Tactile and Crossmodal Change Blindness and its Implications for Display Design

by

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For Mama, Baba, and Robert

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Chapter 1

Introduction

Data-rich environments, such as aviation, military operations, and medicine, impose considerable and continually increasing attentional demands on operators by requiring them to divide their mental resources effectively amongst numerous tasks and sources of information (e.g., Sarter, 2000; Sarter, 2007a; Woods, 1995). Data overload, especially in the visual channel, and associated breakdowns in monitoring already represent a major challenge in these environments. The problem is expected to get worse due to the anticipated introduction of even more tasks and technologies. For example, for military operations, the Office of the Secretary's Defense Roadmap for Unmanned Aircraft Systems (UASs) outlines the need to investigate "appropriate conditions and requirements under which a single pilot would be allowed to control multiple airborne unmanned aircraft simultaneously (Office of Secretary of Defense, 2005)" Currently, 2-3 operators are needed to handle all mission, flight, and management tasks for a single UAV (Unmanned Aerial Vehicle); the ultimate goal, however, is to have one operator handle up to 10 UAVs. This drastic change in the operator-to-UAV ratio presents a major design challenge given operators' limited attentional resources.

One promising means of addressing this challenge is the introduction of multimodal interfaces (i.e., interfaces that distribute information across multiple sensory channels, primarily vision, audition and touch). This approach has been shown to be effective in offloading the overburdened visual channel and thus reduce data overload (e.g., Sarter, 2006a, 2006b, 2007). In addition, multimodal displays can support functions such as spatial orienting, navigation tasks, and the communication of complex concepts and messages (Jones & Sarter, 2008; Oviatt, 2003; Sarter, 2002). However, the effectiveness of these interfaces may be compromised if their design does not take into consideration limitations of human perception and cognition.

One such limitation is a phenomenon called change blindness. Change blindness refers to 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 or transient (Simons, 2000). To date, the phenomenon has been studied primarily in vision but there is limited empirical evidence already that the auditory and tactile modalities may also be subject to change blindness (Eramudugolla, Irvine, McAnally, Martin, & Mattingley, 2005; Vitevitch, 2003; Gallace, Tan, & Spence, 2006). If confirmed, this raises concerns about the robustness of multimodal displays and their use in domains such as UAV control. The body of work reported in this dissertation therefore addresses the following main questions:

1) To what extent, and under what circumstances, is the sense of touch susceptible to change blindness?
2) Does change blindness occur crossmodally – between vision and touch – as well (i.e., is change detection in one modality poor when a coincident event is perceived in the other modality)?
3) How effective are three different types of cueing for overcoming these phenomena?

We will test one design that provides an advance notification of a likely future change to support its detection and two designs that adjust the timing and salience of information presentation in response to operators' change detection performance.

Multimodal and tactile interfaces in support of attention management

As mentioned above, 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 (e.g., Sarter, 2002; Oviatt, 2003). The benefit of employing multiple modalities for information presentation was first suggested by early research on time sharing. This research gave rise to Multiple Resource Theory (Navon & Gopher, 1979; Wickens et al., 1980, 1984, 2002, 2008; Wickens & Liu, 1988) which, in its original version, posits that the different dimensions (like processing codes, modalities, stages, and response types) draw from separate attentional resources. This implies that more tasks and information can be processed simultaneously if they are distributed across multiple sensory channels because resource competition is avoided (Figure 1-1). When used effectively, multimodal interfaces can "reduce mental workload, improve memory, and can potentially make human-computer interaction more natural and intuitive (Oviatt, 1999)."

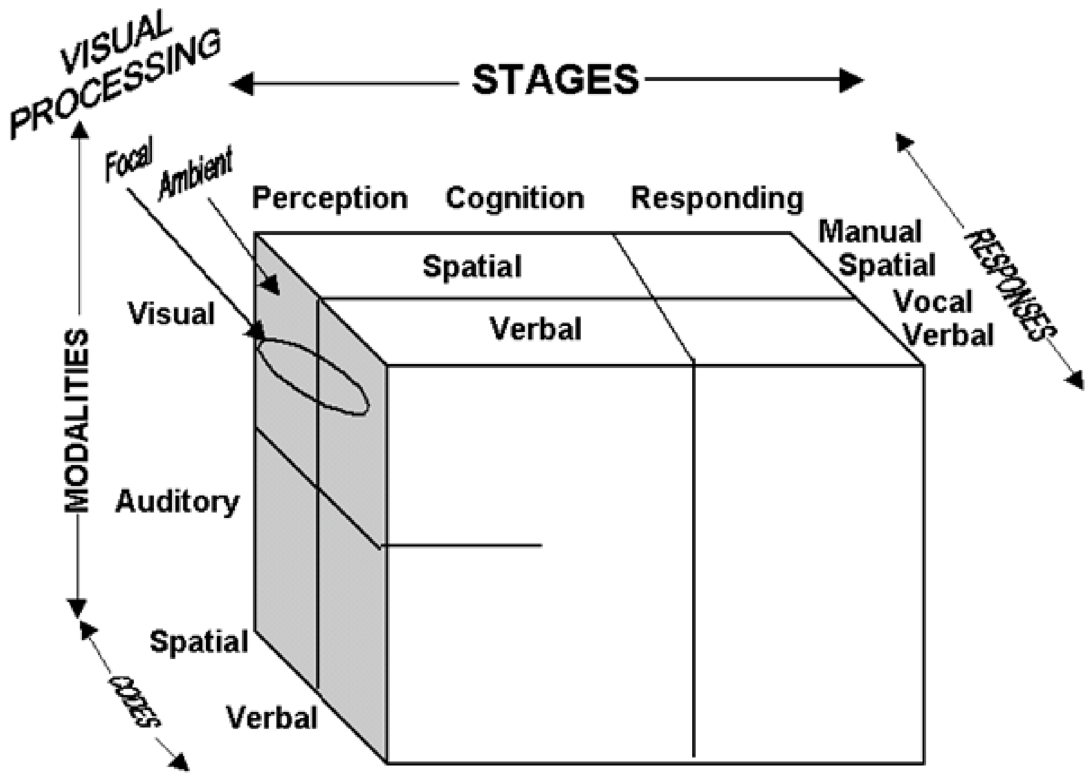

Figure 1-1: The various dimensions associated with separate attentional resources

The prediction of improved time sharing with multimodal displays was confirmed, for example, in two simulation studies that examined a pilot's ability to detect and identify unexpected FMS (Flight Management System) mode transitions when those were presented in peripheral vision or via the tactile channel, thus avoiding conflicts with pilots' ongoing focal visual tasks (Nikolic and Sarter, 2001; Sklar and Sarter, 1999). Both studies showed significantly increased detection rates and high interpretation accuracy for mode transitions without leading to performance decrements on the pilot's primary visual tasks. Numerous studies have since validated the benefits of crossmodal presentation for other types of flight deck information (e.g., Wickens, Goh, Helleberg, Horrey, & Talleur, 2003; Wickens & Colcombe, 2007) as well as supporting multitasking in other domains, including military operations (Prinet, Terhune, & Sarter, 2012; Savick, Elliott, Zubal, & Stachowiak, 2008), and driving (Ho, Spence, & Tan, 2005, 2006; Mohebbi, Gray, & Tan, 2009).

In recent years, one sensory channel in particular – touch – has received considerable attention. 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 a number of characteristics that make it a desirable addition to human-machine interfaces. Tactile signals are (a) high in temporal and spatial sensitivity, (b) effective in capturing attention without being too intrusive, (c) omnidirectional, i.e., signals can be received regardless of spatial orientation of attention, (d) proximal, i.e., in direct contact with the body, thus lending themselves to creating private displays, and (e) able to be presented across a large area of the body. Tactile cues have been used to support interaction with objects (MacLean, 2008), help with orienting/guiding/2D localization (MacLean, 2008), and assist with navigating unfamiliar terrain (Jones, Lockyer, & Piateski, 2006). Tactile cues have also been employed to provide information that is confidential (Jones & Sarter, 2008), and for aiding those with visual or hearing impairments (Kaczmarek & Bach-y-Rita, 1995). Potential drawbacks of this channel are that it may take users longer to perceive and attend to this channel, compared to audition particularly for more urgent messages (Stanney et al., 2004; Lu, Wickens, Sarter, & Sebok, 2011), and that the acceptable level of cue complexity is limited, compared to vision and audition (Lu et al., 2013). Also, tactile spatial discrimination varies considerably across the body, and the few body locations that offer high spatial resolution (e.g. fingertips, tongue) can often not be used for information presentation in workplaces due to practical constraints. In particular, we are interested in determining the vulnerability of this channel, in isolation or when combined with vision, to a phenomenon called change blindness.

Change blindness

Change blindness refers to the failure in detecting even large and **expected** visual changes within a display when these changes coincide with a visual “transient” (i.e., a brief disruption in visual continuity). Note that the word ‘expected’ here refers to the general expectation of **some** change without prior knowledge of the precise nature, timing, or location of the change. It is important to distinguish between change blindness – the focus of the proposed research – and inattentional blindness which is the failure to notice a fully-visible, but **unexpected** object because a person's attention is engaged by another task, event, or object (Simons & Levin, 1997).

Change blindness has been studied and demonstrated using various types of visual transients, including saccades (rapid movements of the eyes, separated by brief fixations during which the eye is relatively still; Grimes, 1996; Hollingworth & Henderson, 2002; Bridgeman, Hendry, & Stark, 1975), luminance transients (Arrington, Lewin, & Varakin, 2006), a blank screen interruption (Rensink et al., 1997), moving the location of the picture at the time of the change (Blackmore, Brelstaff, Nelson, & Trosciank, 1995), and eye blinks (O'Regan, Deubel, Clark, & Rensink, 2000). Change blindness can occur also when an object or scene changes slowly (e.g., a gradual fade; Simons, Franconeri, & Reimer, 2000). For example, in a study by Simons & Rensink (2005), many observers failed to notice when a building in a photograph gradually disappeared over the course of 12 seconds.

For the research presented in this document, we employed two of the most frequently used paradigms for inducing change blindness: (1) "flicker" (a complete or partial masking stimulus that obscures the visual scene; e.g., a blank screen between an original and changed image; Figure 1-2) and (2) "mudsplash" (i.e., small, high contrast shapes relative to the rest of the image that are scattered over part of an image without covering the change itself; Figure 1-3).

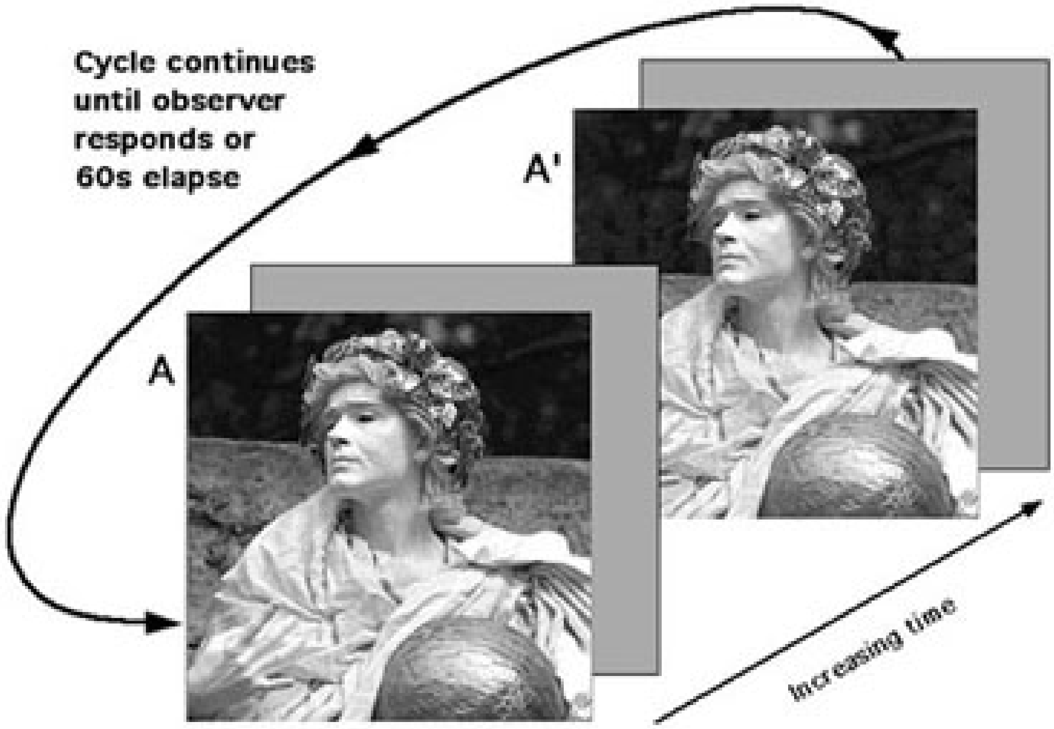

Figure 1-2: General design of the flicker paradigm; in this case, the change is the movement of the background wall level (Rensink, 2002a)

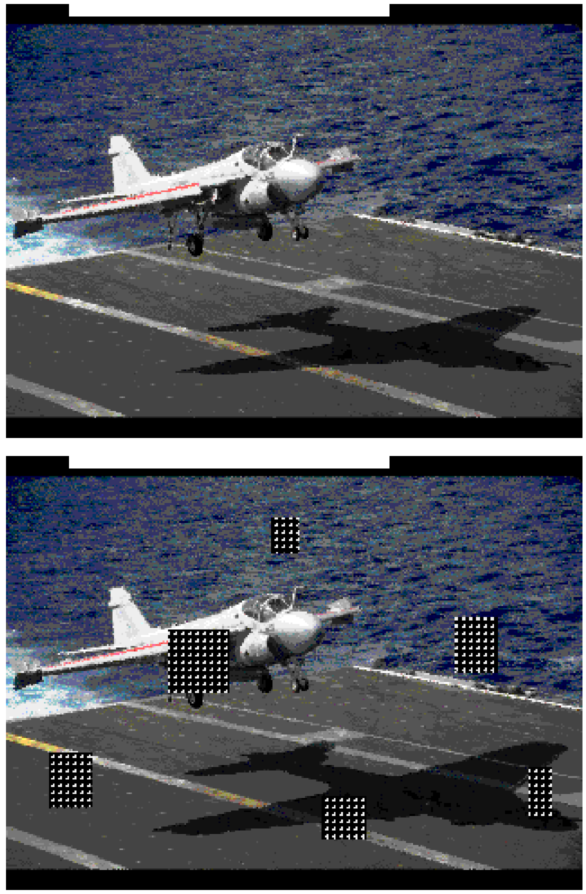

Figure 1-3: General design of the mudsplash paradigm; here, the presentation is continually altering between the two images and the change is the size of the aircraft's shadow (O'Regan, Rensink, & Clark, 1999)

Both flickers and mudsplashes tend to impair change detection and, at the very least, require multiple alterations between the original and the modified image before an observer may spot the difference (Rensink, O'Regan, & Clark, 1997). They represent examples of masking (O'Regan, Rensink, & Clark, 1999; Sperling & Speelman, 1965) which refers to a reduction in the visibility of an object (i.e., the target) caused by the presentation of a second object (i.e., the mask) nearby in space or time (Enns & Di Lollo, 2000). Note that change blindness is comparable to a particular type of masking – simultaneous masking – where a target (in this case, the change) appears at the exact same time as the mask (in this case, the transient).

Tactile and crossmodal visual-tactile change blindness

To date, change blindness has been studied primarily in vision and, to a more limited extent, audition where the phenomenon is referred to as change deafness. For example, people are remarkably poor at detecting the *appearance* and *disappearance* of individual auditory objects in the presence of a white noise mask, especially when they were not visually cued to the potentially changing object (e.g., Eramudugolla et al., 2005; Pavani, 2008). Change deafness occurs regardless of whether the masking interval (equivalent of a visual flicker) between auditory scenes is silent or filled with noise (Pavani & Turatto, 2008). One difference between change blindness in vision and audition is that visual change blindness is worsened if the interval between stimuli is greater than 100 msec; however, the same is not true for auditory change blindness (e.g., Demany, Trost, Serman, & Semal, 2008). This suggests that inherent properties of different sensory channels can modulate the particular expression of the phenomenon.

Tactile change blindness has been demonstrated in a very small number of studies only. A significant performance decrement was observed when subjects had to distinguish between simple vibrotactile patterns from 2-3 tactors (devices that present vibration stimuli to the skin) located across the body in the presence of a vibrotactile mask (vibrotactile stimulation from tactors not related to the pattern of interest; equivalent to a visual mudsplash; Gallace et al., 2006; Gallace, Tan, & Spence, 2007; Ferris, Stringfield, & Sarter, 2010). Even when the tactile stimuli were presented to the highly touch-sensitive fingertip region, change blindness was elicited in the presence of a tactile transient (Malika, Gallace, Hartcher-O'Brien, Tan, & Spence, 2008). Finally, manual control actions, such as pressing a button or turning a steering wheel, have also been shown to elicit tactile change blindness (Gallace, Zeeden, Röder, & Spence, 2010).

In addition to intramodal change blindness in vision, audition, and touch, the possibility of crossmodal change blindness, i.e., change blindness across different modalities, was suggested by research showing that sensory channels are, to some extent, linked to one another. Specifically, spatial and temporal crossmodal links in attention have been demonstrated (Driver & Spence, 1998; Ferris & Sarter, 2008).

Crossmodal spatial links refer to the fact that presenting information in one modality in a particular location leads to an increased readiness to perceive information in other modalities in that same location (Spence et al., 2000; Driver and Spence, 2004). Crossmodal temporal links can take two forms: (1) crossmodal attentional blink and (2) crossmodal inhibition of return (Spence, 2001; Spence & Driver, 1997a, 1997b, 1998; Ward, McDonald, & Lin, 2000). In the case of the crossmodal attentional blink, two unrelated cues are presented via different modalities in very close temporal proximity (on the order of 50-100 ms). In this case, the second cue is likely to be missed (Arnell & Jolicoeur, 1999). Crossmodal inhibition of return is observed when a cue is missed or detected late after it is presented within a certain time window in the same location as a preceding cue in a different modality (Klein, 2000; Spence & Driver, 1998).

The existence of these crossmodal links in attention implies that change blindness may be experienced across modalities as well. However, this phenomenon has been studied to an even lesser extent than tactile change blindness. It has been documented only between vision and touch, using a mudsplash paradigm. In this case, patterns of tactile stimuli that were presented to various locations across the body changed in the presence of coincident visual masking stimuli (equivalent to a visual mudsplash) and vice versa (Auvray, Gallace, Tan, & Spence, 2007; Gallace et al., 2006; Auvray Gallace, Hartcher-O'Brien, Tan, & Spence, 2008).

