *p* = .019; Figure 3.11) on correct rejection accuracy. With movement type, correct rejections were highest in the sitting (accuracy = 81%) condition compared to all other movement types (*p* = .001 for both pairwise comparisons). There was no difference between standing and walking. For tactile cue type, accuracy was the highest with single-step changes compared to all other tactile cue types (accuracy = 84%; *p* < .010 for all pairwise comparisons) and location/intensity changes (accuracy = 68%) were significantly lower than graded changes (accuracy = 76%; *p* = .029). For body location, correct rejection rate was higher on the arm (accuracy = 83%) than on the back (accuracy = 66%). There were no significant two-way or three-way interactions, however of note is the mean accuracy of walking for the back (58%) which was lower than the other accuracy types.

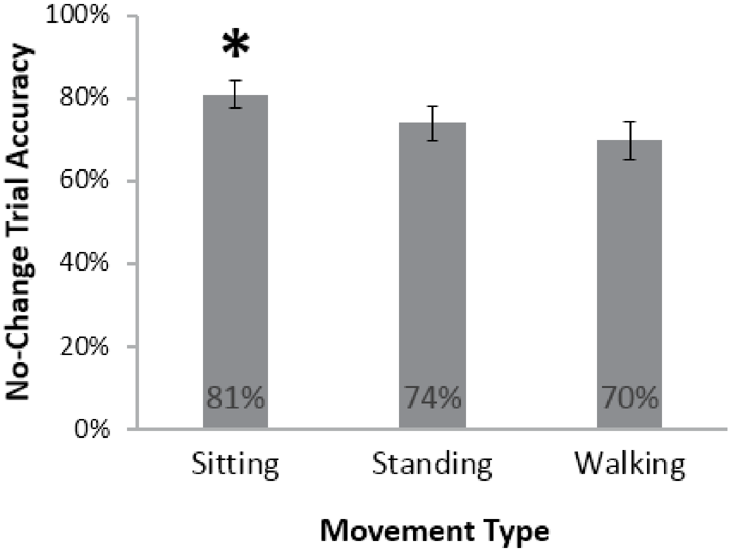


Figure 3.9: No-change trial accuracy for each movement type (error bars represent standard error; asterisk represents significance)

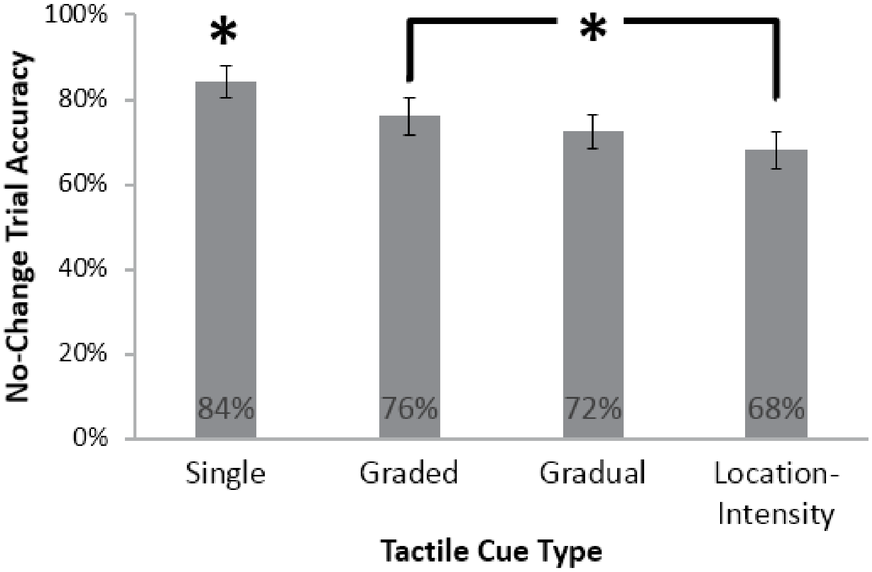


Figure 3.10: No-change trial accuracy for each tactile cue type (error bars represent standard error; asterisks represent significance or significance between types)

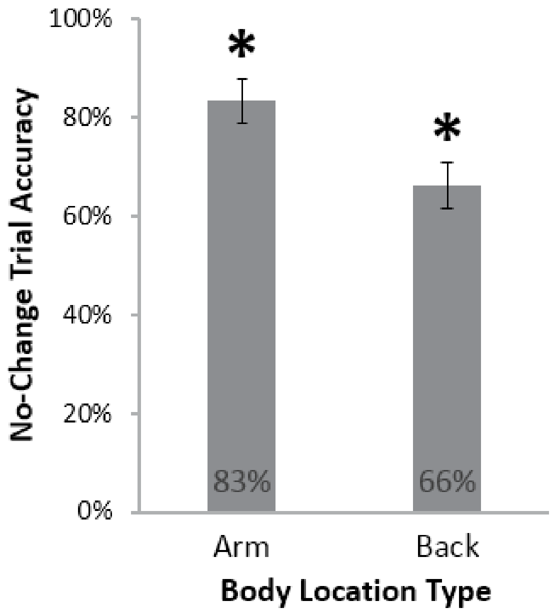


Figure 3.11: No-change trial accuracy for each body location (error bars represent standard error; asterisks represent significance)

Location-Intensity: No-Change Trial Accuracy

Response accuracy for the location-intensity cue was investigated to determine the frequency of false alarms. Figure 3.12 shows the percentage of participant responses to location-intensity changes (i.e., no change, single, graded, gradual, and location). False alarms rates (i.e., indicate change when the correct response was “no change”) were the highest with graded and gradual cues and were 14% and 15% respectively. Participants correctly rejected no-change trials 68% of the time.