Further examining tactile and crossmodal visual-tactile change blindness is of particular importance because: (1) while the tactile modality is currently still the most underutilized channel for presenting information, demonstrations of its effectiveness for supporting various cognitive functions has recently led to an increased use and interest and (2) given that most workplaces involve primarily visual tasks, the simultaneous experience of visual and tactile cues is likely to increase.

The role of attention and memory in change blindness

Attention is a critical prerequisite and limiting factor for change detection. Although attention can be divided between 4-5 items simultaneously, only a single change can be detected at any moment (‘change simultagnosia’; Rensink, 2002b). Change detection is a function of both top-down and bottom-up influences on attention. It occurs in a bottom-up fashion when a salient change draws attention involuntarily. Top-down factors can override this mechanism. For example, changes to semantically important items (Rensink et al., 1997) and regions (Stirk & Underwood, 2007; Wright, 2005) are detected faster than less critical changes in other locations, even when the changes are of equal salience (Kelley, Chun, & Chua, 2003).

Attention alone may not be sufficient to detect changes, however. For example, studies using eye tracking to measure the focus of a person’s visual attention have shown that, even when an item was fixated, changes to that item were sometimes missed (William & Simons, 2000; Treisch, Ballard, Hayhoe, & Sullivan, 2003). It appears that successful change detection requires five distinct steps involving both attention and memory (Jensen, Yao, Street, & Simons, 2011):

1. Direct attention to the change location.
2. Encode into memory what was shown at the target location before the change.
3. Encode what is presented at the target location after the change.
4. Compare the mental representations of the information at the target location before and after the change.
5. Consciously recognize the discrepancy.

Failures at any of these five steps can lead to change blindness. For example, the pre-change stimulus may never be encoded into memory in the first place – a failure to perform step 2 (Noë, Pessoa, & Thompson, 2000; O’Regan & Noë, 2001; O’Regan, 1992; Gibson, 1986). This explanation for change blindness has been proposed based on the fact that visual change detection depends on two forms of memory: (1) iconic memory and (2) visual short-term memory (VSTM; Demany, 2008). Information is stored in VSTM for a relatively and sufficiently long time, compared to iconic memory (Phillips, 1974); however, the capacity of VSTM is limited to five objects at most (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997). This low capacity may make it impossible for people to encode into memory information at the target before a change. It is important to note that the capacity of tactile short term memory (TSTM) is limited also. Previous research has shown that TSTM is limited to three stimuli when counting the number of stimuli presented simultaneously seven body locations (Alluisi, Morgan, & Hawkes, 1965; Geldard & Sherrick, 1965; Riggs et al., 2006; Gallace et al., 2007)

Another possible explanation for change blindness is that the post-change stimulus may overwrite or disrupt access to the pre-change stimulus (Rensink et al, 1997; Levin, Simons, Angelone, & Chabris, 2002; Beck & Levin, 2003). In this case, change blindness occurs because the first representation is no longer available for comparison. Or an observer may encode both the pre- and post-change stimuli successfully, but never bother to compare the two (Scott-Brown, Baker, & Orbach., 2000; Mitroff, Simons, & Levin, 2004; Hollingworth, 2003).

Which of these mechanisms is ultimately responsible for change blindness is still a matter of debate. Still, the existence of the phenomenon has been demonstrated and calls for countermeasures to ensure the reliable detection of potentially critical changes and events in a range of real-world domains.

Countermeasures to tactile change blindness

Observations of tactile change blindness call for the development of countermeasures to ensure reliable detection of relevant changes and events, even when they coincide with a transient. Given the likely role of memory limitations in change blindness, relying on global (rather than local) processing may be one way of overcoming change blindness because global processing leads to chunking and thus the number of items that need to be encoded is reduced. To date, the only study on change blindness that has examined the benefit of global processing was conducted by Austen

& Enns (2000). They found that change detection in displays containing 3-5 items was faster when changes were made to “global” letters (i.e. changing the overall letter configuration of smaller letters, Figure 1-4) compared to “local” letters (i.e. changing individual the letters within overall letter configuration).

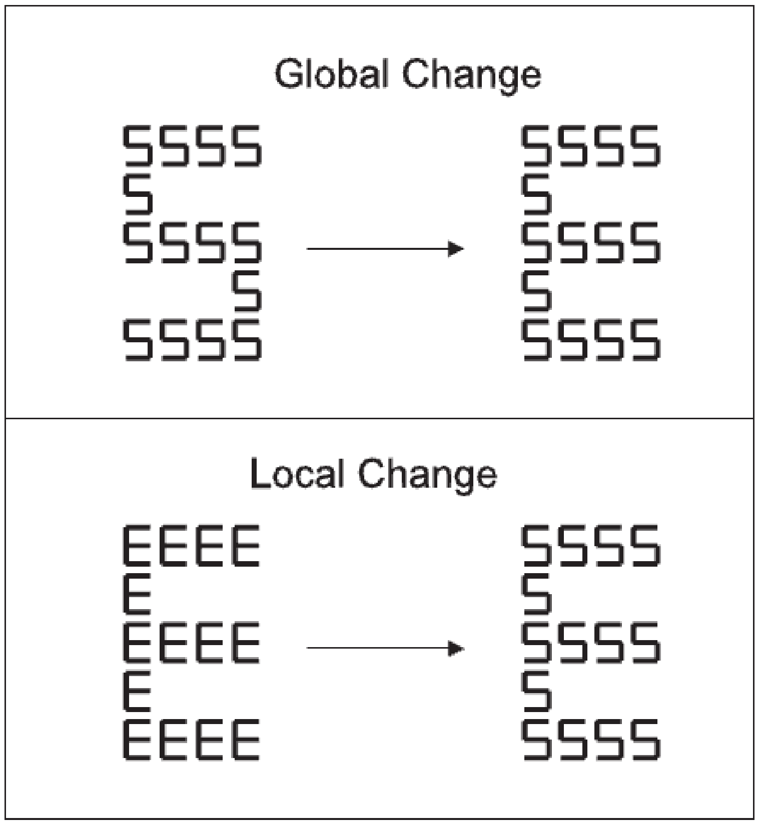

Figure 1-4: Global and local changes used by Austen & Enns (2000)

Previous work has investigated employing change detection tools by logging in a table every change that occurs in a dynamic situation (CHEX; Smallman & John, 2003), but is unable to prevent change blindness for more complex tasks (Vallieres, Hodgetts, Vachon, & Tremblay, 2012). Training, is another alternative that has been explored, but has been found to have no measureable effect in helping people to identifying changes to complex three-dimensional objects (Williams & Simons, 2000). In the present research, we focused on a different approach to avoiding change blindness, namely the development and testing of three forms of cueing that support steps 1 through 4 of the change detection process (Jensen et al., 2011): (1) direct attention to the change (location), (2) encode into memory what was shown at the target location before the change (3) encode what is presented at the target location after the change, and (4) compare the mental representations of the information at the target location before and after the change. In particular, we focused on countermeasures to tactile change blindness.

Since attention is critical to change detection, all the countermeasures were designed to support step 1. To support step 2, we introduced a fast pulsing tactile signal that was presented just before the potential occurrence of a tactile change to alert participants and ensure that they direct their attention to the tactile stimuli and to help encode the target before a change. To support steps 3 and 4, we introduced context-sensitive information presentation in the form of adaptive interfaces, i.e., interfaces that adjust the nature of information presentation in response to various sensed parameters and conditions (e.g., Trumbly, Arnett, & Johnson, 1994; Scerbo, 1996; Sarter, 2007b). A considerable number of possible drivers for display adaptation have been proposed in the literature (e.g., Hollnagel & Woods, 2005). They include personal preference, temporal and task demands, norms/standards of the work environment, and environmental conditions.

For our purposes, we focused on participant change detection performance as the driver of adaptation. If a participant failed to notice a change (i.e., increase in the intensity of a tactile stimulus), they would then be presented with one of two cues: (1) a tactile pulse at an even higher intensity than the post-change pulse or (2) a tactile signal that combined, in sequence, the pre- and post-change levels of tactile intensity, with no time interval in between the two. The latter presentation was intended to support a direct comparison of both intensities, rather than require an absolute judgment. Chapter 4 describes and discusses these countermeasures in more detail.

Application domain: Unmanned aerial vehicle (UAV) control

UAV control was chosen as the application domain for this research because it is an increasingly data-rich environment that imposes considerable attentional demands on operators. UAV control currently requires multiple operators to supervise the Intelligence, Surveillance and Reconnaissance (ISR) missions of a single vehicle. The role of these operators is to plan, re-plan if necessary, and monitor the overall mission health based on data transmitted by individual UAV mounted sensors and cameras (Cummings, Bruni, Mercier, & Mitchell, 2007). Together, the UAV and its operators constitute an Unmanned Aerial System (UAS). The vision of the Office of the Secretary of Defense (Office of Secretary of Defense, 2005) and Committee on Autonomous Vehicles in support of Naval Operations (Naval Studies Board, 2005) is to increase the operator/UAV ratio to the point where a single operator handles all mission, flight, and sensor management tasks for up to 10 UAVs.

Already, some studies suggest that this can be expected to result in problems related to visual change blindness. For example, Parasuraman, Cosenzo, and De Visser (2009) showed that change detection was overall poor in the context of an Uninhabited Ground Vehicle (UGV) control task. Fewer changes were detected when there were visual transients (flashing of a UAV status bar) compared to when transients were not present (13% and 35%, respectively). Change blindness was demonstrated also in the context of the Army's Force XXI Battle Command Brigade and Below (FBCB2) system, which like UAV control, provides real-time command and control information. Durlach and Chen (2003) found that, when map icon changes coincided with switching between different windows, only 50% of the icon changes were detected, compared with a detection rate of 90% when there was no switching between screens.

Intellectual merit and broader impact

The findings from this research make a significant contribution to a better understanding of tactile and multimodal information processing and its associated limitations. Specifically, it provides empirical evidence on tactile and crossmodal change blindness, a phenomenon that represents a growing concern in many data rich and high risk environments. The research examined, in a systematic fashion, (a) to what extent and under what circumstances tactile and crossmodal visual-tactile change blindness are experienced and (b) how these phenomena and their related performance costs can be reduced or overcome through display design. The insights gained from the applied aspect of this work, namely the development and testing of countermeasures to change blindness, can be applied to the design of future more effective multimodal interfaces, not only for UAV operations but other complex data-rich domains, such as aviation, the medical domain, and the automotive domain. By avoiding that operators experience change blindness and miss potentially critical signals, such designs can be expected to increase safety in a range of workplaces and thus benefit society at large.

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Chapter 2

Crossmodal Matching between Tactile and Visual Transients

Introduction

Multimodal displays and multisensory information processing have received considerable attention over the past decade (e.g., Calvert, Spence, & Stein, 2004; Ferris & Sarter, 2008; Sarter, 2006). A significant body of empirical work has demonstrated benefits of distributing information across modalities, including improved time-sharing and more effective attention and interruption management, (e.g., Brickman, Hettinger, & Haas, 2000; Ho, Nikolic, & Sarter, 2001; Latorella, 1999). However, with few exceptions (e.g., Brill, Gilson, & Mouloua, 2007; Brill, Mouloua, Gilson, Rinalducci, & Keneedy, 2008; Brill, Mouloua, & Hendricks, 2009; Garcia, Finomore, Burnett, Baldwin, & Brill, 2012), studies on multimodal information processing involve an important limitation: they have not included (or, at least, not reported) any crossmodal matching procedure prior to conducting an experiment. Crossmodal matching refers to a technique whereby an observer matches the perceived intensities of stimuli across two sensory modalities. Failure to perform this step raises concerns because it involves the risk of confounding modality with other signal characteristics, most notably salience.

Our recent review of the multimodal attention literature since 2000 revealed that only two of 93 relevant studies (2.2%) performed or reported crossmodal matching (Pitts, Lu, & Sarter, 2012). Not only have few studies employed cross-modal matching, but most of the ones that have done so do not provide a detailed description of the procedure or its results. Furthermore, studies that performed and reported cross-modal matching did not all employ the same method. For example, Stevens (1959) employed the method of bracketing, i.e., turning some aspect of stimuli, such as loudness, alternatively too high or too low, in order to "zero in" on equality, without allowing participants to see the dial on the stimulus control. Galinsky, Warm, Dember, Weiler, and Scerbo (1990) adapted a similar method of bracketing for matching the perceived loudness of noise to the perceived brightness of a visual stimulus. In contrast, Brill et al. (2007, 2008) asked participants to match successively the apparent loudness of auditory and tactile stimuli to that of a visual stimulus.

Given the criticality of cross-modal matching in research on multimodal information processing, we performed two experiments in advance of our studies on change blindness to:

1) compare the effectiveness and feasibility of two variations of a crossmodal matching procedure and
2) identify appropriate and equivalent intensities for visual and tactile transients to be used in the change blindness studies described in Chapters 3 and 4.

The techniques that were evaluated and compared rely on the method of adjustments, in which participants are asked to vary the intensity of a given stimulus until it matches that of the originally presented signal. Importantly, in contrast to most earlier work, participants were asked to perform the same match multiple times to examine the consistency and reliability of their judgments. The two experiments described below examined crossmodal matching between vision and touch only.

EXPERIMENT 1

Methods

Participants

Fifteen University of Michigan undergraduate and graduate students participated in this experiment (average age = 22.5 years, SD = 2.1). Participants were required to possess normal or corrected-to normal vision, no compromised sense of touch (confirmed with the subjects after they signed the consent form to make sure they did not have any injuries or conditions that would compromise their sense of touch on their back), and no history of epilepsy (flickering displays may trigger epileptic seizures).

Visual and tactile transients

Given the focus of this thesis on tactile and crossmodal visual-tactile change blindness, we used crossmodal matching to identify equivalent visual and tactile transients, i.e. brief obscurations of a visual or tactile display, for the later experiments. The two transients that were matched were "flickers" (a complete masking of the display, Figure 2-1) and "mudsplashes" (a partial masking of the display, Figure 2-2). These two types of transients are the ones most often employed in previously published work on change blindness (Rensink, O'Regan, & Clark, 1997; O'Regan, Rensink, & Clark, 1999). The luminance of the visual flicker and mudsplash ranged from 0-10 fL, i.e. the range which participants could select from to match the tactile transients presented. The transients were presented on a 20" monitor, placed about 30" away from the participant, which showed a 3x3 array of video feeds from nine UAVs (the setup to be used in our subsequent experiments in Chapters 3 and 4).

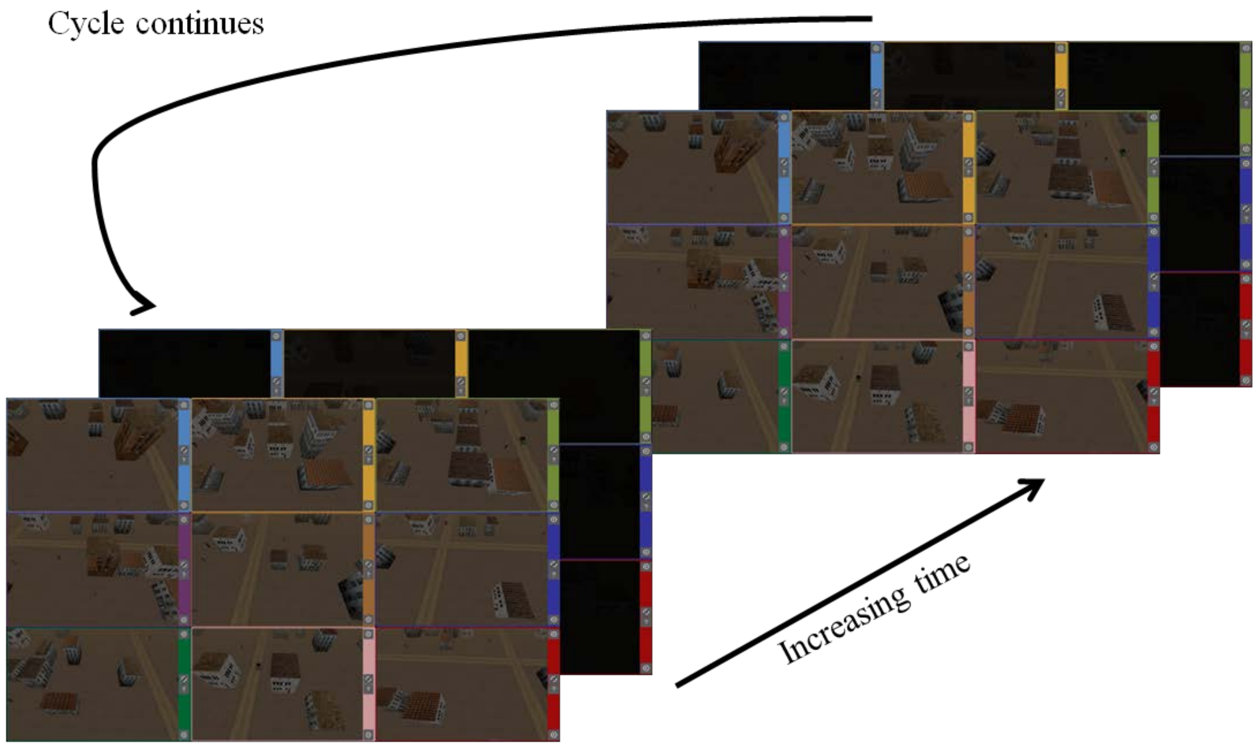

Figure 2-1: Depiction of the sequence of events for a flicker on the UAV control display

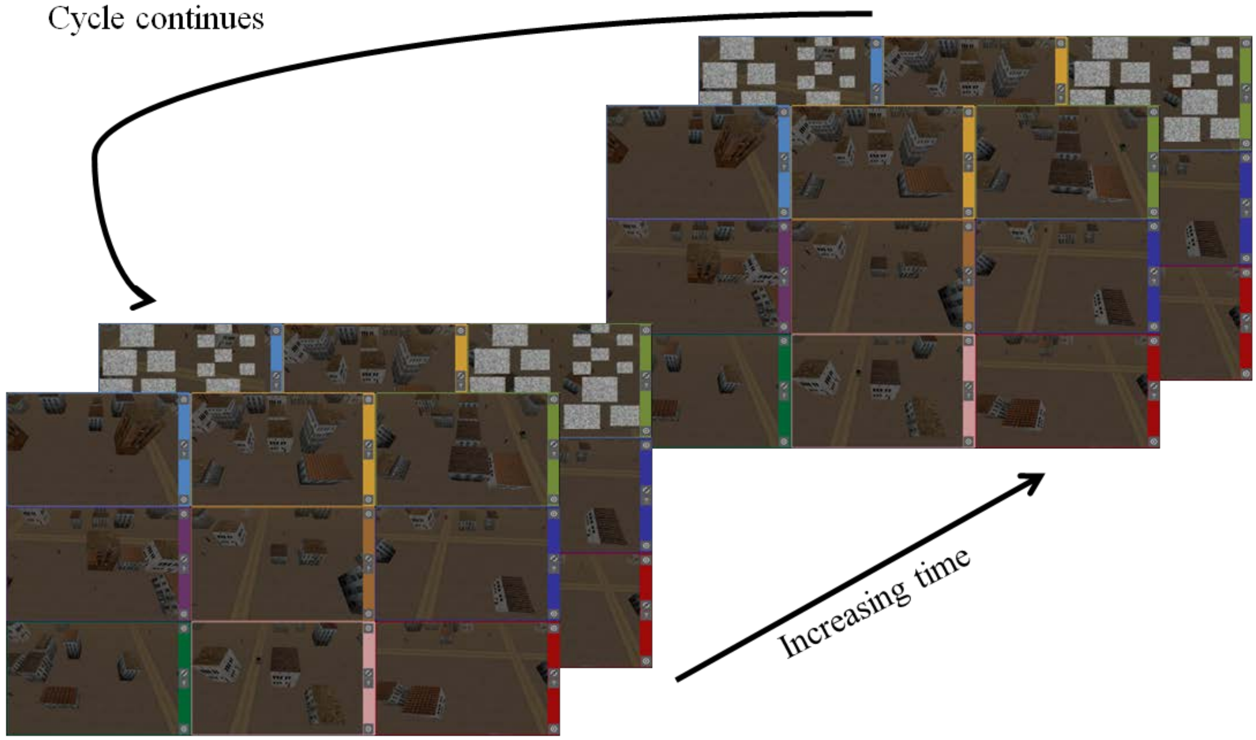

Figure 2-2: Depiction of the sequence of events for a mudsplash on the UAV control display

The tactile transients consisted of vibrations at 250 Hz that were presented using C-2 tactors (commercially available piezo-buzzers inside a 1” x 1/2" x 1/4” plastic housing). The tactors were attached, in a 3x3 array, to a belt and vest that was worn over clothing (Figure 2-3). The tactor array mapped onto the nine UAV feeds on the monitor. Note that three pairs of tactors were placed in the central column to avoid direct contact with the spine. The intensity with frequency held constant at 250 Hz and the tactile signal’s gain ranged from 0-18 dB (maximum gain from C-2 tactors), i.e. the range which participants could select from to match the visual transients presented. White noise was played over the headphones to eliminate the audible component associated with the tactor vibrations.

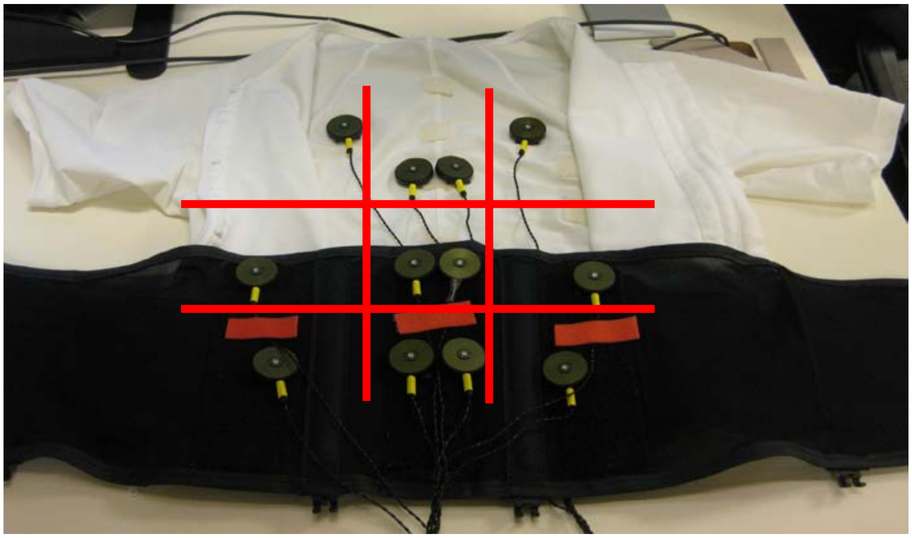

Figure 2-3: Tactor vest (top) and belt (bottom), with 12 tactors divided over 9 sectors to map onto the 9 UAV feeds on the monitor

Crossmodal matching task and technique

Participants performed a series of 80 matching task trials, using the interface shown in Figure 2-4 where an image of a tactor signified the tactile modality while an image of the nine UAV feeds referenced the visual modality. For each trial, participants were presented with a '*reference transient*' (labeled A in Figure 4) in one of two modalities (vision or touch). The luminosity for visual reference transients and the frequency for tactile reference transients were fixed and set by the experimenter. The participant would then use the slider below the two images to match the intensity of the '*variable transient*' (labeled B) in the other modality to that of the reference stimulus**.** They could use the 'Play' button to replay the reference transient and were asked to press the 'Done' button once they felt they had achieved the correct match.

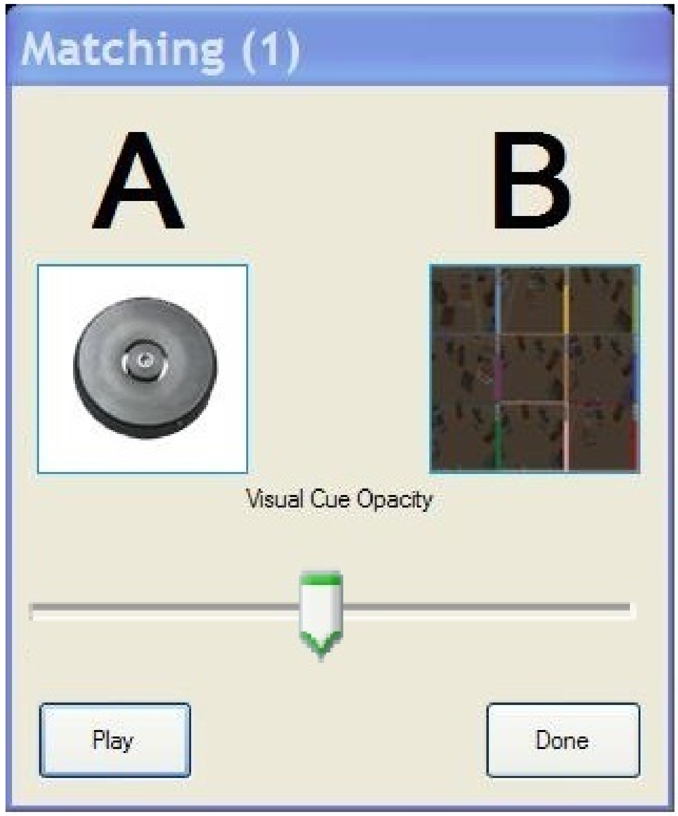

Figure 2-4: Crossmodal matching task interface (here, the variable transient is visual)

A schematic below shows a hypothetical sequence of events beginning with a tactile and visual reference cue (Figure 2-5).

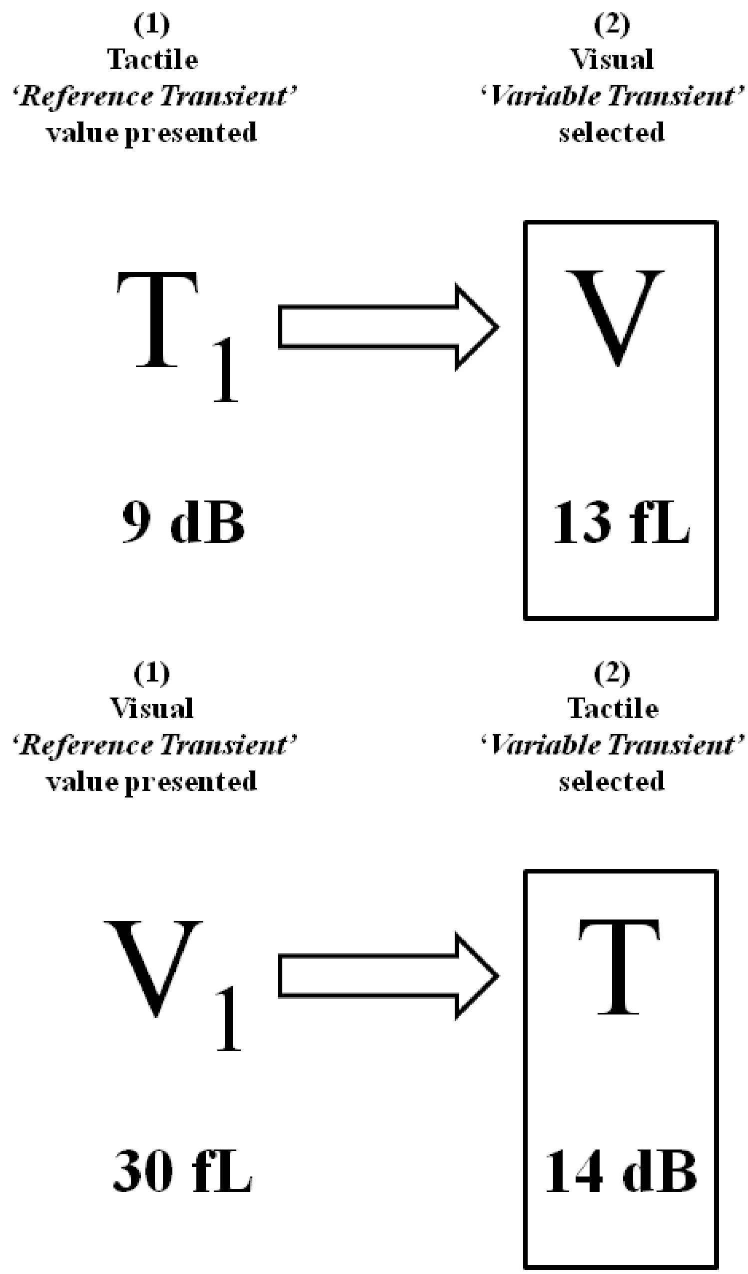

Figure 2-5: Sequence of events for trials starting with a tactile reference transient (top) or a visual reference transient (bottom)

Experimental design

The experiment employed a 2 (matching tasks: visual-tactile, tactile-visual) x 2 (transient type: flicker, mudsplash) within-subject full factorial design. Altogether, this resulted in 24 trials starting with the tactile modality as the reference transient for both types of transients (12 for tactile flickers, 12 for tactile mudsplashes) and 16 trials starting with the visual modality (eight for visual flickers, eight for visual mudsplashes). Participants repeated each match four times for a total of 40 matching tasks for the two modalities and two types of transients. The order in which participants were presented with the various matches was randomized. Dependent measures in this study were the matched values for the visual and tactile variable transients.

Procedure

The participants were allowed to explore the full spectrum of possible intensity values for each type of transient in both modalities before the start of and during any trials. Next, participants completed the 40 matching tasks, with a 5-minute break approximately half way through. Participants were instructed to "adjust the variable cue until you feel that its intensity is equal to that of the reference cue." All variable cue intensities were set to the middle of the sliding scale, and could be increased and decreased by dragging the slider up or down, respectively. Once participants were satisfied with their selection, they pressed the 'done' key on the crossmodal matching task interface, which allowed them to proceed to the subsequent matching task. After the experimental session, participants were asked to comment or make suggestions regarding the design of the interface and the experimental procedure.

Results

Intermediate matches

Tables 2-1 and 2-2 show the average match values for the visual and tactile transients. Note that a lower brightness for both visual flickers and mudsplashes translated into a more salient disruption and thus corresponded to a higher intensity for tactile transients. Thus, if participants perceived the visual cue to be more salient (lower brightness measured in fL), then they would select a higher tactile intensity as the matched value. Overall, as expected, the matched brightness values for visual transients tended to decrease with increasing tactile reference values. Visual matches seemed consistently higher for tactile mudsplashes, compared to tactile flickers. In contrast, the tactile matches for visual flickers and mudsplashes did not differ much for the two visual reference transient intensities or the two types of transients.

Table 2-1: Average visual match values for tactile reference transients (frequency constant at 250 Hz; standard deviation in parentheses)

	Tactile Reference Transient Intensities (gain in dB)		
Matched Visual Variable Transient Brightness (fL)	*3.5 dB*	*9.2 dB*	*18 dB*
Flicker	6.8 fL (1.6)	4.0 fL (1.7)	1.2 fL (1.1)
Mudsplash	8.2 fL (1.5)	7.1 fL (1.8)	4.8 fL (2.4)

Table 2-2: Average tactile match values for visual reference transients (standard deviation in parentheses)

	Visual Reference Transient Intensities (fL)	
Matched Tactile Variable Transient Intensity (dB)	*2.0 fL*	*0.0 fL*
Flicker	14.0 dB (3.2)	15.3 dB (3.0)
Mudsplash	15.4 dB (2.3)	15.5 dB (2.4)

Experiment 1 represented a first exploratory step towards establishing a more reliable method for crossmodal matching. As expected, the results show considerable differences between participants' matches – the main reason for performing crossmodal matching to begin with – but they also highlight considerable within-subject variability which raises concerns regarding reliability. Therefore, a second experiment was run using a variation of the technique to try and reduce within-subject variability.

EXPERIMENT 2

The second experiment evaluated a modified version of the matching task. In this case, the sliding scale was removed from the interface because a number of participants in Experiment 1 indicated in the debrief that the sliding scale (rather than the perceived intensity of the cue itself) may have influenced their selections. In Experiment 2, participants used the left and right arrows on the computer keyboard, in the absence of any visual indications, to adjust the intensity of the variable cue until it matched that of the reference cue.

Methods

Participants

Six University of Michigan undergraduate and graduate students (not the same as in Experiment 1) participated in this experiment (average age = 25.3 years, SD = 2.7). Participants were required to possess normal or corrected-to normal vision, no compromised sense of touch (this was again confirmed with the subjects after they signed the consent form to make sure they did not have any injuries or conditions that would compromise their sense of touch on their back), and no history of epilepsy (flickering displays may trigger epileptic seizures).

Crossmodal matching task and technique

The visual and tactile transients and the means of presentation were the same as in Experiment 1. In this case, however, the participants used the arrow keys on the keyboard to increase or decrease the luminosity when the ‘variable transient’ was visual or the amplitude when it was tactile. Participants performed a series of 36 matching task trials where the presentation order was randomized, using the interface shown in Figure 2-6. Note that this interface did not include a visible sliding scale.

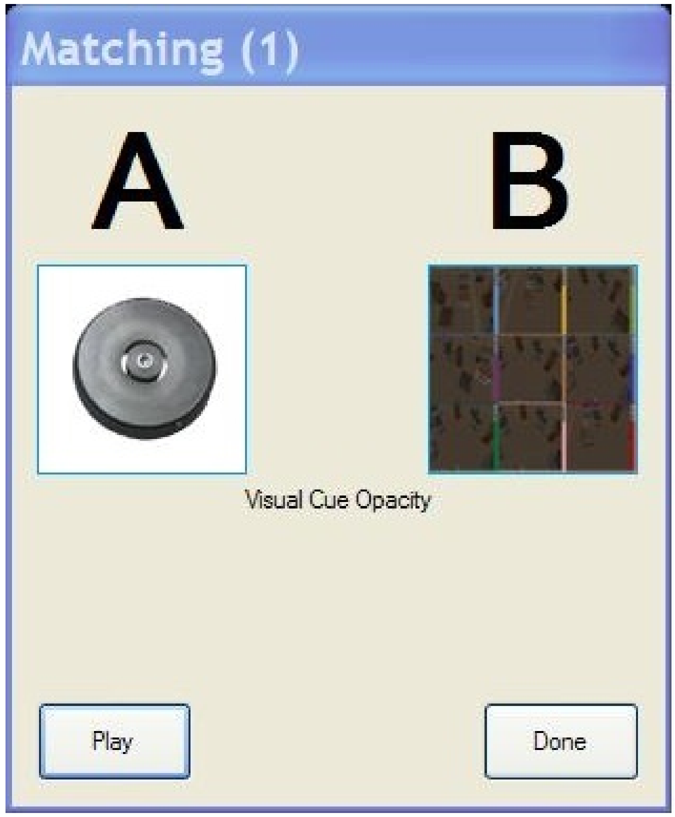

Figure 2-6: Crossmodal matching task interface (in this case, the reference transient is tactile)

Experimental design and procedure

This experiment employed a 2 (reference modality: visual, tactile) x 2 (transient type: flicker, mudsplash) within-subject full factorial design. Altogether, this resulted in 18 trials starting with the tactile modality as the reference transient for both types of transients (9 for tactile flickers, 9 for tactile mudsplashes) and 18 trials starting with the visual modality (9 for visual flickers, 9 for visual mudsplashes). Participants repeated each match three times for each reference value for the two modalities and two types of transients. All variable intensities were set to lowest possible value on the scale, to minimize any bias in participant selection of matches and could be increased and decreased by using the arrow keys on the keyboard. The order in which participants were presented with the various matches was randomized. The procedure was the same as in Experiment 1, and the dependent measures were the intensity values for the variable transients.

Results

Matched values

Tables 2-3 and 2-4 show the average matched values for the different reference modality/transients combinations.

Table 2-3: Average matched values for tactile reference transients (frequency constant at 250 Hz; standard deviation in parentheses)

	Tactile Reference Transient Intensities (gain in dB)		
Matched Visual Variable Transient Brightness (fL)	*3.6 dB*	*9.0 dB*	*14.4 dB*
Flicker	7.5 fL (1.9)	4.8 fL (2.4)	2.3 fL (1.2)
Mudsplash	9.1 fL (1.6)	7.2 fL (2.7)	4.6 fL (1.9)

Table 2-4: Average matched values for visual reference transients (standard deviation in parentheses)

	Visual Reference Transient Intensities (fL)		
Matched Tactile Variable Transient Intensity (dB)	*8.0 fL*	*5.0 fL*	*2.0 fL*
Flicker	3.8 dB (4.2)	7.6 dB (5.0)	11.1 dB (5.6)
Mudsplash	7.2 dB (4.3)	11.7 dB (4.14)	14.3 dB (4.1)

A mixed ANOVA was conducted to determine whether there were statistically significant differences in residual values for the various reference values and reference modalities. Residuals were calculated for each participant and each reference value by first subtracting the selected matched value from the mean for that reference value and then using the absolute value. For example, if a participant selected 10 dB, 13 dB, and 13 dB as the tactile matches to a visual reference transient value of 2.0 fL, then the mean tactile match value would be 12 dB. The three corresponding residuals used for the data analysis would then be 2 dB (|12 dB - 10 dB|), 1 dB (|12 dB - 13 dB|), and 1 dB (|12 dB - 13 dB|).