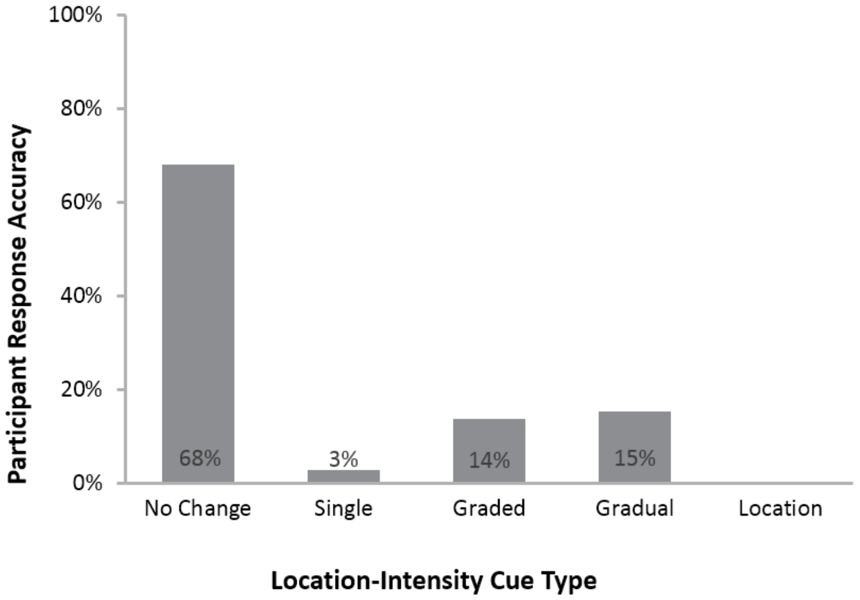


Figure 3.12: Location-intensity tactile cue type frequency for participant responses for no-change trials

Figure 3.13 shows the participant response frequency for each response to no-change trials for the location-intensity tactile cue type.

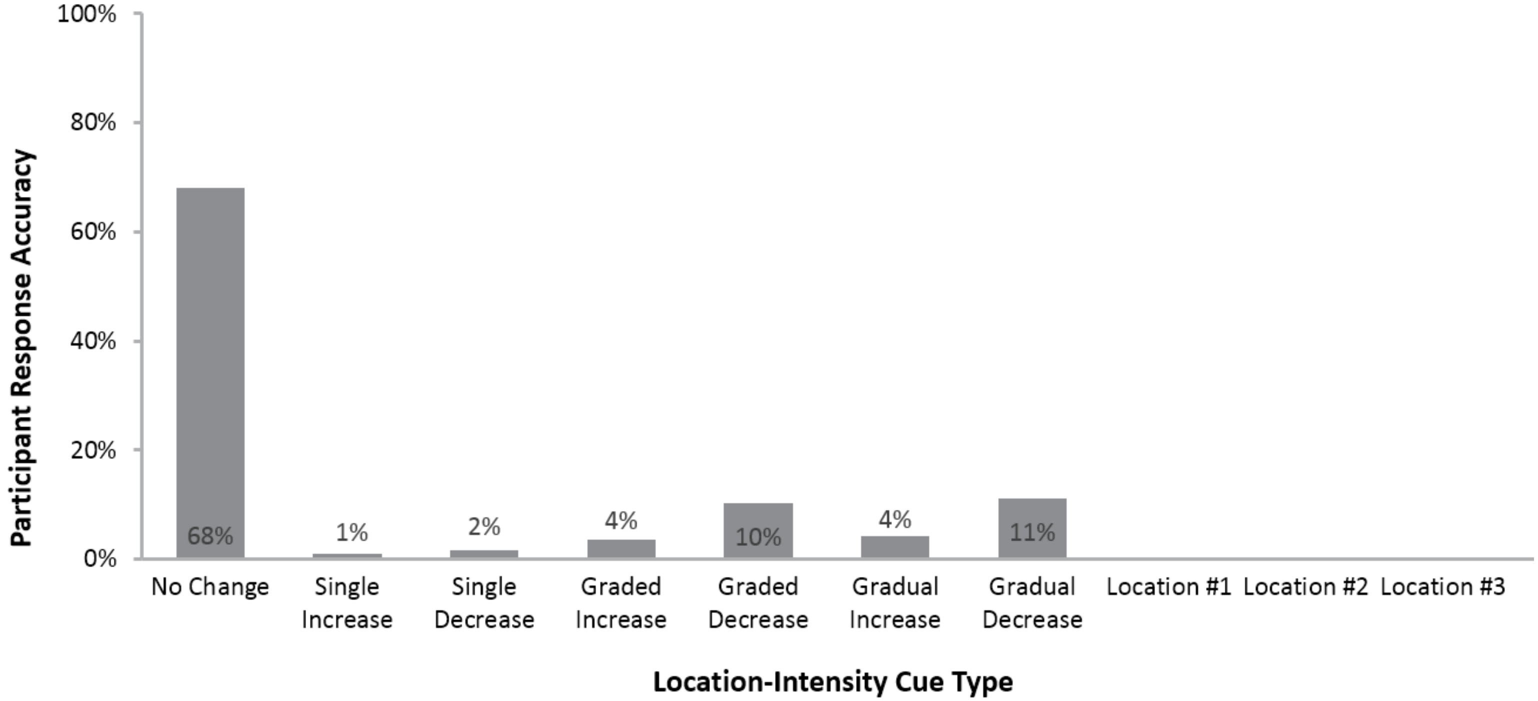


Figure 3.13: Location-intensity tactile cue frequency for participant responses for no-change trials

Debrief Questionnaire Responses

Participants were asked to "rate how difficult it was to monitor the tactile displays while performing the following movements and tasks" for sitting, standing, and walking (see Appendix for debrief questionnaire). The possible response options included: very easy, easy, somewhat easy, neutral, somewhat difficult, difficult, and very difficult. Responses were translated to a numerical value ranging from 1 to 7 – where 1 = very easy and 7 = very difficult. Figure 3.14 shows the mean ranking of difficulty for each movement type where walking was rated the most difficult (rating = 5.7), followed by standing (rating = 3.6) and then sitting (rating = 2.4).

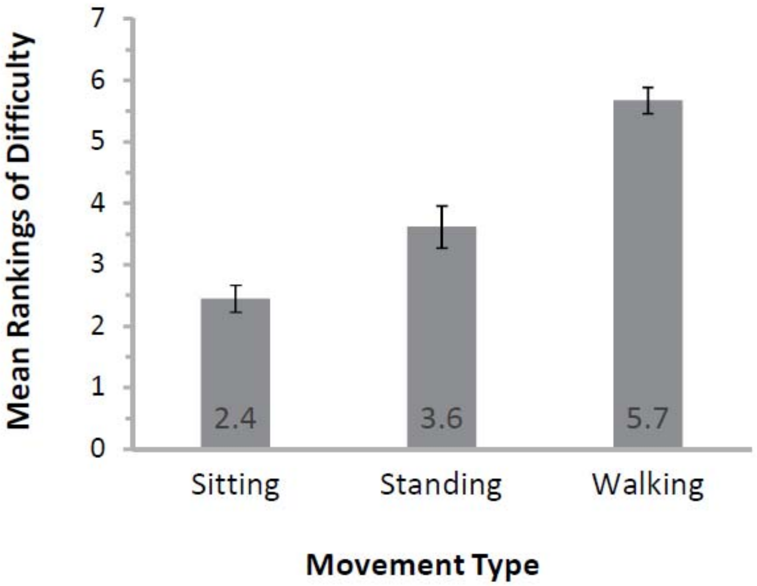


Figure 3.14: Mean ranking of each movement type (1 = very easy, 4 = neutral, and 7 = very difficult)

When asked to explain their rankings for each movement condition, four out of the nine participants that wore the back garment stated the tactor belt conformed to their body better when sitting compared to standing or walking and one-third of participants thought that it was easier to focus while sitting. One-third of participants indicated that they found maintaining their balance to be distracting in the standing condition. Similarly, half of the participants responded that walking was also distracting and it was hard to focus. When participants were asked to, "describe any strategy you adopted while monitoring the tactile displays," ten participants indicated that they adopted a strategy of counting pulses to distinguish between graded or gradual tactile cues during the location-intensity conditions.