There was a significant effect of reference modality on residual value. The mean residual value was higher when the reference modality was tactile (mean = 7.844), compared to when the reference modality was visual (mean = 6.081). Reference value did not have a significant effect on residual value ($F(2, 33) = 1.775$, $p = .185$), and there was no transient type*reference value nor transient type*reference modality interaction (respectively $F(2, 33) = .654$, $p = .527$; $F(1, 34) = .831$, $p = .368$). As in Experiment 1, there was a trend for visual matches to be higher for tactile mudsplashes, compared to tactile flickers. Also, to a larger extent than in the previous experiment, tactile matches for visual transients were consistently higher for mudsplashes than for flickers.

A reference value*reference modality interaction ($F(2, 33) = 20.048$, $p < .001$) was observed such that, for the lowest reference value (20), the residuals for the matches starting with the visual modality were significantly higher than when the reference modality was tactile. Other the other hand, for the intermediate and highest reference values, the opposite was true: residual values were higher when the reference modality was tactile compared to when the visual modality was the reference modality.

Discussion and Conclusion

The purpose of the two experiments described in this chapter was to (1) contribute to the development and validation of a more reliable crossmodal matching technique that is easy to administer and (2) determine the transient values to be used in the change blindness studies described in Chapters 3 and 4.

Overall, the findings from this research confirm the need for improved crossmodal matching procedures. Current techniques that involve a single match only do not account for the high degree of intra-individual variability across matches observed in the first and, to a lesser extent, the second experiment. As part of a larger overarching study (Pitts, Sarter, & Lu, 2014), Experiment 2 showed that an apparently minor modification of the technique, namely the removal of the sliding scale, was successful in reducing within-subject variability. This improvement, in combination with comments provided by participants during a debriefing, confirms that visually displaying an intensity scale is inadvisable as it results in participants trying to remember and match the earlier slider position, rather than focusing on their actual perceptual experience in each case and each modality.

Since inconsistencies in matches were observed both within and between subjects and for all transient intensities, the highest tactile transient intensity – a frequency of 250 Hz and a gain of 14.4 dB – was chosen for the experiments reported in Chapters 3 and 4. This intensity had a strong masking effect, but did not startle participants. Based on the findings from Experiment 2, the corresponding visual flicker intensity would be 2.3 fL. However, to account for the large variability between subjects, the corresponding standard deviation of 1.1 fL was subtracted. Thus, 1.2 fL was ultimately determined to be the equivalent visual transient brightness when tactile transients were presented at 250 Hz, 14.4 dB.

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Chapter 3

Tactile and Crossmodal Visual-Tactile Change Blindness: The Effect of Transient Type, Transient Duration, and Task Demands

Introduction

As discussed in the previous chapters, multimodal interfaces (i.e., interfaces that employ visual, auditory and/or tactile signals) are a promising means of supporting a range of cognitive functions, such as attention and interruption management (Hopp-Levine, Smith Clegg, & Heggestad, 2006; Sarter, 2002). In recent years, tactile displays, in particular, have received considerable attention, and their benefits have been highlighted in several studies. However, the overall effectiveness of both tactile and, more generally, multimodal displays depends on considering in their design both affordances and limitations of human perception and attention. One important question in this context is the extent to which the tactile modality may be susceptible to change blindness, i.e. the failure to detect even large and expected changes when these changes coincide with a "transient" stimulus.

To date, change blindness has been studied primarily in the visual domain but recent research suggests the existence of an analog of change blindness in the tactile modality, especially for tasks involving pattern change recognition. The present line of research –

consisting of three experiments – therefore examined whether tactile change blindness, as well as crossmodal visual-tactile change blindness. Intramodal visual change blindness was included in the first experiment to ensure that the phenomenon could be replicated and to compare its severity to the other two conditions. The effect of transient type (in particular, the flicker versus mudsplash paradigm – Experiment 1) as well as transient duration (Experiment 2) on the likelihood of change blindness was investigated. Also, the effect of task demands (specifically single- versus dual-task performance – Experiment 3) on change detection was explored. The latter question is important since most real-world domains require task sharing which has not been considered in many change blindness studies to date. Finally, the predictive power of individual differences (such as level of extraversion) was examined. The application domain for this research was Unmanned Aerial Vehicle (UAV) control, a domain that imposes considerable attentional demands on operators.

Note that change blindness in the auditory channel (i.e. change deafness) was not examined as part of this dissertation research; its main purpose was to examine the tactile modality, the least utilized modality to date, both by itself and in relation to the visual modality, which is still the predominant channel of information presentation in most domains. Change deafness is, however, mentioned as potential future work described in Chapter 5.

Overall, the findings from the three experiments add to the knowledge base in multimodal information processing and presentation and help inform the design of adaptive and graded displays to prevent change blindness. These displays, and their empirical evaluation, are described in Chapter 4.

EXPERIMENT 1

Experiment 1 examined intramodal tactile, intramodal visual, and crossmodal visual-tactile change blindness. The main goals of Experiment 1 were to determine (1) if two types of tactile transients (flickers and mudsplashes), implemented as changes in the vibration intensity of a tactile display worn on the participant's back, induce intramodal tactile and crossmodal visual-tactile change blindness and (2) if global visual changes, in this case changes to the background brightness of a UAV feed, induce intramodal visual and crossmodal tactile-visual change blindness while participants were engaged in a visual monitoring task.

Methods

Participants

Eleven undergraduate and graduate students from the University of Michigan participated in this study (7 males and 4 females; mean age = 22.4, stdev = 3.4). Participants were required to possess normal or corrected-to-normal vision, have no known disorders or injuries that may impair their sense of touch, and have no history of epilepsy (flickering displays may trigger epileptic seizures).

Experimental setup

Each participant played the role of an Unmanned Aerial Vehicle (UAV) operator and was responsible for responding to long range radar indications in a simulated combat scenario. Long range indications were potential targets that could not be seen in a UAV's field of view, but were detected by the UAV's radar system. The UAV simulation that was used in all experiments was developed in the THInC Lab (The Human-Automation Interaction and Cognition Lab) and closely resembles the 'Vigilant Spirit Control Station' which is used by the Air Force to develop interfaces for controlling and supervising multiple combat UAVs with a limited number of operators.

Visual display

The simulation ran on a 20” monitor, positioned at a distance of 30” from the participant. It displayed nine dynamic UAVs feeds (Figure 3-1). When a UAV detected the potential or actual presence of a long range target, it communicated this information to the participants by increasing the background brightness of the respective video feed. To the right of each UAV feed, three buttons were presented and used by participants to respond to visual and tactile cues (see ‘Response to long range target indications’ section for a more detailed description and explanation of each button).

Figure 3-1: Screenshot of 9 UAV video feeds on the monitor

Tactile display

The tactile display consisted of 12 C-2 tactors (1”x 0.75”x 0.5” piezoelectric devices; Engineering Acoustics, Inc.) that applied vibrations to the participant’s back to communicate the (potential) presence of a long range target. The tactors were attached to a vest (a medical compression garment designed to maintain a consistent pressure over the maximum surface area on the torso) and a belt. The latter was used because it conformed to different body shapes, namely different sized waists, better than the vest alone (Figure 3-2). A men's size medium[1] vest and an adjustable Velcro tactor belt were able to accommodate all participants in this research.

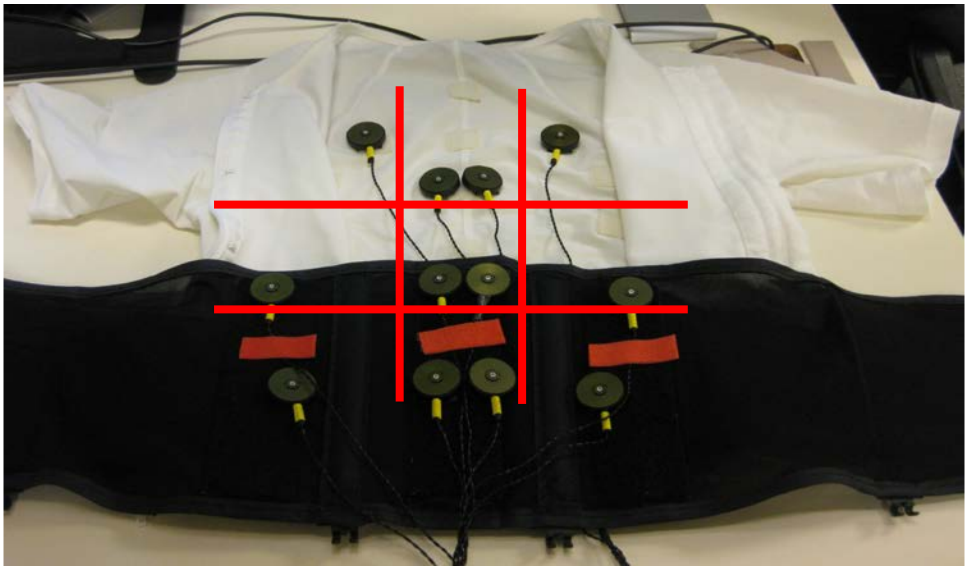

Figure 3-2: Tactor vest (top, Veronique brand) and belt (bottom) divided into nine sectors to map onto the nine UAV feeds on the monitor

The locations of the tactors mapped onto the locations of the nine video feeds on the monitor[2]. This natural mapping (Norman, 1990) was used to minimize the need for training and ensure proper attention allocation by exploiting crossmodal spatial links between vision and touch (Ferris & Sarter, 2008; Driver & Spence, 1998).

The entire experimental setup including the visual display and tactile display can be seen in Figure 3-3.

[1] http://showcase.designveronique.com/designveronique/index.php/shop/postsurgical/men-1/zippered-compression-vest-with-arms.html
[2] The middle column consisted of two tactors to avoid vibrations directly on the participants' spines.

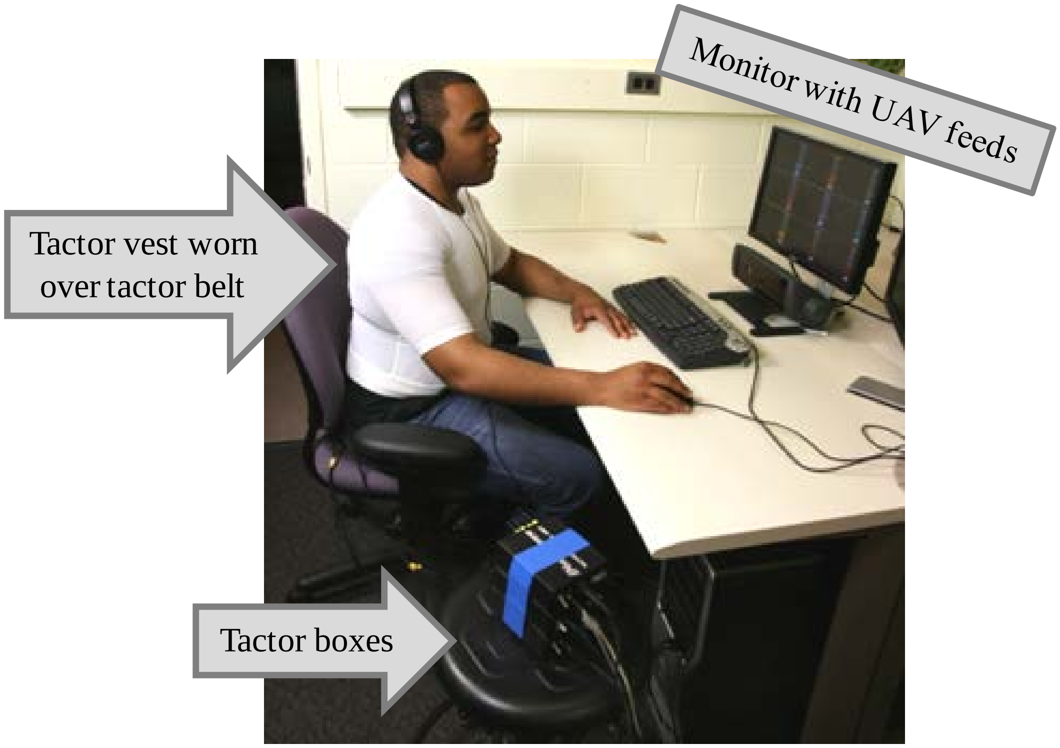

Figure 3-3: Experimental set up and layout of UAV simulation

Long range target indications

As mentioned earlier, the presence of a long range target in one of the nine sectors was communicated through tactile or visual indications, i.e., by increasing the vibration intensity of the respective tactor or the brightness of the corresponding UAV feed. Pilot tests verified that both the visual and tactile changes were reliably perceived, when presented in isolation, and slightly above the just noticeable difference (JND) threshold.

Visual long range target indications

A trial started when a UAV radar system detected a *potential* long range target. The respective UAV feed illuminated at a slightly higher than baseline level of brightness to draw the participant's attention to the UAV feed of interest. If the potential target turned out not to be a threat, then the UAV background would remain at the low level of brightness for the entire 8.5 sec trial. If the potential target turned out to be an actual threat, then the brightness of the UAV feed would increase further (to the highest level brightness), either two, four, or five seconds after the start of a trial. These times were varied to minimize predictability and ensure that participants remained vigilant during the entire 8.5 sec trial. If an actual target triggered a brightness change, the background would remain at the highest level of brightness for the remainder of the 8.5 sec trial. The low level brightness was 6.6 fL[3], and the high level brightness was 10 fL.

Tactile long range target indications

For tactile target indications, a trial also started when a UAV radar system detected a *potential* long range target. In this case, the tactor corresponding to the relevant video feed began pulsing at a low intensity (250 Hz and 5.4 dB[4]) at a rate of one pulse/750 msec to alert the participant to a possible threat. If the potential target was benign, then the tactor continued to pulse at the low intensity for the entire 8.5 sec trial. Otherwise, if the potential target was ultimately deemed to be a threat, then the vibration intensity would increase to a higher intensity (250 Hz and 10.8 dB) two, four or five seconds after the start of a trial. As with the visual indication, the tactile signal was presented at this higher intensity for the remainder of the 8.5 sec trial. Participants used the buttons next to the respective UAV feed on the screen to indicate whether or not an intensity change had occurred.

Sixty-six percent of the trials involved an actual target, associated with either a visual or tactile change (‘change trials’), while the other 34% of the trials involved no change (‘no-change trials’). Presentations of visual and tactile changes were randomized for the nine video feeds and tactors.

[3] Measured with a Sekonic Model L-558 Cine light meter.
[4] Measured with a Quest Technologies VI-100 vibration meter.

Response to long range target indications

When video feed brightness or tactile cue intensity changed to the highest intensity level, indicating the presence of an actual threat, participants had to press the “Target” button in the top right hand corner of the respective UAV feed to indicate to Command Central the presence of a long range target. When, during a trial, there were no changes in brightness/intensity, participants were instructed to press the “No Target” button. If participants were unsure whether or not there was a change, they were asked to press the “?/Unsure” button. Participants could make a selection at any time during the 8.5 sec trial, with the final response being used for data analysis (See Figure 3-4 for each of the buttons).

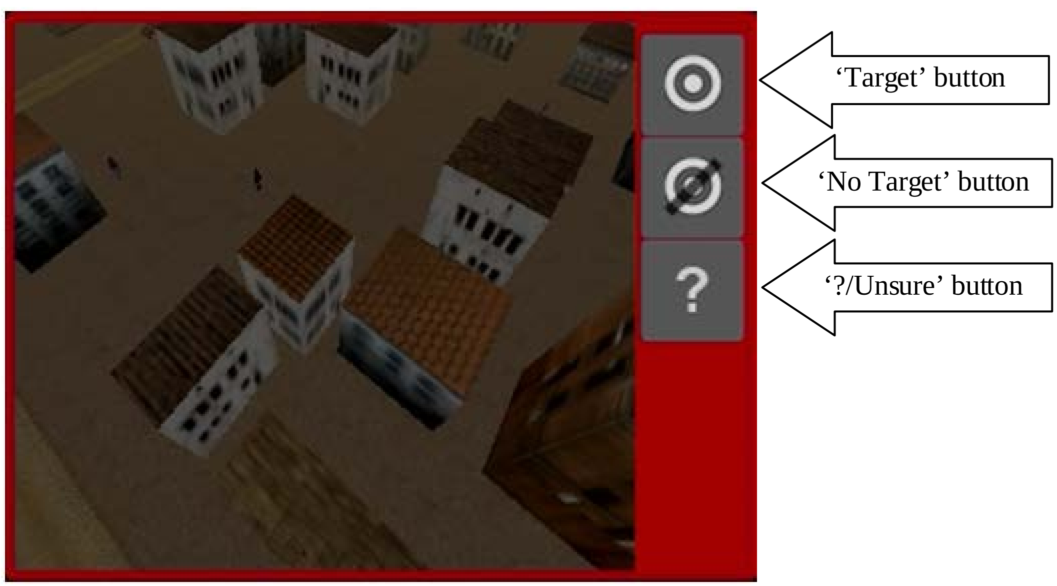

Figure 3-4: Zoomed in version of one of the nine UAV feeds with the response buttons

Change blindness paradigms: Flickers and mudsplashes

The flickers and mudsplashes used in this study were modeled after the paradigms used in earlier visual and tactile change blindness studies (see Chapter 1). Participants were told that the transient stimuli represented “bugs” or “interference” from the UAVs’ environment and to ignore them to the best of their ability. Pilot testing was used to ensure that the flicker and mudsplash transients were equally "salient" in both modalities (see the crossmodal matching methods described in Chapter 2). The visual and tactile transients occurred 2, 4, or 5 seconds after the start of a trial and lasted 750 msec. In the case of 'change trials', they overlapped completely in time with the visual or tactile change. For an illustration of the various cue-transient combinations included in this study, see Figures 3-5 and 3-6.

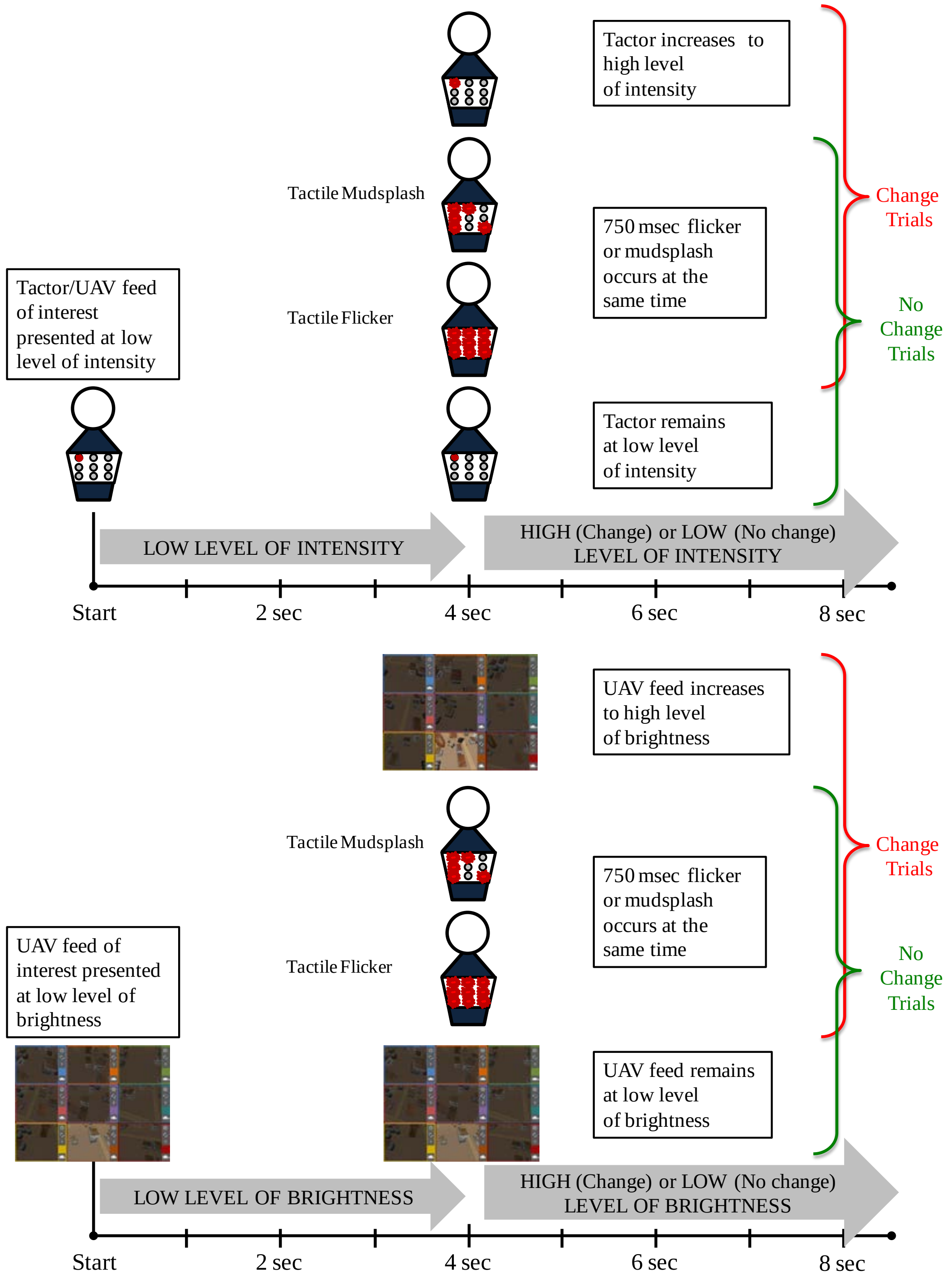

Figure 3-5: The six tactile transient cue-transient combinations (top: tactile transients with tactile cues, bottom: tactile transients with visual cues)

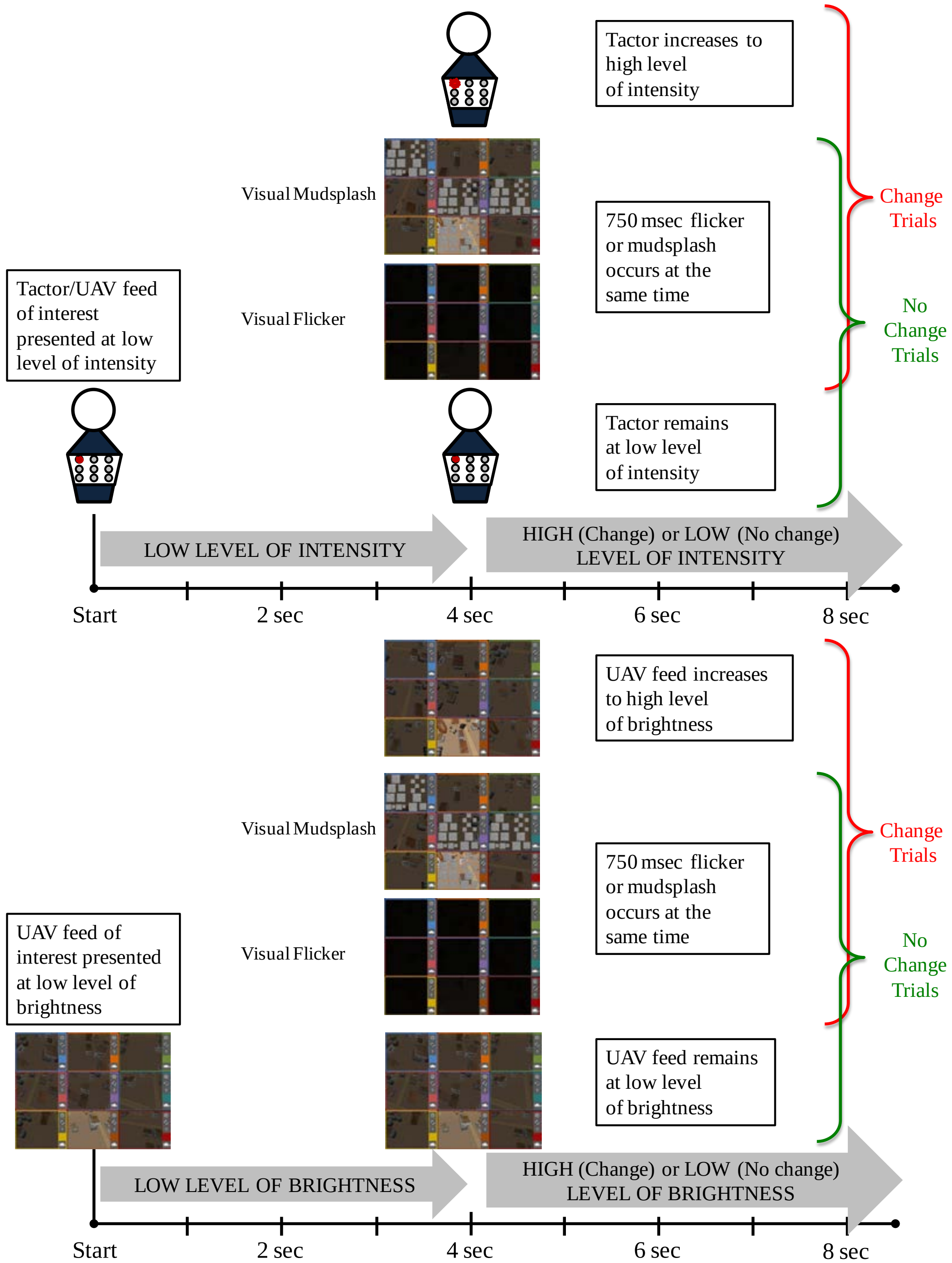

Figure 3-6: The six visual transient cue-transient combinations (top: visual transients with tactile cues, bottom: visual transients with visual cues)

In each of the two blocks – one dedicated to visual transients, the other to tactile transients – the six cue-transient combinations were randomized across the experimental trials. For both modalities, there were four ‘no-change’ trials for each cue-transient combination, seven ‘change trials’ each for the baseline combinations, and eight ‘change trials’ each for the combinations with a transient.

Procedure

Upon arrival, participants read and signed the consent form for the study. After a brief explanation describing the reason for conducting the study (i.e., the goal of the Department of Defense to drastically increase the UAV-to-operator ratio), the experimenter described the visual and tactile cues, the participants’ tasks, and then guided the participants through an interactive training session where the experimenter explained their tasks, cues and required responses.

Next, participants completed two 8-minute training sessions which allowed them to practice the visual and tactile baseline combination, i.e. the long range target/change detection task in the absence of concurrent transients. By the end of the second training session, participants were required to achieve at least 90% accuracy in determining whether a brightness or intensity change had occurred in the tactile or visual baseline combination, respectively. Upon successful completion of the training sessions, participants were shown a demonstration of the transients.

Participants were asked to wear headphones which were playing white noise to mask the sound of tactor activation. The participants then completed two blocks of trials: (1) 70 trials involving visual transients and (2) 70 trials involving tactile transients. Participants were provided a 5-minute break between blocks. Each block lasted about 13 minutes, and participants had to respond either to a visual or tactile change trial every 11.5 sec. The order of the two blocks was counterbalanced between subjects. In total, the experiment lasted about an hour.

Experimental design

This study employed an unbalanced nested design. The two main factors were transient modality (tactile, visual) and cue-transient combination (six for tactile transients (Figure 3-5) and six for visual transients (Figure 3-6). Within cue-transient combinations, there were two levels, that is, whether there was a cue change or no cue change. The design was unbalanced in the sense that there was an unequal number of trials for each cue-transient combination. Since this study was interested in change blindness, there were more 'change trials' (56% of all trials), compared to 'no-change trials' (44% trials) in each scenario.

Dependent measure

The dependent measure was accuracy (either detection of a change ("hit") or "correct rejection" when there was no change). Signal Detection Theory analysis measures, sensitivity (d') and response bias (c), were also calculated.

Results

Repeated measures linear models (General Linear Model formulation in SPSS 16.0) were used to identify main and interaction effects, and two-tailed Fisher's LSD post-hoc tests were performed to determine differences between means for significant effects. Performance data for each participant were first analyzed using Signal Detection Theory. Based on hits, misses, correct rejections, and false alarms, we calculated sensitivity (d`) and response bias (c) for each participant under each combination of factor levels.

Hit rate

Hit rates were defined as the percentage of trials in which the participant noticed and correctly reported a change. The hit rate values for Experiment 1 can be found in Figures 3-7 and 3-8. Hit rate was significantly affected by transient modality ($F(1, 10) = 9.382$, $p = .012$), cue-transient combination ($F(5, 6) = 13.680$, $p = .003$), and an interaction between transient modality and cue-transient combination ($F(5, 6) = 23.047$, $p = .001$). For 'change trials' involving tactile transients, the lowest accuracy was observed for the two intramodal tactile cue-transient combination (both 37%; $p < .001$); note that these two combinations did not differ significantly as a function of tactile transient type (flicker or mudsplash). Accuracy in the tactile baseline combination (80%) was significantly higher than for the two intramodal tactile transient cases, but lower than for the visual baseline and crossmodal visual-tactile combinations which all approached a performance ceiling ('visual cue, baseline,' $p = .027$; 'visual cue, tactile mudsplashes,' $p = .030$).

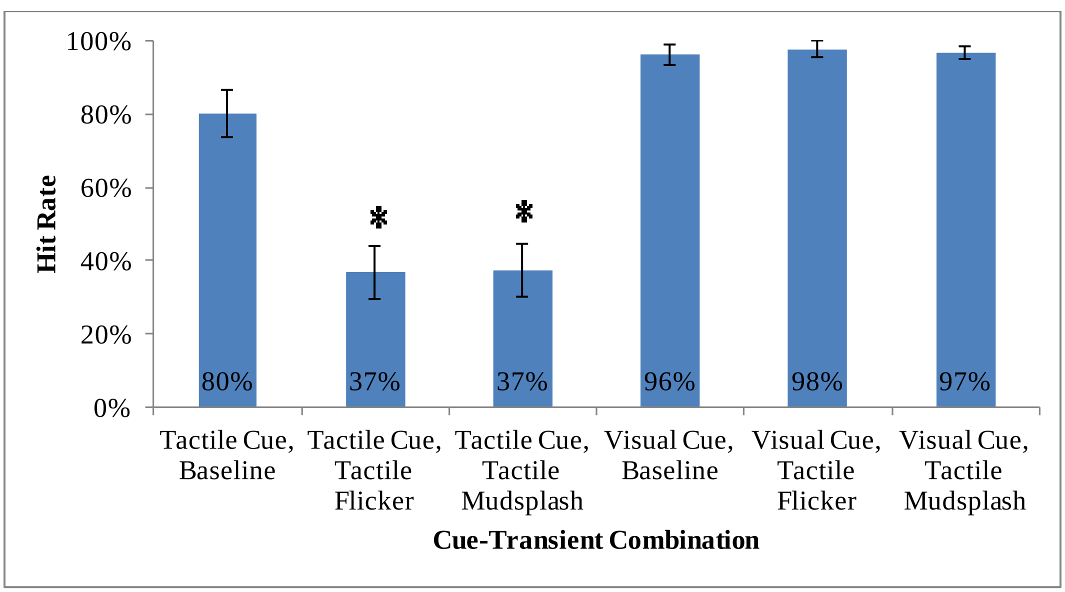

Figure 3-7: Hit rate for 'change trials' in the presence of tactile transients (errors bars represent standard error)

For trials involving visual transients, hit rates were again lowest for the two intramodal cue-transient combinations (visual flicker: 67%; visual mudsplash 72%; $p<.05$ in both cases), but these combinations did not differ from each other. Hit rates in all other combinations ranged from 93-97% detection, suggesting another ceiling effect (Figure 3-8).

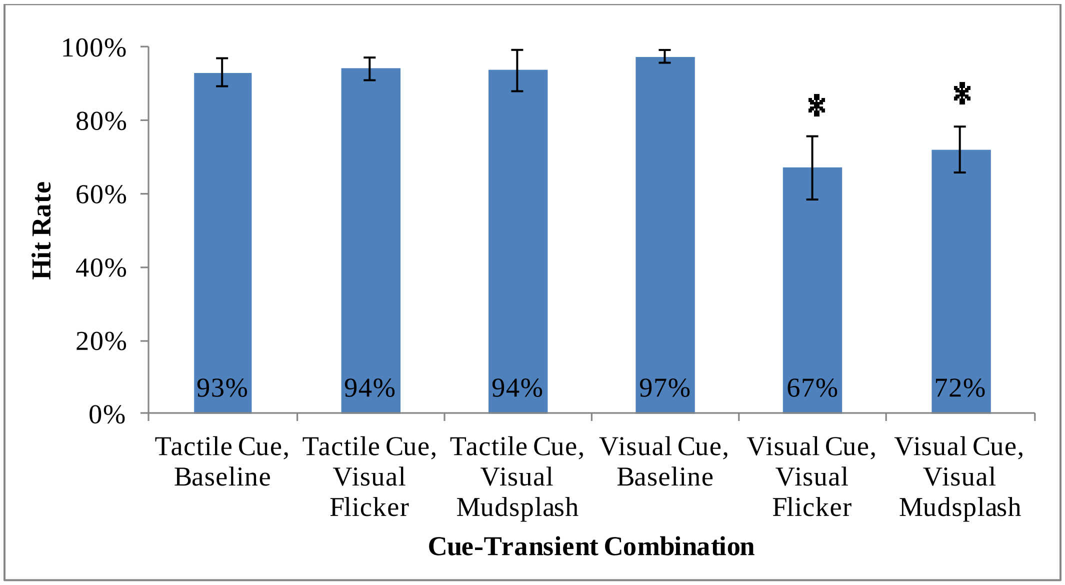

Figure 3-8: Hit rate for 'change trials' in the presence of visual transients (errors bars represent standard error)

Correct rejection rate

Correct rejection rate was defined as the percentage of 'no-change trials' to which participants responded correctly (i.e., indicating the absence of a change). Correct rejections were not affected by transient modality ($F(1, 10) = .742$, $p = .409$), cue-transient combination ($F(4, 7) = 2.467$, $p = .140$), nor was there a transient modality*cue-transient combination interaction ($F(4, 7) = .488$, $p = .745$). The correct rejection rates for both tactile and visual trials approached a ceiling, with accuracy ranging between 86-100%.

Sensitivity (d`) and response bias (c)

For the Signal Detection Theory analysis, misses were calculated by subtracting the hit rate percentages from 100%, and false alarm rates were calculated by subtracting the correct rejection percentages from 100%. The option to select the ‘?/Unsure’ button or not to respond at all was chosen in only 2% of all cases. Instances where the ‘?/Unsure’ button was chosen or no response was made were included in the ‘miss’ category for ‘change trials’ or the ‘false alarm’ category for ‘no-change trials’.

Figures 3-9 and 3-10 show the sensitivity (d`; bars associated with the left axis) and response bias (c; squares associated with the right axis) data for the tactile transient and visual transient combinations, respectively. Sensitivity, d`, is a measure of the ability to distinguish a signal from noise. Sensitivity was significantly affected by transient modality ($F(1, 10) = 12.026$, $p = .006$) and cue-transient combination ($F(5, 6) = 30.166$, $p < .001$). A transient modality*cue-transient combination interaction was observed also, such that the sensitivity was significantly different for the tactile and visual intramodal cue-transient combinations ($F(5, 6) = 16.301$, $p = .002$). In other words, d` was significantly lower in the intramodal visual and tactile combinations when a transient occurred, compared to all other combinations.

Figures 3-9 and 3-10 also show the response bias, c, which represents a top-down influence on decision making. The measure c refers to the readiness of a person to interpret a signal as a ‘target’ (a change; negative c values) or as ‘no target’ (nochange; positive c values). Response bias was significantly affected by transient modality ($F(1, 10) = 5.884$, $p = .036$) and cue-transient combination ($F(5, 6) = 17.193$, $p = .002$). More importantly, a transient modality*cue-transient combination interaction showed that c increased significantly in the intramodal tactile combinations only ($F(5, 6) = 27.520$, $p < .001$ for both pairwise comparisons). In those combinations, all c values were positive, indicating an overall tendency for participants to respond that a change had not occurred. In contrast, for trials involving a visual change, the c values approached zero, suggesting that participants showed no response bias.