Learning Effect

Table 3.1 overviews how well participants performed in the first block, second block, and third block. Overall, accuracy was 79-80% for the first, second, and third blocks. A one-way ANOVA showed there was no learning effect on overall trial accuracy (*F*(2, 34) = .09, *p* = .917).

Table 3.1: Average trial accuracy for each block

Block	Overall Trial Accuracy	Overall Trial Accuracy (Arm)	Overall Trial Accuracy (Back)
First	80%	83%	76%
Second	79%	84%	75%
Third	79%	83%	76%

CHAPTER FOUR

DISCUSSION

The goal of this study was to investigate whether movement and tactile cue complexity result in tactile change blindness. Tactile change blindness has been demonstrated with various transients that include: blank tactile intervals, masked/flicker tactile intervals, tactile mudsplashes, gradual tactile intensity changes, visual LEDs (Ferris et al., 2010; Gallace, Auvray, et al., 2006; Riggs & Sarter, 2016) and of particular interest to this study, movement (Gallace et al., 2010; Juravle et al., 2016). The tactile modality is a promising alternative that can help address visual and auditory data overload; however, the design of tactile displays also needs to take into consideration limitations that include change blindness.

Movement was found to have a significant effect on accuracy. Specifically, walking was shown to result in lower overall and no-change accuracy compared to sitting. The findings of the current study confirm those of previous work (Gallace et al., 2010; Karuei et al., 2011; Oakley & Park, 2008). Unexpectedly, there was no main effect of movement on change trial accuracy and the results show that there were more false alarms than there were misses for the standing and walking conditions. For sitting, the no-change false alarm rate was only 2% higher than change trial miss rate, but in the standing and walking conditions, no-change trial false alarm rates were respectively 9% and 10% higher compared to change trial miss rates. The current study findings are in line with Ferris et al. (2010) as false alarm rates can be calculated from the sensitivity data and are 6-13% higher than miss rates for the various tactile cue types. The debriefing questionnaire in the current study provides insight into possible causes for the higher frequency of false alarms for standing and walking. Many participants indicated that while walking, the tactors seemed to shift slightly and provide less contact with the tactor belt. In another question, half of the participants stated that in the walking condition, movement was distracting and made it hard to focus. It appears that there may have been periods of time during standing and walking that body contact was not optimal. Reduced tactor contact with the body, distractions caused by movement, and lack of focus may have exacerbated false alarms.

Tactile cue complexity was found to have a significant effect on accuracy. Low complexity cues had the highest accuracy, followed by medium complexity cues, and then the high complexity cue. Participants could accurately distinguish when a high complexity cue increased or decreased in intensity, but often mistook the cue type (e.g., mixing up gradual and graded cues). The current study supports the findings of Ferris et al. (2010) that more complex changes such as gradual intensity changes were shown to have worse detection rates compared to lower complexity (i.e., single-step) changes. An additional item to note on cue complexity is that feedback from the debriefing questionnaire showed that decreases in intensity were more apparent than increases which the change trial accuracy levels confirm. This was expected as there was a greater difference in the intensity change magnitude from medium to low compared to medium to high.

Body location was not found to have an interaction effect with movement therefore the findings indicate that the arm and back are both equally affected by movement. The current study confirms the findings of a previous study that found no interaction effect between body location and movement (Karuei et al., 2011). Body location was found to have a significant effect on accuracy as the arm band was found to have better overall accuracy than the belt. This further provides support for the use of the arm location (Ferris & Sarter, 2011; Karuei et al., 2011; Shapiro et al., 2015). Unexpectedly, the false alarm rate for the back was twice that of the arm. The feedback discussed earlier (that the tactors were not contacting the skin well, movement caused distractions, and lack of focus) was provided primarily by those that wore the back garment and this provides insight into the higher than expected false alarm rates.

Now each expected result will be discussed in turn.

Expected Result #1: Sitting will have a higher tactile change detection accuracy compared to standing and walking

On average, participants had the highest accuracy in the sitting condition compared to the walking condition. This aligns with previous literature that shows that movement elicits tactile change blindness (Gallace et al., 2010), which is especially exacerbated by walking (Karuei et al., 2011; Oakley & Park, 2008). Sitting and standing overall were not significantly different and confirm the findings of previous work that also used tactors on the back (Terrence et al., 2005). Additionally, Karuei et al. (2011) found approximately a 15% reduction in detection rate from sitting compared to walking which is slightly higher than this study where a 6% reduction was found. However, it is important to note that the tactile cue complexity was higher in the study conducted by

Karuei et al. (2011; 13 total tactor locations across the body and five intensity levels). Movement has been discussed in previous work as possibly causing disruption to the identification of tactile parameters and in general causing a masking effect to tactile perception performance in the presence of motor functions (Gallace et al., 2010; Oakley & Park, 2008). Many participants in the current study also provided feedback that walking was distracting which suggests that movement tasks increase physical workload which in turn may affect tactile perception. Participants reported in the debriefing questionnaires that sitting allowed the tactors to have maximum contact with the body thus resulting in higher accuracy. Furthermore, many participants indicated that they needed to shift their weight and/or bend their knees while standing to remain balanced and the act of walking was distracting to the task at hand and added an extra challenge in detecting tactile changes.

Expected Result #2: Low complexity tactile cues will have a higher tactile change detection accuracy compared to high complexity tactile cues

Tactile cue complexity was found to have a significant effect on accuracy. On average across all trial types, the low complexity cue generally had the highest detection accuracy, followed by medium complexity cues, and then the high complexity cue. For medium complexity cues, the magnitude of each stepwise change affected change detection rates. Gradual change blindness has been previously demonstrated for vision in a study where participants viewed scene changes such as a chimney gradually dissolving from a house and it was found that gradual changes do not draw as much attention as large changes (Simons, Franconeri, & Reimer, 2000).