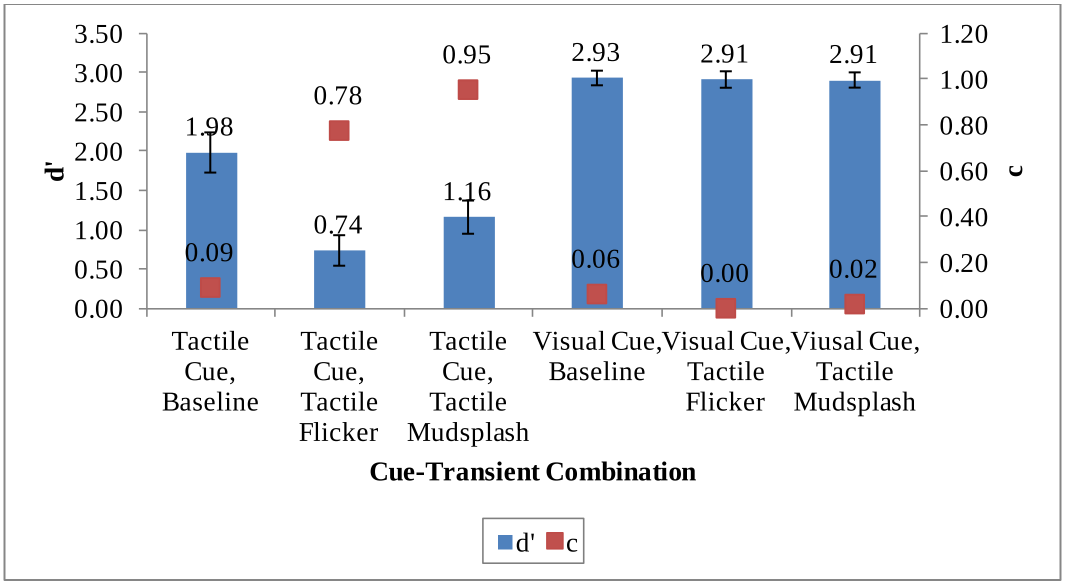

Figure 3-9: Sensitivity (d`) bars associated with the left axis and response bias (c) squares associated with the right axis for the tactile transient cue-transient combination (errors bars represent standard error for d')

For trials involving visual transients, c was again significantly higher in the two intramodal combinations, compared to all other combinations ($p < .05$ for all cases), but did not differ between the two intramodal combinations. The c value was also significantly higher in the tactile change-visual mudsplash combination, compared to the tactile change baseline case ($p = .019$).

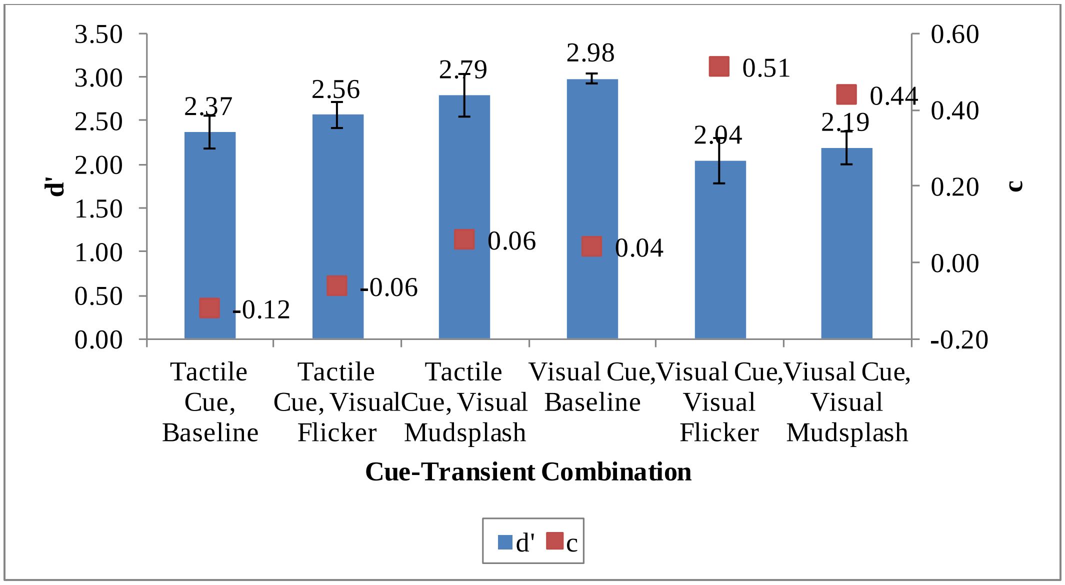

Figure 3-10: Sensitivity (d`) bars associated with the left axis and response bias (c) squares associated with the right axis for the visual transient cue-transient combination (errors bars represent standard error for d')

EXPERIMENT 2

In Experiment 2, we examined whether transient duration, and consequently the extent of simultaneous masking of the critical pulse, affects the ability to detect changes for the same intra- and crossmodal combinations employed in the first two studies. To that end, the transient length was shortened from 750 msec to 500 msec. This means that, in contrast to Experiment 1 where the transient completely overlapped in time with the critical pulse of a tactile cue (indicating either a change or no-change), participants could potentially perceive, in isolation, the last 250 msec of the pulse which might result in improved change detection and suggest a countermeasure to change blindness (Figure 3-11).

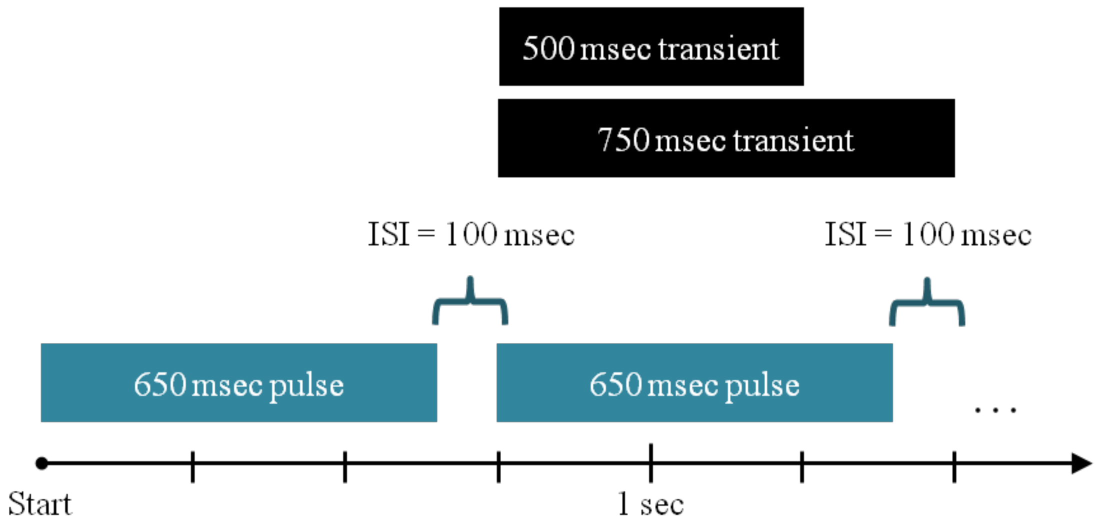

Figure 3-11: Comparison of partial overlap (750 msec transient; Experiment 2) and complete overlap (500 msec transient; Experiment 1) for tactile cues

Methods

Participants

Twenty undergraduate and graduate students from the University of Michigan participated in this study (8 males and 12 females; mean age = 22.5, stdev = 3.4). The requirements for participation were the same as for Experiments 1.

Experimental design, task, and procedure

The experimental design, procedure and dependent measures were the same as in Experiment 1. The same long range target detection task from Experiment 1 was used. However, in this experiment, the duration of all transients was shortened from 750 msec to 500 msec. Also for the tactile cues, highlighting the background of the respective UAV feed was added to direct attention (Hameed, Ferris, Jayaraman & Sarter, 2009; Prinet, Terhune, & Sarter, 2012; Lu et al., 2012, 2013) and ensure the participants used the appropriate buttons to respond to tactile trials. Participants in

Experiment 1 had commented on the potential for confusion about the location of the tactile signal when there was no visual highlighting of the relevant UAV feed. Pilot testing of tactile change trials with visual highlighting showed that it did not result in any performance differences for tactile cues, compared to Experiment 1. Finally, in this experiment, participants filled out a debriefing questionnaire which included questions about their fatigue level, the number of video games played per week, and how difficult it was to complete the long range target detection task under the various combinations. It also included open-ended questions about any strategies participants adopted to perform their tasks, and it was used to measure two personality dimensions: extraversion and conscientiousness (Goldberg, 1992). The 17 personality-related questions (eight related to extraversion and nine concerned with conscientiousness) were part of the abbreviated version of the big five assessment used at Pace University[5] (see Appendix 1 for details on the debrief). Overall, the experiment lasted about an hour.

Results

Hit rate

The hit rate values for Experiment 2 can be found in Figures 3-12 and 3-13. Shortening the transient length had no effect on hit rate ($F(1, 10) = 1.172$, $p = .304$). However, for the shorter 500 msec transients, hit rate was significantly affected by transient modality ($F(1, 19) = 54.611$, $p < .001$) and cue-transient combination ($F(5, 15) = 17.065$, $p < .001$). There was also a significant transient modality*cue-transient combination interaction ($F(5, 15) = 14.862$, $p < .001$). For trials with tactile transients, hit rates were significantly lower for the two intramodal cue-transient combinations, compared to all other combinations. The two intramodal combinations did not differ significantly from each other (tactile flickers: hit rate = 47%; tactile mudsplashes: hit

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[5] http://aomlists.pace.edu/scripts/wa.exe?A3=ind0710&L=ob&P=1479018&E=2&B=------%3D_Part_7661_26143781.1192142899802&N=Big+Five+Inventory.doc&T=application%2Fmsword

rate = 53%; p < .001 for all cases). Hit rate for the baseline tactile cue combination was significantly higher than in the two intramodal tactile cue-transient combinations, but significantly lower than for cases involving visual changes, all of which approached a performance ceiling (85%; p < .05 for all cases).

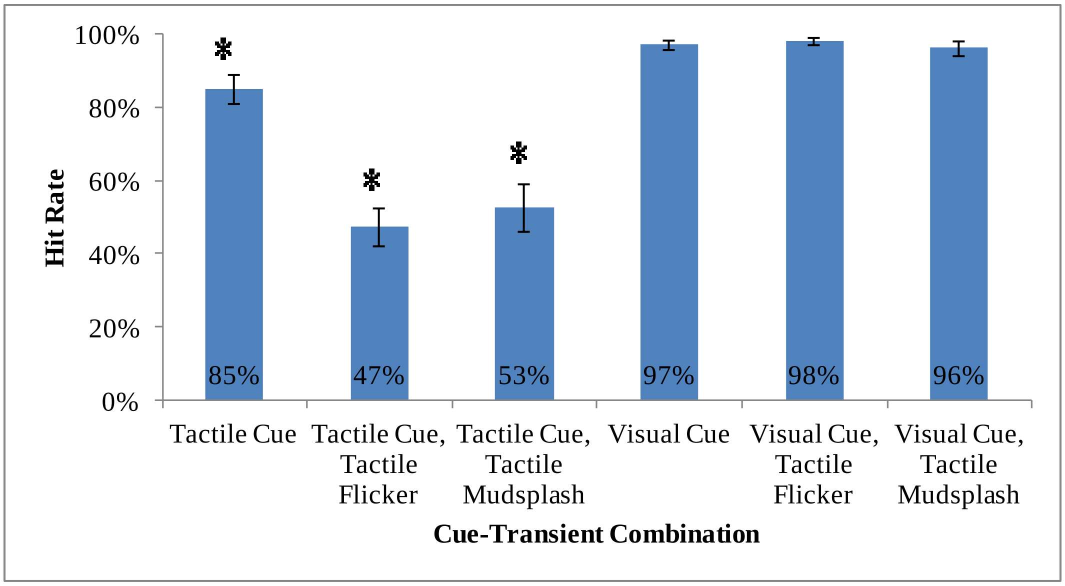

Figure 3-12: Hit rate for 'change trials' in the presence of tactile transients (errors bars represent standard error)

For trials involving visual transients, hit rates were significantly lower for the intramodal mudsplash combination (88%), compared to the baseline tactile and visual combinations (98%; p = .036 and 96%; p = .041, respectively).

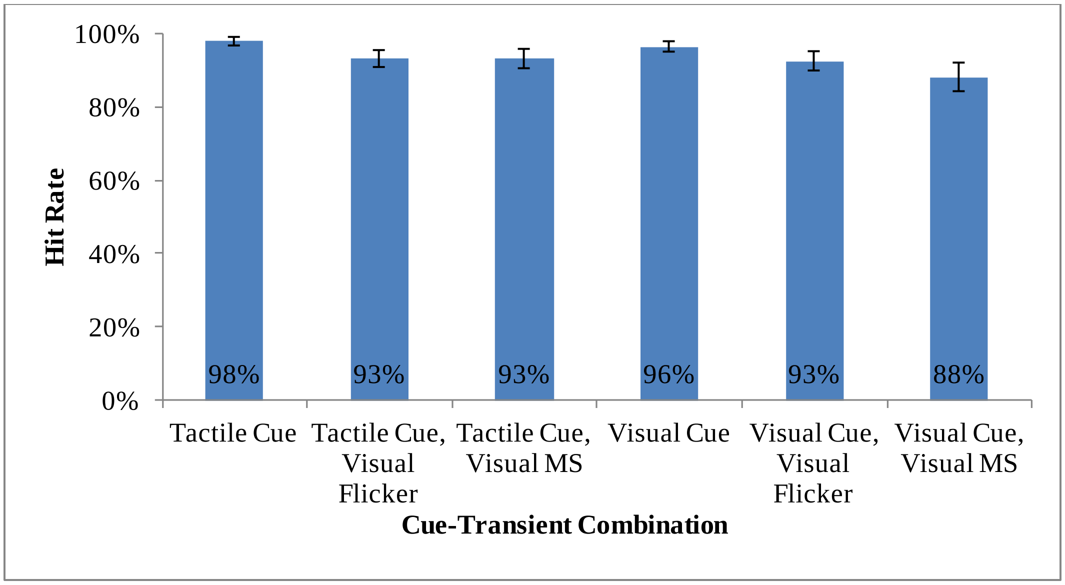

Figure 3-13: Hit rate for 'change trials' in the presence of visual transients (errors bars represent standard error)

Correct rejection rate

Comparing Experiment 1 and 2, there was no observed effect of shortening the transient duration on correct rejection rates ($F(1, 10) = 3.224$, $p = .103$). Also, when considering only Experiment 2, correct rejections were not affected by transient modality ($F(1, 9) = .798$, $p = .383$) or cue-transient combination ($F(5, 15) = 2.192$, $p = .110$), nor was there a transient modality*cue-transient combination interaction ($F(5, 15) = 1.219$, $p = .348$).

Sensitivity (d`) and response bias (c)

When comparing Experiments 1 and 2, a significant cue-transient combination*transient length interaction was found ($F(5, 6) = 6.562$, $p = .020$). Post hoc tests showed that sensitivity was higher with shorter transients for the following combinations: tactile cue with no transient (750 msec d` = 2.18; 500 msec d` = 2.70), tactile cue with a tactile or visual transient (750 msec d` = 1.65; 500 msec d` = 2.04), and visual cue with a tactile or visual transient (750 msec d` = 2.477; 500 msec d` =

2.865). In fact, there was a trend towards increased sensitivity for all combinations, suggesting that a change can be more readily detected when the transient length is shortened and the participant can perceive the last part of the signal in isolation.

Figure 3-14 and 3-15 show the sensitivity and response bias values for tactile and visual transients. For the 500 msec transients used in Experiment 2, sensitivity was affected by cue modality ($F(1, 19) = 88.939$, $p < .001$) and tactile transient type ($F(2, 18) = 8.784$, $p < .001$). A cue modality*tactile transient type interaction showed that for tactile transients, sensitivity was significantly lower in the intramodal cue-transient combinations (tactile flicker: d` = 1.44; tactile mudsplash: d` = 1.55). When considering visual transient combinations, sensitivity was affected by transient type ($F(2, 18) = 3.638$, $p = .047$), but not cue modality ($F(1,19) = .429$, $p = .520$) and nor was there was a cue modality*visual transient type interaction ($F(2, 18) = 1.331$, $p = .289$). Post hoc tests showed that sensitivity was lower when there were visual transients present (visual flicker: d` = 2.754; visual mudsplash: d` = 2.660).

With the shortened transient length, there was no effect of transient length on response bias ($F(1, 10) = .020$, $p = .891$). However when considering only the shorter transient length data from Experiment 2, response bias was significantly affected by cue modality ($F(1, 19) = 60.711$, $p < .001$) and tactile transient type ($F(2, 18) = 41.380$, $p < .001$). A cue modality*tactile transient type interaction indicated that response bias was significantly higher in the intramodal tactile cue-transient combinations ($F(2, 18) = 11.418$, $p = .001$). For visual transients, there was no effect on cue modality ($F(1, 19) = 1.006$, $p < .329$) nor visual transient type ($F(2, 18) = 1.323$, $p < .291$).

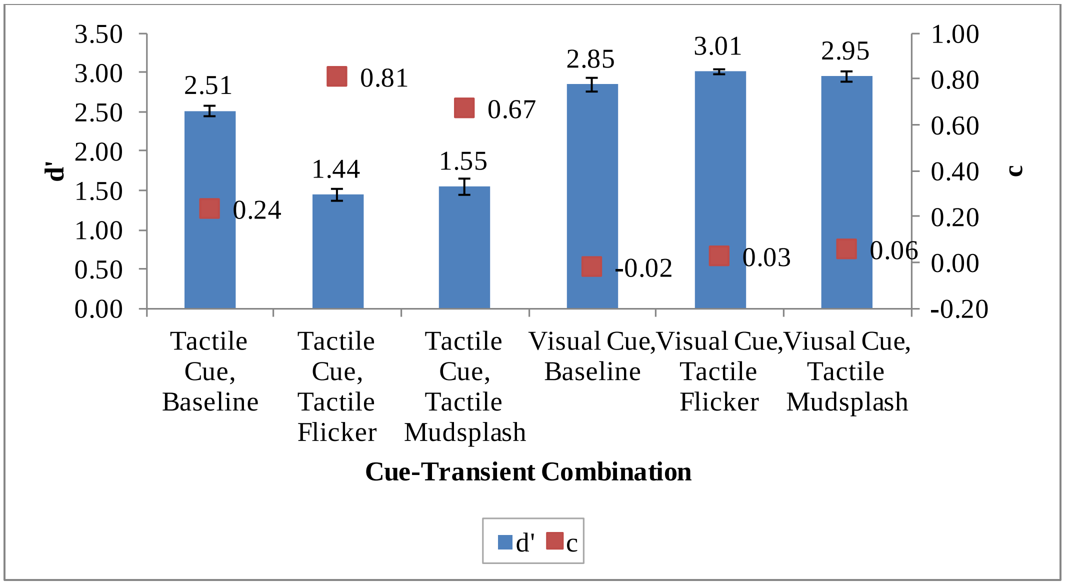

Figure 3-14: Sensitivity (d`) bars associated with the left axis and response bias (c) squares associated with the right axis for the tactile transient combinations (errors bars represent standard error)

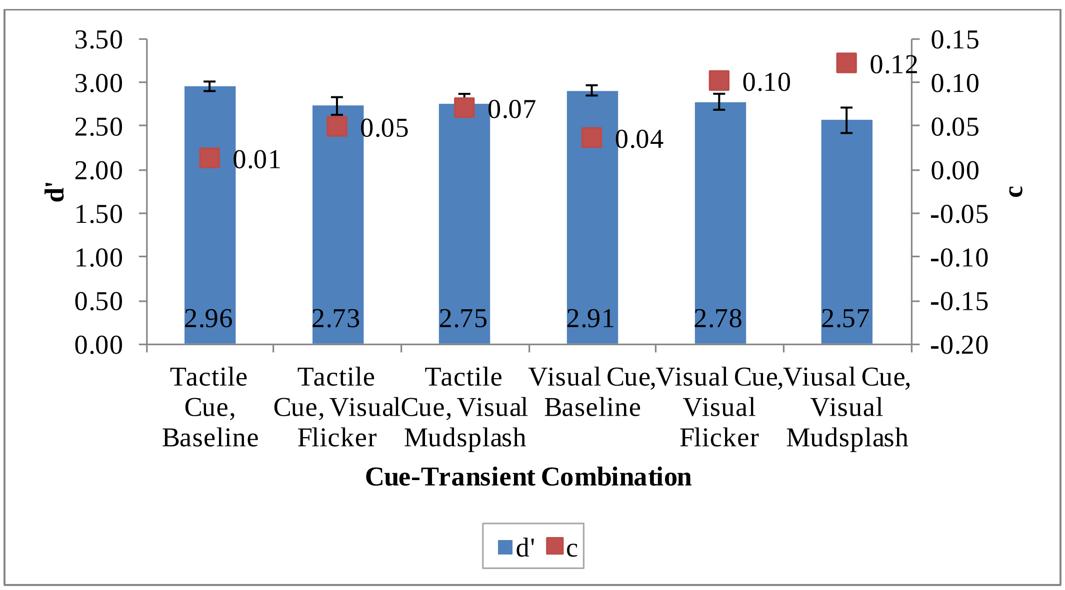

Figure 3-15: Sensitivity (d`) bars associated with the left axis and response bias (c) squares associated with the right axis for the visual transient combinations (errors bars represent standard error)

Debrief responses

Multiple regression analyses were run to determine whether hit rate accuracy for 'change trials' can be predicted based on participant's fatigue level, hours of video games played per week, extraversion level, and conscientiousness level. All of these variables predicted response accuracy for visual cue changes in the presence of a tactile flicker ($F(4, 15) = 2.86$, $p < .05$; adjusted $R^2 = 28.1\%$), but only extraversion level added statistically significantly to the prediction of response accuracy, ($p = .036$). The regression coefficients and standards errors can be found in Table 3-1.

Table 3-1: Summary of multiple regression analysis of hit rate accuracy for visual cue changes in the presence of a tactile flicker[6]

Variable	**B**	**SE_β**	**β**
Intercept	.435	.292	
Fatigue level	-.015	.018	-.177
Video games played/week	.007	.030	.050
Extraversion level	.016	.007	.497*
Conscientiousness level	.005	.007	.191

Answers to the open ended questions regarding difficulties and strategies participants adopted in performing the task suggested that a few participants felt that it was not easy to stay focused for the entire 13 minutes for the two experimental blocks. These comments further motivated us to conduct Experiment 3, where we added a second task in an attempt to keep participants engaged and alert and also examine the effects of competing task demands on change detection.

[6] * denotes $p<.05$, B = unstandardized regression coefficient; SE_β = standard error of the coefficient; β = standardized coefficient

Interim Summary of Findings: Experiments 1 and 2

Experiment 1 shows that change blindness occurs for both intramodal visual and intramodal tactile cue-transient combinations. However, when visual transients are shortened from 750 msec to 500 msec, visual change detection was affected only by visual mudsplashes while both transient durations for the intramodal tactile transient combinations result in lower detection rates. Correct rejections of 'no-change trials' were unaffected for all cue-transient combination in both experiments. Sensitivity and response bias were significantly different for intramodal combinations for both experiments, with lower sensitivity and higher response bias. When transient length was shortened from 750 msec to 500 msec, sensitivity on average increased for all cue-transient combinations, but there was no effect on response bias.

EXPERIMENT 3

In Experiment 3, our goal was to determine if adding a second search task would affect change detection in the visual and/or tactile modality. This is an important question because operators in many real world domains experience the need to timeshare two or more tasks; they need to divide their attention which may further exacerbate the problem of change blindness. This concern has not been addressed by change blindness research to date. Also, adding the second task may have helped combat the loss of alertness (Engstrom, Johansson, & Ostlund, 2005) which were some of the concerns voiced by participants in the open-ended portion of the previous experiment's debrief.

Methods

Participants

The same 20 undergraduate and graduate students from Experiment 2 participated in Experiment 3. To ensure there was no effect of training, half of the participants completed Experiment 3 on the first day and Experiment 2 on the second day. The requirements for participation were the same as for Experiments 1 and 2.

Experimental design and procedure

The experimental design and procedure were the same as in Experiment 2, except that participants in Experiment 3 were required to attend to two ongoing tasks. In all, the experiment lasted about an hour.

Participants' tasks

Participants had to perform the same long range target detection task as in Experiment 1, but they were also required to attend to a secondary visual search task for short range targets that appeared in the highlighted UAV feed. Short range targets included armed enemy soldiers, tanks, and other military vehicles (Figure 3-16 for examples). Participants were instructed to assume any of the suspicious activity spotted were enemies.

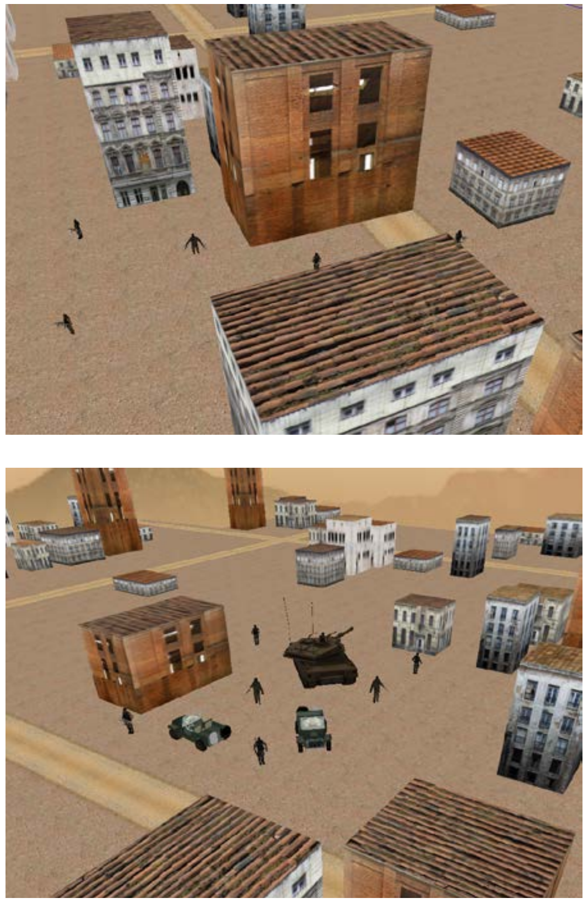

Figure 3-16: Examples of short range targets that would require participants to press the ‘tank’ button

As soon as the participants spotted any short range targets, they had to press the ‘tank’ button on the lower right-hand side of the video feed (Figure 3-17). They were instructed that both long and short range target detection were of equal importance. A short range target appeared in 22% of the trials.

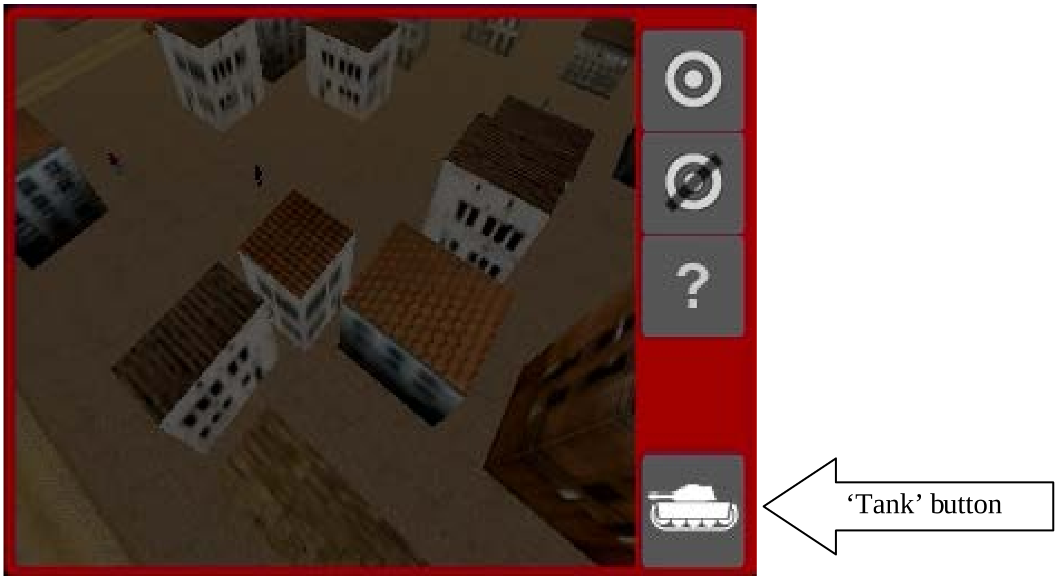

Figure 3-17: Zoomed in version of one of the nine UAV feeds with the tank button labeled

Results

Hit rate

The hit rate values for Experiment 3 can be found in Figures 3-18 and 3-19. Hit rate was again significantly affected by transient modality ($F(1, 19) = 41.727$, $p < .001$) and cue-transient combination ($F(5, 15) = 9.926$, $p < .001$), but not by the number of tasks participants had to perform (single versus dual task; $F(1, 19) = .101$, $p = .754$). There was a significant transient modality*cue-transient combination interaction ($F(5, 15) = 9.423$, $p < .001$), such that hit rate was significantly lower for the two intramodal tactile cue-transient combinations (tactile flickers: 47%; tactile mudsplashes: 49%, $p < .001$). These two cue-transient combinations were not significantly different from each other. Hit rates for visual changes in the crossmodal combinations were near perfect, ranging from 92-97%; they ranged from 92-97% in all six visual transient combinations.

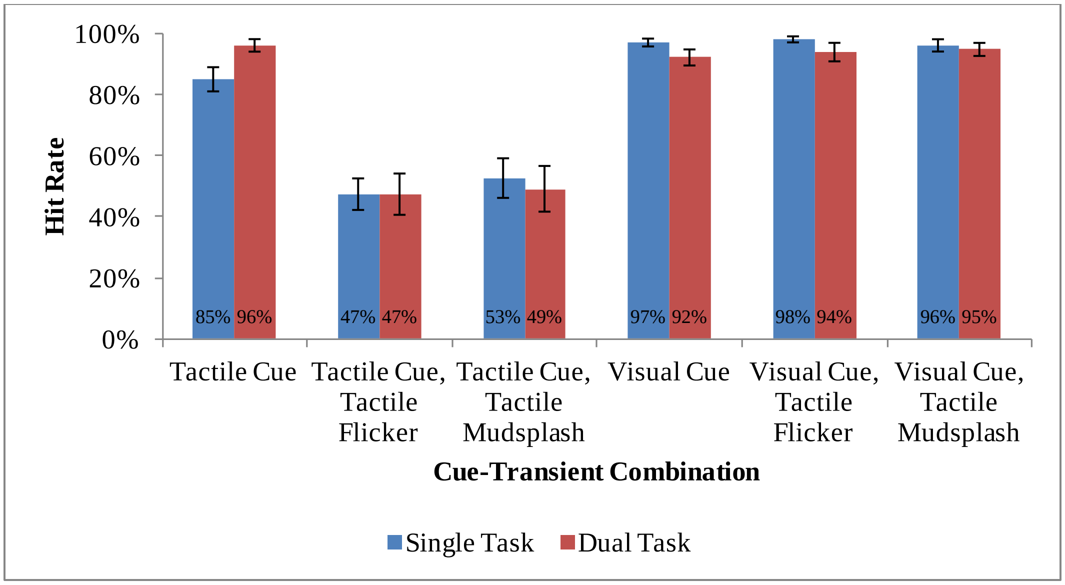

Figure 3-18: Hit rate for 'change trials' in the presence of tactile transients for single and dual task conditions (errors bars represent standard error)

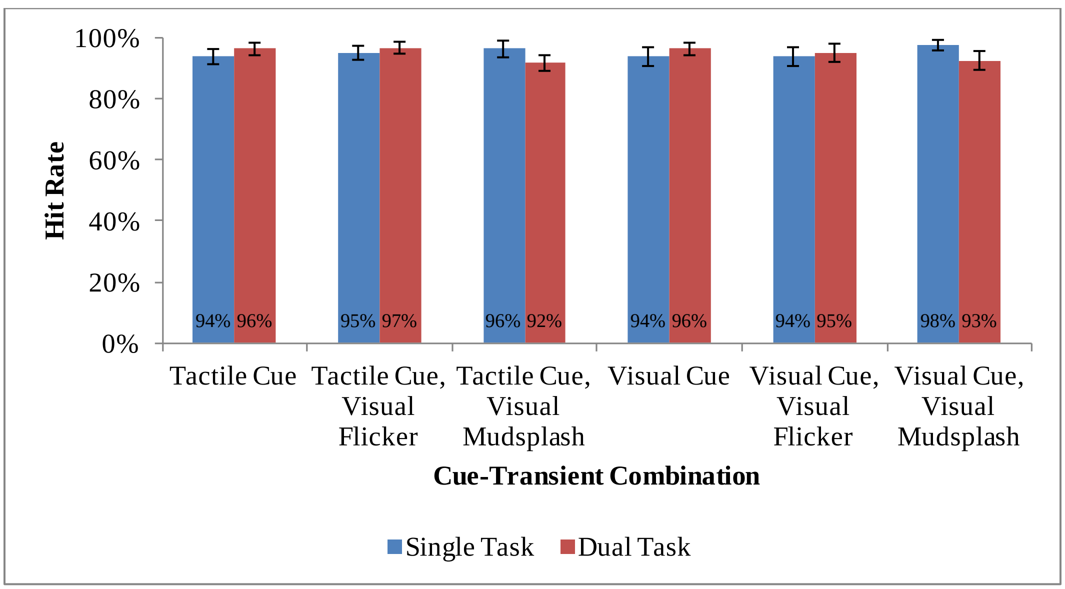

Figure 3-19: Hit rate for 'change trials' in the presence of visual transients for single and dual task conditions (errors bars represent standard error)

Correct rejection rate

The correct rejection rate values can be found in Figures 3-20 and 3-21. Correct rejection rates were significantly affected by the number of tasks ($F(1, 19) = 5.305$, p =

.033) with correct rejection rates being higher in the single-task (98%) than in the dual-task (95%) condition. Correct rejection rates were not affected by transient modality ($F(1, 19) = 1.149$, $p = .297$) or cue-transient combination ($F(5, 15) = .265$, $p = .925$), nor were there any two-way or three-way interactions between the factors ($p > .183$ for all cases). Note that correct rejection rates approached a ceiling.

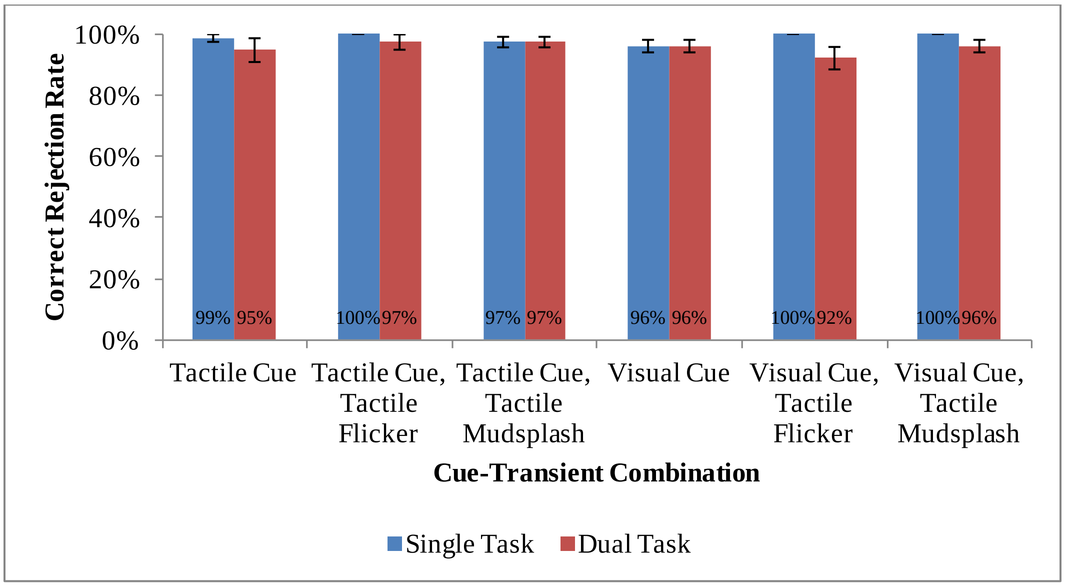

Figure 3-20: Correct rejection rate for ‘no-change trials’ in the presence of tactile transients(errors bars represent standard error)

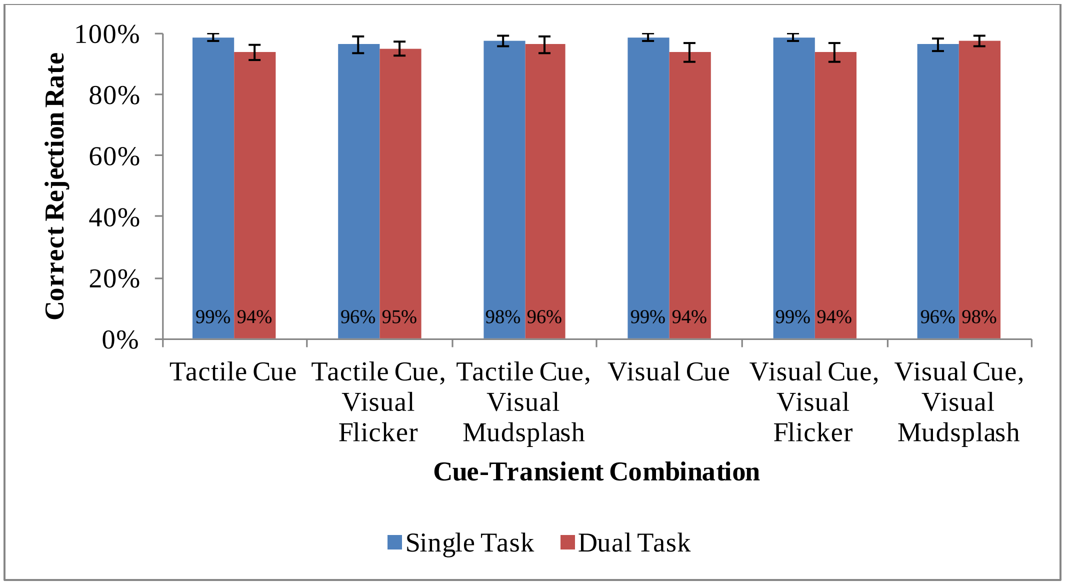

Figure 3-21: Correct rejection rate for 'no-change trials' in the presence of visual transients (errors bars represent standard error)

Sensitivity (d`) and response bias (c)

Figure 3-22 show the sensitivity (d`; bars associated with the left axis) and response bias (c; squares associated with the right axis) data for the tactile transient combinations. Adding a second task did not lead to any changes in sensitivity ($F(1, 19) = 1.227$, $p = .282$). However, considering only the results from Experiment 3, sensitivity was affected by cue modality ($F(1, 19) = 23.582$, $p < .001$), tactile transient type ($F(2, 18) = 7.172$, $p = .005$), and there was a cue modality*tactile transient type interaction ($F(2, 18) = 24.371$, $p < .001$; Figure 3-22). Sensitivity for the intramodal tactile cue-transient combinations was significantly lower than in the baseline tactile combination ($p < .001$ for both cases).