The findings show that the rate at which changes occur affects change detection. Hit rates for graded cues where the intensity change gradually increased/decreased in four equivalent steps were higher than for gradual cues where the change occurred in eight steps. However, previous studies have also shown that people are generally poor at detecting gradual changes – similar to the graded and gradual change in this study – regardless of whether they occur on the order of seconds (Ferris et al., 2010) or milliseconds (Riggs & Sarter, 2016).

Accuracy was worst for the high complexity (location-intensity) tactile cue. This finding was expected as previous literature has shown that the amount of information that can be effectively encoded in the tactile channel is less than the auditory and visual channels (Erp, 2007; Lu et al., 2011; Sebok, Wickens, Sarter, & Koenecke, 2012)

Expected Result #3: The back location will have a higher tactile change detection accuracy compared to the arm location when walking

There was no two-way interaction effect between body location and movement on change detection accuracy. The results show that the arm display is not significantly different than a back display due to an interaction effect from movement. The current study confirms the findings of a previous study that found no interaction effect of body location and movement as back and arm accuracy experienced a similar decrement when walking (Karuei et al., 2011).

The findings were unexpected but may possibly be explained by the review of Juravle et al. (2016). Walking has been shown to cause greater tactile suppression (i.e., tactile detection performance decrement due to movement) on moving body parts compared to stationary body parts (Juravle et al., 2016), therefore it was expected that the arms would experience a greater accuracy decrement compared to the back while walking. The rationale for this was based on the conjecture that the arms naturally swing and move more than the back when walking. A possible explanation for the findings is that goal-directed movements (e.g., pointing, reaching, grasping, throwing, and catching) have been shown to have higher rates of tactile masking effects compared to passive movements like walking in the current study (Juravle et al., 2016).

Another explanation for the current study findings is that both the arm and back are susceptible to the effects of tactile suppression (Van Damme, Van Hulle, Danneels, Spence, & Crombez, 2014). This finding shows that tactile detection accuracy of other non-limb body areas such as the back can be negatively impacted due to localized movements (Van Damme et al., 2014). Walking may cause the back to move more than anticipated which may increase tactile suppression effects in a similar manner to the arm. If this is the case, the potential for an interaction effect would be minimized. Overall, the findings indicate that both the arm and back are equally affected when passively walking.

With respect to the effect of body location on change detection accuracy, the arm was found to have higher accuracy than the back. The work of Karuei et al. (2011) provides insight as they found that lower body sites (i.e., thighs and feet) were the most affected by walking compared to other sites such as the arm and upper back. As the lower back is approaching the lower body, perhaps this can be generalized to support the finding that the lower back has lower accuracy when walking. The upper arm is a common location chosen for various studies (Ferris & Sarter, 2011; Karuei et al., 2011; Shapiro et al., 2015) and the findings indicate that the arm is a promising location for tactile displays.

Limitations

The findings may not be generalizable to the population because of the low mean and range of age of participants. In fact, almost 50% of anesthesiologists are older than 50 years of age (Baird, Daugherty, Kumar, & Arifkhanova, 2014). Ideally the findings will help inform the design of tactile devices to be used by anesthesiologists, but future work should recruit a wider age range so that age related tactile sensory decline is taken into account, especially given that the target population are anesthesiologists (e.g., Cole, Rotella, & Harper, 1998).

The debriefing questionnaire revealed another limitation in that the garments may have shifted slightly in the standing and walking conditions. Even though measures were taken to ensure a consistent fit of the tactile belt and vest for each participant throughout the study, the shifting garments may have increased the difficulty of detecting tactile changes. To increase the likelihood of the proposed technology in the context of anesthesiology, it is important that future work looks at garments that not only ensure that tactile cues are detected appropriately, but also simplify the process to wear them. Future work can consider using rubber elastic compression garments (Ferris et al., 2010), spandex (Jones et al., 2009), Lycra (Krausman, Elliott, & Pettitt, 2005), or adhesives directly on the skin (Riemer et al., 2010) which has been shown to be effective in adhering tactors to the body.

Another limitation was whether the pink noise volume completely masked sounds from the tactors, particularly at higher intensities. The volume was set at a constant level for participants that during previous pilot testing was deemed to be a comfortable volume to listen to for the entire the duration of the study. Although the current study setup was similar to other studies as headphones were used to mask tactors (e.g., Gallace, Tan, et al., 2006; Oakley & Park, 2008; Riggs & Sarter, 2016), some participants noted they could still hear tactors, especially when the tactors were located on the arm. However no participants indicated that this provided them an advantage in making the correct selection. Future studies can consider taking additional measures to mask subsidiary sounds from the tactors or investigate if there is a crossmodal effect between audition and touch which has been demonstrated between vision and touch (Gallace, Auvray, et al., 2006).

Impacts and Implications

The operating room imposes considerable attentional demands for anesthesiologists to their visual and auditory channels. The current study has shown that tactile displays have the potential to achieve a high accuracy even in the presence of movement over long durations. The findings show that low and medium complexity cues that varied intensity achieved approximately 80-90% accuracy and shows promise for tactile displays to be used in the operating room. Using salient intensity changes as well as having equal perceived differences for both intensity step increases and decreases (assuming priority for both is equal) are important to achieve high detection rates. However, higher complexity cues that varied more than one parameter resulted in a higher number of misses and false alarms. To this end, researchers will need to assess and minimize the number of tactile parameters and levels to be used. Under the context of anesthesiology, the findings show that tactile displays offer the potential to communicate increases or decreases in physiological variables (e.g., heart rate, pulse oxygenation, and body temperature) and changes in alarm states (e.g., ventilator disconnect, apnea, and arrhythmia).

The findings also show that movement and ongoing tasks are important considerations in the design of tactile displays to be used in the operating room. As the main effect of movement was shown to affect no-change trial accuracy to a greater extent than change trials, ensuring continuous monitoring accuracy where the signal is constant (i.e., no change) will be a priority. To address this challenge, technology designers of tactile displays could take into account environment demands or individual differences. For instance, setting intensity levels on an individual basis such as in the study of Gallace, Tan, et al. (2006) or pairing an accelerometer with vibrotactile devices to vary the intensity accordingly may alleviate some of the issues found with movement adversely impacting tactile perception.

Anesthesiologists not only need to move from location to location, but they also need to discuss issues of the ongoing surgery to other clinicians, enter information in the electronic health record (EHR) system, prepare drugs and equipment for the next surgery, and perform inventory tasks. These tasks can occur while performing different postures and movements, and therefore it is important to investigate whether tactile change blindness would be elicited by naturalistic goal-directed movements (i.e., walking to a location, or reaching, grasping, bending or twisting to retrieve an item) common in the operating room. Future studies should ideally recruit anesthesia providers as participants to ensure successful adoption of the technology by the experts for which it is intended and in the context of simulated real-world tasks.

Overall, the current study adds to the knowledge base of tactile perception and its limitations. The results showed that movement and the complexity of tactile cues affect tactile change detection and provided insights on the phenomenon of tactile change blindness. These insights not only inform the design of tactile displays to help mitigate alarms from being masked in the operating room, but also address challenges associated with visual data overload in other data-rich environments that include the automotive industry (automated driving), military operations, and aviation. Ultimately, the findings can help improve operations and safety in these work domains.

APPENDICES

Appendix A

Debriefing Questionnaire

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?

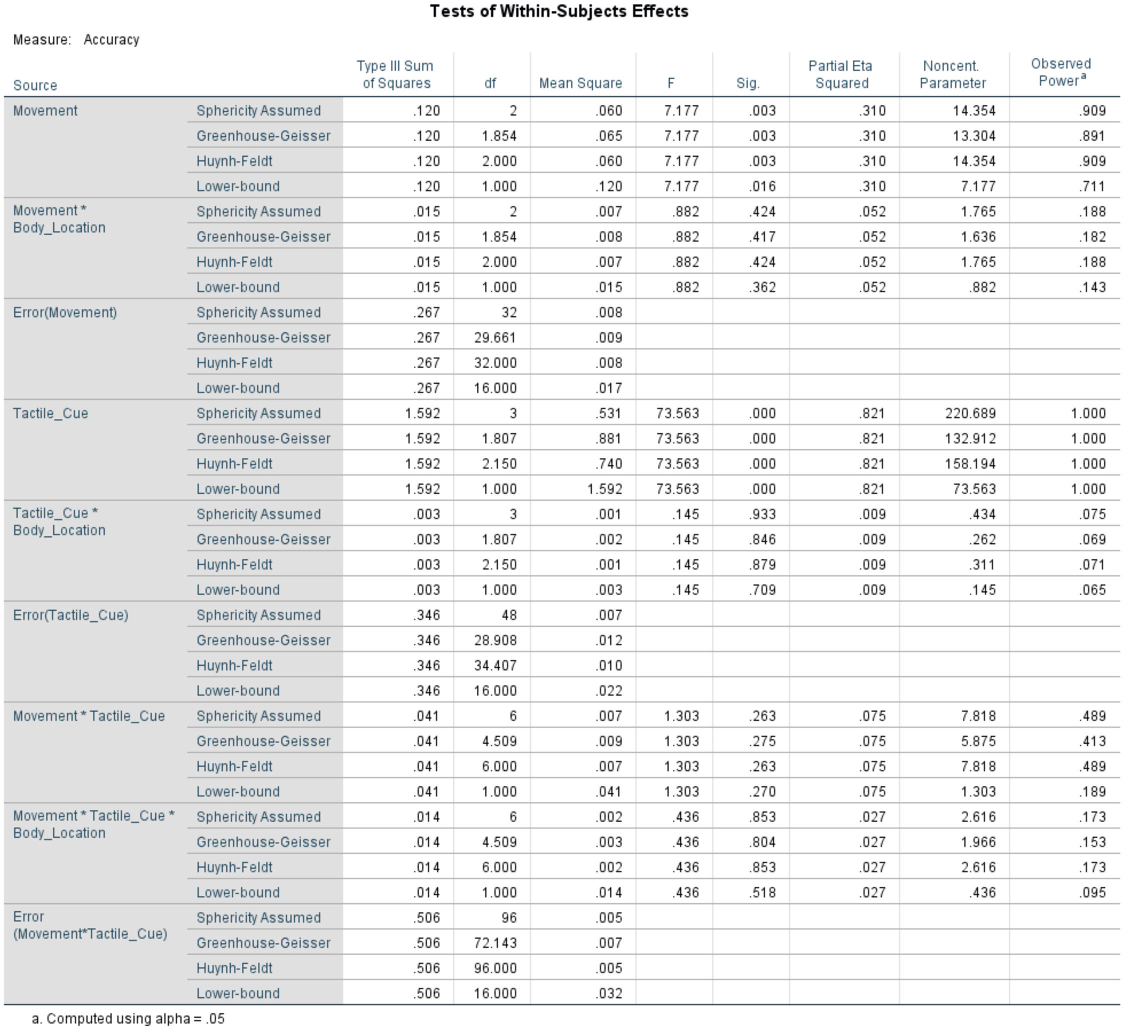
7. Why did you rate *walking* how you did in question #4?

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 B

ANOVA Tables



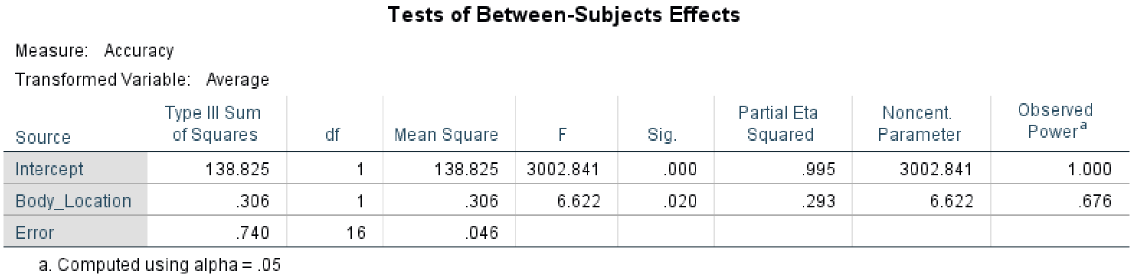
Tests of Within-Subjects Effects

Measure: Accuracy

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Movement	Sphericity Assumed	.120	2	.060	7.177	.003	.310	14.354	.909
	Greenhouse-Geisser	.120	1.854	.065	7.177	.003	.310	13.304	.891
	Huynh-Feldt	.120	2.000	.060	7.177	.003	.310	14.354	.909
	Lower-bound	.120	1.000	.120	7.177	.016	.310	7.177	.711
Movement * Body_Location	Sphericity Assumed	.015	2	.007	.882	.424	.052	1.765	.188
	Greenhouse-Geisser	.015	1.854	.008	.882	.417	.052	1.636	.182
	Huynh-Feldt	.015	2.000	.007	.882	.424	.052	1.765	.188
	Lower-bound	.015	1.000	.015	.882	.362	.052	.882	.143
Error(Movement)	Sphericity Assumed	.267	32	.008					
	Greenhouse-Geisser	.267	29.661	.009					
	Huynh-Feldt	.267	32.000	.008					
	Lower-bound	.267	16.000	.017					
Tactile_Cue	Sphericity Assumed	1.592	3	.531	73.563	.000	.821	220.689	1.000
	Greenhouse-Geisser	1.592	1.807	.881	73.563	.000	.821	132.912	1.000
	Huynh-Feldt	1.592	2.150	.740	73.563	.000	.821	158.194	1.000
	Lower-bound	1.592	1.000	1.592	73.563	.000	.821	73.563	1.000
Tactile_Cue * Body_Location	Sphericity Assumed	.003	3	.001	.145	.933	.009	.434	.075
	Greenhouse-Geisser	.003	1.807	.002	.145	.846	.009	.262	.069
	Huynh-Feldt	.003	2.150	.001	.145	.879	.009	.311	.071
	Lower-bound	.003	1.000	.003	.145	.709	.009	.145	.065
Error(Tactile_Cue)	Sphericity Assumed	.346	48	.007					
	Greenhouse-Geisser	.346	28.908	.012					
	Huynh-Feldt	.346	34.407	.010					
	Lower-bound	.346	16.000	.022					
Movement * Tactile_Cue	Sphericity Assumed	.041	6	.007	1.303	.263	.075	7.818	.489
	Greenhouse-Geisser	.041	4.509	.009	1.303	.275	.075	5.875	.413
	Huynh-Feldt	.041	6.000	.007	1.303	.263	.075	7.818	.489
	Lower-bound	.041	1.000	.041	1.303	.270	.075	1.303	.189
Movement * Tactile_Cue * Body_Location	Sphericity Assumed	.014	6	.002	.436	.853	.027	2.616	.173
	Greenhouse-Geisser	.014	4.509	.003	.436	.804	.027	1.966	.153
	Huynh-Feldt	.014	6.000	.002	.436	.853	.027	2.616	.173
	Lower-bound	.014	1.000	.014	.436	.518	.027	.436	.095
Error (Movement*Tactile_Cue)	Sphericity Assumed	.506	96	.005					
	Greenhouse-Geisser	.506	72.143	.007					
	Huynh-Feldt	.506	96.000	.005					
	Lower-bound	.506	16.000	.032					

a. Computed using alpha = .05

Overall accuracy ANOVA table for within-subjects variables



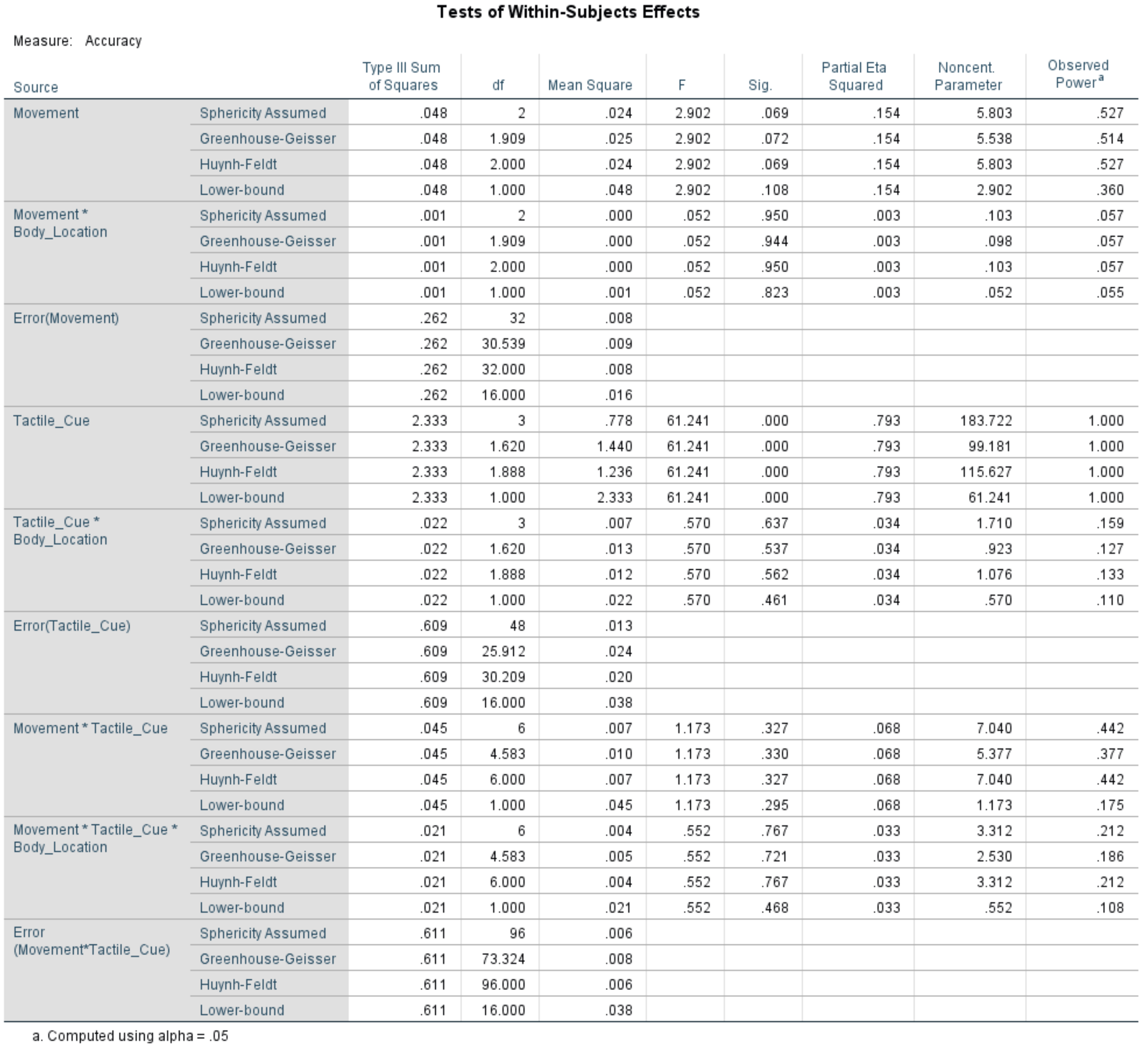
Tests of Between-Subjects Effects

Measure: Accuracy
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power^{a}
Intercept	138.825	1	138.825	3002.841	.000	.995	3002.841	1.000
Body_Location	.306	1	.306	6.622	.020	.293	6.622	.676
Error	.740	16	.046					

a. Computed using alpha = .05

Overall accuracy ANOVA table for between-subjects variable



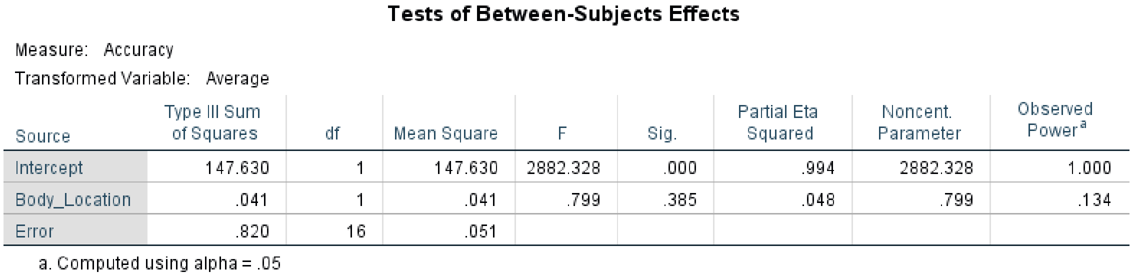
Tests of Within-Subjects Effects

Measure: Accuracy

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power^{a}
Movement	Sphericity Assumed	.048	2	.024	2.902	.069	.154	5.803	.527
	Greenhouse-Geisser	.048	1.909	.025	2.902	.072	.154	5.538	.514
	Huynh-Feldt	.048	2.000	.024	2.902	.069	.154	5.803	.527
	Lower-bound	.048	1.000	.048	2.902	.108	.154	2.902	.360
Movement * Body_Location	Sphericity Assumed	.001	2	.000	.052	.950	.003	.103	.057
	Greenhouse-Geisser	.001	1.909	.000	.052	.944	.003	.098	.057
	Huynh-Feldt	.001	2.000	.000	.052	.950	.003	.103	.057
	Lower-bound	.001	1.000	.001	.052	.823	.003	.052	.055
Error(Movement)	Sphericity Assumed	.262	32	.008					
	Greenhouse-Geisser	.262	30.539	.009					
	Huynh-Feldt	.262	32.000	.008					
	Lower-bound	.262	16.000	.016					
Tactile_Cue	Sphericity Assumed	2.333	3	.778	61.241	.000	.793	183.722	1.000
	Greenhouse-Geisser	2.333	1.620	1.440	61.241	.000	.793	99.181	1.000
	Huynh-Feldt	2.333	1.888	1.236	61.241	.000	.793	115.627	1.000
	Lower-bound	2.333	1.000	2.333	61.241	.000	.793	61.241	1.000
Tactile_Cue * Body_Location	Sphericity Assumed	.022	3	.007	.570	.637	.034	1.710	.159
	Greenhouse-Geisser	.022	1.620	.013	.570	.537	.034	.923	.127
	Huynh-Feldt	.022	1.888	.012	.570	.562	.034	1.076	.133
	Lower-bound	.022	1.000	.022	.570	.461	.034	.570	.110
Error(Tactile_Cue)	Sphericity Assumed	.609	48	.013					
	Greenhouse-Geisser	.609	25.912	.024					
	Huynh-Feldt	.609	30.209	.020					
	Lower-bound	.609	16.000	.038					
Movement * Tactile_Cue	Sphericity Assumed	.045	6	.007	1.173	.327	.068	7.040	.442
	Greenhouse-Geisser	.045	4.583	.010	1.173	.330	.068	5.377	.377
	Huynh-Feldt	.045	6.000	.007	1.173	.327	.068	7.040	.442
	Lower-bound	.045	1.000	.045	1.173	.295	.068	1.173	.175
Movement * Tactile_Cue * Body_Location	Sphericity Assumed	.021	6	.004	.552	.767	.033	3.312	.212
	Greenhouse-Geisser	.021	4.583	.005	.552	.721	.033	2.530	.186
	Huynh-Feldt	.021	6.000	.004	.552	.767	.033	3.312	.212
	Lower-bound	.021	1.000	.021	.552	.468	.033	.552	.108
Error (Movement*Tactile_Cue)	Sphericity Assumed	.611	96	.006					
	Greenhouse-Geisser	.611	73.324	.008					
	Huynh-Feldt	.611	96.000	.006					
	Lower-bound	.611	16.000	.038					

a. Computed using alpha = .05

Change trial accuracy ANOVA table for within-subjects variables



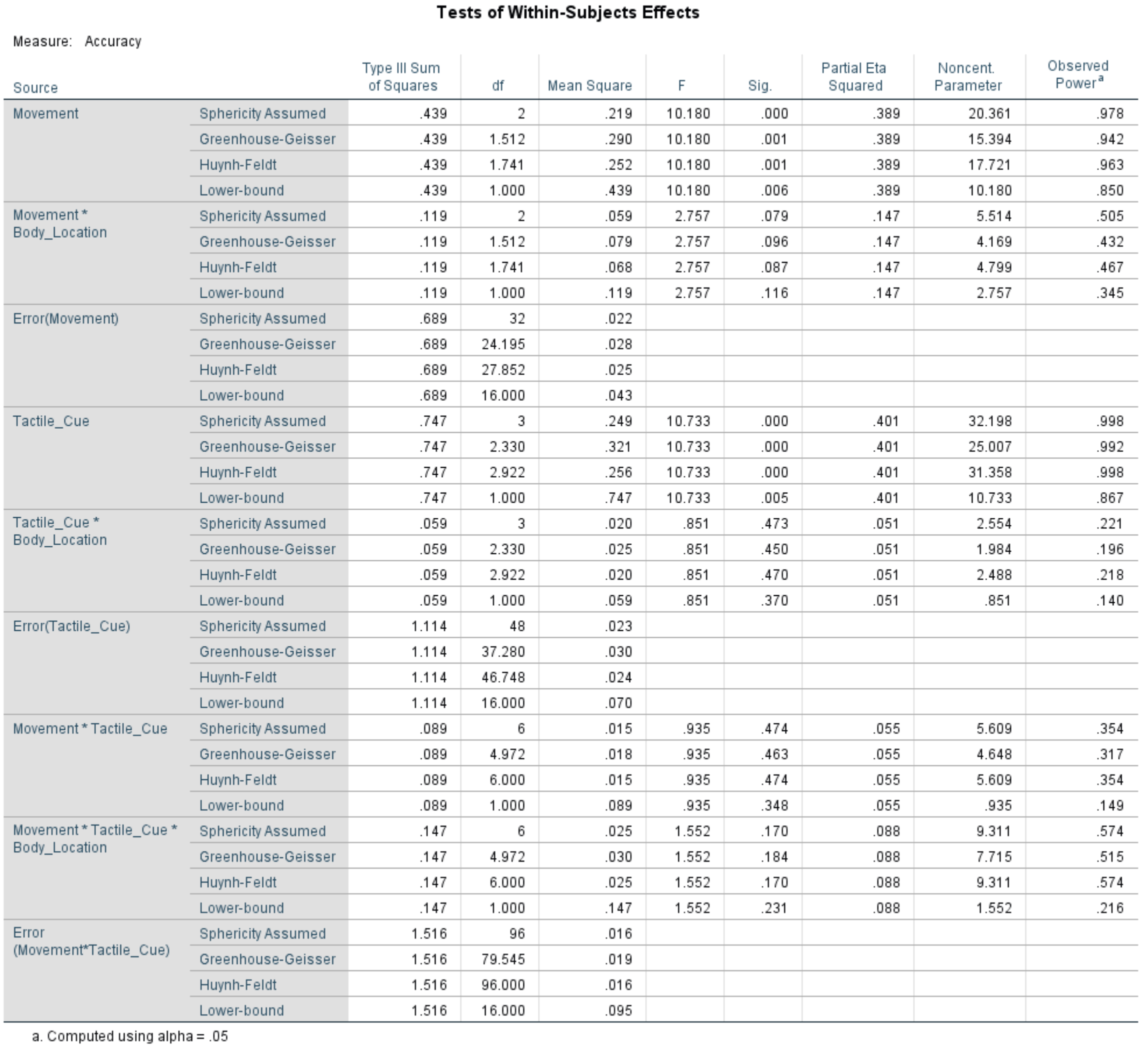
Tests of Between-Subjects Effects

Measure: Accuracy
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Intercept	147.630	1	147.630	2882.328	.000	.994	2882.328	1.000
Body_Location	.041	1	.041	.799	.385	.048	.799	.134
Error	.820	16	.051					

a. Computed using alpha = .05

Change trial ANOVA table for between-subjects variable



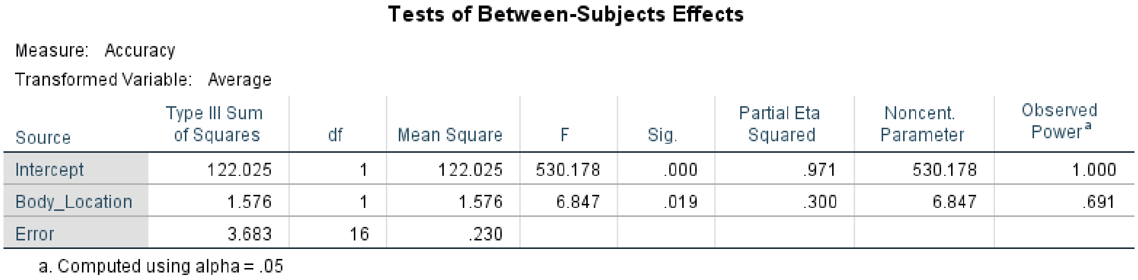
Tests of Within-Subjects Effects

Measure: Accuracy

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Movement	Sphericity Assumed	.439	2	.219	10.180	.000	.389	20.361	.978
	Greenhouse-Geisser	.439	1.512	.290	10.180	.001	.389	15.394	.942
	Huynh-Feldt	.439	1.741	.252	10.180	.001	.389	17.721	.963
	Lower-bound	.439	1.000	.439	10.180	.006	.389	10.180	.850
Movement * Body_Location	Sphericity Assumed	.119	2	.059	2.757	.079	.147	5.514	.505
	Greenhouse-Geisser	.119	1.512	.079	2.757	.096	.147	4.169	.432
	Huynh-Feldt	.119	1.741	.068	2.757	.087	.147	4.799	.467
	Lower-bound	.119	1.000	.119	2.757	.116	.147	2.757	.345
Error(Movement)	Sphericity Assumed	.689	32	.022					
	Greenhouse-Geisser	.689	24.195	.028					
	Huynh-Feldt	.689	27.852	.025					
	Lower-bound	.689	16.000	.043					
Tactile_Cue	Sphericity Assumed	.747	3	.249	10.733	.000	.401	32.198	.998
	Greenhouse-Geisser	.747	2.330	.321	10.733	.000	.401	25.007	.992
	Huynh-Feldt	.747	2.922	.256	10.733	.000	.401	31.358	.998
	Lower-bound	.747	1.000	.747	10.733	.005	.401	10.733	.867
Tactile_Cue * Body_Location	Sphericity Assumed	.059	3	.020	.851	.473	.051	2.554	.221
	Greenhouse-Geisser	.059	2.330	.025	.851	.450	.051	1.984	.196
	Huynh-Feldt	.059	2.922	.020	.851	.470	.051	2.488	.218
	Lower-bound	.059	1.000	.059	.851	.370	.051	.851	.140
Error(Tactile_Cue)	Sphericity Assumed	1.114	48	.023					
	Greenhouse-Geisser	1.114	37.280	.030					
	Huynh-Feldt	1.114	46.748	.024					
	Lower-bound	1.114	16.000	.070					
Movement * Tactile_Cue	Sphericity Assumed	.089	6	.015	.935	.474	.055	5.609	.354
	Greenhouse-Geisser	.089	4.972	.018	.935	.463	.055	4.648	.317
	Huynh-Feldt	.089	6.000	.015	.935	.474	.055	5.609	.354
	Lower-bound	.089	1.000	.089	.935	.348	.055	.935	.149
Movement * Tactile_Cue * Body_Location	Sphericity Assumed	.147	6	.025	1.552	.170	.088	9.311	.574
	Greenhouse-Geisser	.147	4.972	.030	1.552	.184	.088	7.715	.515
	Huynh-Feldt	.147	6.000	.025	1.552	.170	.088	9.311	.574
	Lower-bound	.147	1.000	.147	1.552	.231	.088	1.552	.216
Error (Movement*Tactile_Cue)	Sphericity Assumed	1.516	96	.016					
	Greenhouse-Geisser	1.516	79.545	.019					
	Huynh-Feldt	1.516	96.000	.016					
	Lower-bound	1.516	16.000	.095					

a. Computed using alpha = .05

No-change trial accuracy ANOVA table for within-subjects variables



Tests of Between-Subjects Effects

Measure: Accuracy
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Intercept	122.025	1	122.025	530.178	.000	.971	530.178	1.000
Body_Location	1.576	1	1.576	6.847	.019	.300	6.847	.691
Error	3.683	16	.230					

a. Computed using alpha = .05

No-change trial ANOVA table for between-subjects variable

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