Response bias was affected by the addition of a second task in Experiment 3. It was higher in the single-task case ($c = .182$), compared to dual-task performance ($c = .121$; $F(1, 19) = 5.702$, $p = .027$). This suggests that, with the added second task, participants are closer to the ideal c value of zero and may be more likely to interpret a signal as a 'target' in the dual task condition. In the dual task case, response bias was significantly affected by cue modality ($F(1, 19) = 31.160$, $p < .001$), tactile transient type ($F(2, 18) = 15.034$, $p < .001$), and there was a cue modality*tactile transient type interaction ($F(2, 18) = 21.689$, $p < .001$). For tactile cues, response bias was significantly higher when there was transient present, compared to the tactile baseline combination when there were no tactile transients ($p < .001$ for both cases). There was no difference between c values for all other combinations, including visual transient ones.

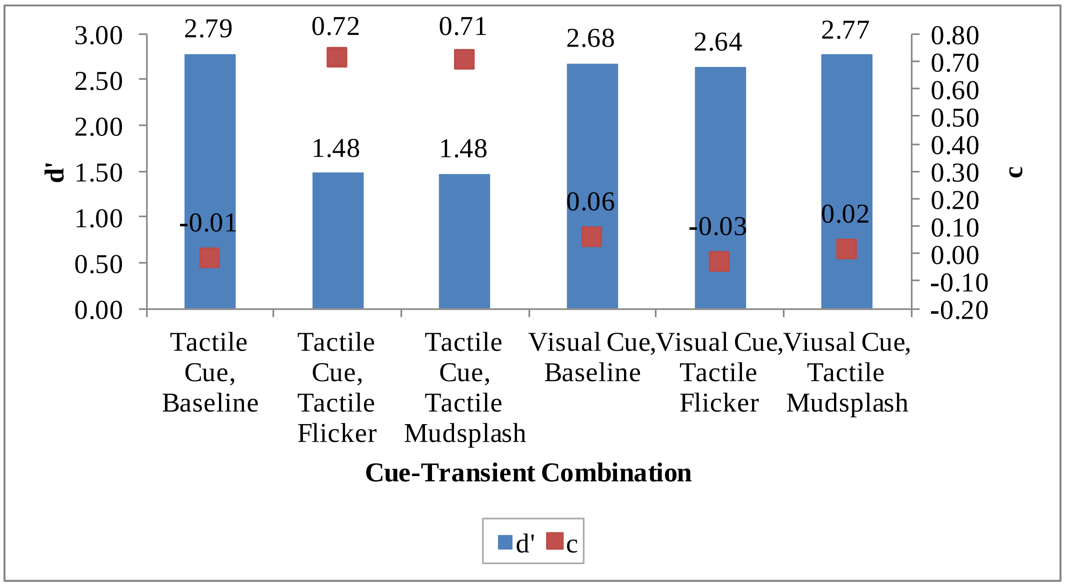

Figure 3-22: Sensitivity (d`) bars associated with the left axis and response bias (c) squares associated with the right axis for the tactile transient combinations (errors bars represent standard error)

Multitasking performance

So far, the data analysis has focused on the detection of long range targets overall. Figures 3-23 and 3-24 below show change detection performance (i.e. long range target detection) for only those cases where a long range target coincided with a short range target. In the tactile transient block, the number of tactile changes dropped significantly (75%) in the presence of a short range target. This suggests that in the ‘no-change trials’, participants had a difficult time or forgot to attend to concurrent visual tasks when tactile transients could potentially occur. For all other combinations, hit rates and correct rejections were high for visual and tactile changes. For the ‘change trials', there appears to be an intramodal trend, where multitasking performance was worse when the cue and transient were both the same modality. Figure 3-25 show that short range target detection performance was not significantly different between tactile and visual transient blocks ($p > .20$).

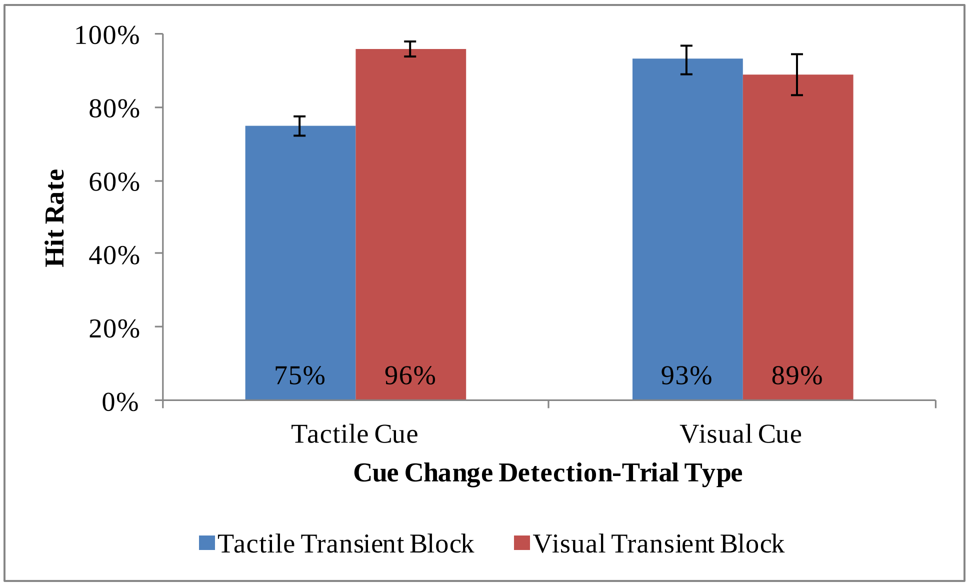

Figure 3-23: Hit rate for 'change trials' when a short range target was present (bars respresent standard error)

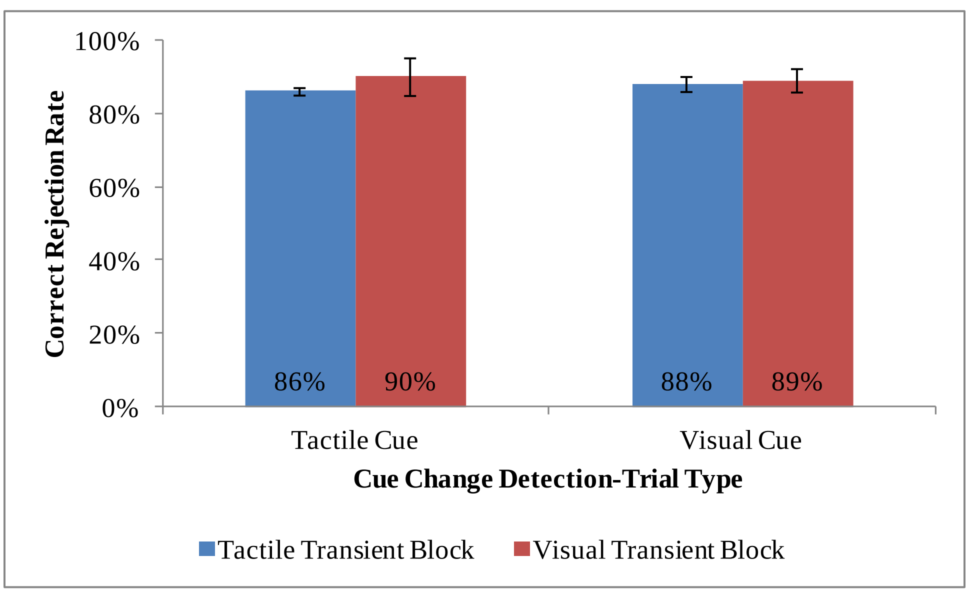

Figure 3-24: Correct rejection rate for 'no-change trials' when a short range target was present (bars respresent standard error)

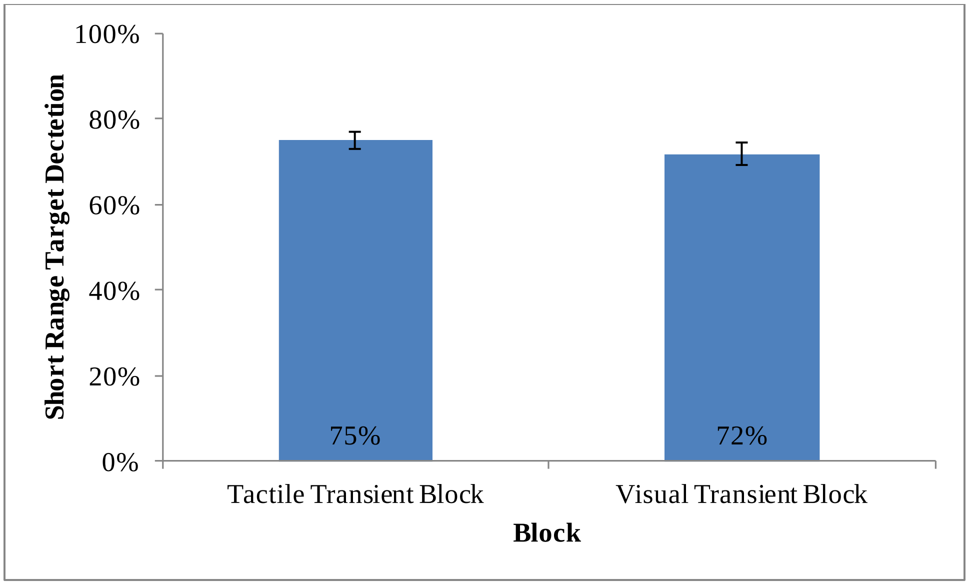

Figure 3-25: Short range target detection rates for both tactile and visual transient blocks (bars respresent standard error)

Debrief responses

Multiple regression analyses found that participants' fatigue level, hours of video games played per week, extraversion level, and conscientiousness level were not able to predict hit rates to 'change trials' when a second task was added.

Interim Summary of Findings: Experiments 2 and 3

Overall, the addition of a second task did not significantly affect hit rates; however, intramodal tactile change blindness was still observed with the second task. The addition of a second task had a negative effect on correct rejection rates, but note that these rates were overall very high in both single and dual task scenarios, ranging between 92-97% across all tactile and visual transient cue-transient combinations.

Sensitivity was lower and response bias was higher for the intramodal tactile and visual cue-transient combinations. Response bias was lower in the dual task scenario, compared to the single task scenario. Also, multitasking performance was significantly worse in the intramodal tactile combination, i.e. when a tactile cue appeared simultaneously with a tactile transient in the presence of a short range target.

Discussion

The introduction of tactile and multimodal displays has been advocated as a promising means to offload the visual channel which is overburdened in many complex data-rich domains. To ensure the effectiveness of these displays, their design needs to take into consideration perceptual and attentional abilities and limitations, such as the potential for change blindness which, to date, has been studied primarily in vision. The goal of the three experiments described in this chapter was to determine whether and under what circumstances intramodal tactile, intramodal visual, and crossmodal tactile-visual change blindness occur and how it is affected by transient type, transient duration, and task demands.

Intramodal visual change blindness

First, we replicated, to some extent, the widely studied phenomenon of intramodal visual change blindness in our research. In both Experiments 1 and 2, the phenomenon was observed in the presence of visual mudsplashes which adversely affected hit rates, decreased sensitivity, and increased response bias.

In Experiment 3, there was no intramodal visual change blindness when the transients were shortened from 750 msec to 500 msec. This finding may be explained in various ways. One possibility is that longer transients more strongly affect the development of visual representations during early stages of visual processing (Rensink, 1997). According to the coherence model (Rensink et al., 1997; Rensink, 2000), consciously recognizing a change requires focused attention during these early stages. The coherence theory suggests that: (1) since only a small number of items can be given focused attention, most of the image will not a have a coherent representation, and (2) if attention is not drawn to the location of a change, then the change will likely not be seen. Focused attention can withstand brief interruptions but a longer transient may have interfered with encoding and/or developing a visual representation (Rensink, O'Regan, & Clark, 2000; Rensink, 2002).

Previous studies consistently induced change blindness with both visual flickers and mudsplashes, but in our experiments, this was the case only with the longer 750 msec transients. When tactile cues were accompanied by visual highlighting in Experiment 2, change detection with the mudsplash paradigm was significantly lower compared to when there was no transient present. It is possible that mudsplashes continued to affect performance because the random set of stimuli characteristic of this type of transient more strongly draws attention away from a change, compared to a more uniform flicker.

Another possible reason why visual change blindness disappeared in Experiment 3 is the nature of the visual stimuli in this study. Visual change blindness has been documented primarily when participants were required to detect changes to one element in complex scenes/displays consisting of five or more stimuli (Rensink et al., 2000). In contrast, the changes in the present study involved a change that was global in nature – a change in the background brightness of the UAV feed of interest. In the case of global visual changes, the number of visual stimuli that need to be encoded is reduced to one – a much easier and more easily automated task.

Also, global changes can be perceived in peripheral vision and are thus detected faster and more reliably than local ones (Austen & Enns, 2000; Jonides & Irwin, 1981; Navon, 1977) Previous work has shown that peripheral visual stimuli elicit an automatic shift of attention and are effective in capturing attention (Jonides, 1981). In the context of aviation, for example, Nikolic and Sarter (2001) showed that local changes (in this case, changes to alphanumeric Flight Mode Annunciations (FMAs) on the Primary Flight Display) led to poor detection performance. However, when a bar was introduced that extended horizontally across two displays in front of the pilot and changed color in case of an FMA transition, pilots detect nearly all changes. The bar represented a more global change and could be seen in peripheral vision, independent of head orientation or fixation.

Intramodal tactile change blindness

Intramodal tactile change blindness was observed across all experiments. The presence of tactile transients adversely affected tactile change detection, decreased sensitivity, and increased response bias, which confirms the findings from a number of previous studies that showed the same trend (Auvray, Gallace, Hartcher-O'Brien, Tan, & Spence, 2008; Gallace, Auvray, Tan, & Spence, 2006).

One explanation for tactile (and visual) change blindness is due to a lack of awareness of where the change will occur (Thornton & Fernandez-Duque, 2002; Gallace, Tan, & Spence, 2006). However, the findings from this study do not support this notion. Here, tactile changes were accompanied by visual highlighting which, by exploiting crossmodal spatial links between vision and touch, indicated the location to participants. Tactile cueing of visual attention has shown to be effective (Ho, Tan, & Spence, 2005; Jones, Gray, Spence, & Tan, 2008), however, visual cueing of tactile stimuli has received much less attention. The findings from this body of work may imply inherent differences between the two modalities and the benefits of cueing between modalities may not be equivalent.

Previous studies have also demonstrated that longer masking intervals may adversely affect the ability to hold a detailed representation of the tactile signal in short-term memory (Gallace, Tan, Haggard, & Spence, 2008) – a prerequisite for step 4 in the change detection process (comparing the representation from the target before and after the change; Jensen et al., 2011). However, the findings from this study show that both 750 and 500 msec transient lengths resulted in the same performance decrements. In fact, even shorter transients have elicited tactile change blindness (10 msec; Gallace et al., 2007). This suggests that there are inherent differences in encoding a target between the two channels. For example, it takes less than a second to capture the general idea of a visual scene (Biederman, Rabinowitz, Glass, & Stacy 1974; Thorpe, Fize, & Marlot. 1996), although it is argued that such a representation may not be very detailed or complete (Rensink, 2002; Rensink et al., 1997, 2000). Tactile encoding, on the other hand, requires sampling the objects in a scene one at a time and a representation of the scene is subsequently built by integrating the inter-object relations over time (Newell, Woods, Mernagh, & Bülthoff, 2005). Also, previous studies examining tactile change blindness have shown that change detection is adversely affected when the pre- and post-change display is separated by a blank inter-stimulus interval (Gallace et al, 2005; 2006; 2007). This suggests that the design of tactile displays needs to prevent any form of disruptions that may interfere with developing a mental representation in order to maximize the likelihood that a tactile change is detected.

It is important to note that tactile change detection is affected not only by the presence of a transient or blank interval present, but also by the length of the tactile target that is to be detected and encoded. When the time between the onset of the transient and the onset of the change is very short, the masking effect is the strongest and leads to very poor tactile change detection (Craig & Evans, 1995; Sherrick & Cholewiak, 1986). In all three experiments described in this chapter, the maximum change blindness effect was seen when the onset of the transient and the onset of a change coincided. Thus, our findings confirm previous work and add to it by demonstrating that this effect is particularly strong for the case of intramodal change detection.

It is also worth noting that the tactile transients used in this study were of a higher intensity than the two levels of the tactile cue, which may have contributed to tactile change blindness. The tactile mudsplashes and flickers have characteristics, i.e. motion properties (by appearing) and higher intensity levels, that can garner attention better than a change at the target (Breitmeyer & Ganz, 1976). This supports the idea that the masking effects from flickers and mudsplashes inherently draw more attention compared to changes in the tactile display (Rensink et al., 1997; Franconeri, Hollingworth, & Simons, 2005; Gallace, Tan, & Spence, 2007). The finding may also suggest that change blindness occurs due to a limited capacity affecting information processing when there is multiple stimulation from transients (Gallace et al., 2007; Wright, Green, & Baker, 1999).

Crossmodal change blindness

Because the introduction of tactile displays may be most beneficial in environments that heavily load the visual channel, we also examined crossmodal visual-tactile change blindness. Previous studies have shown that the detection of changes to visual and tactile displays was impaired by a transient in the other modality (Auvray, Gallace, Tan, & Spence, 2007a); however, in our own research, there was not a statistically significant crossmodal effect. This may be attributed to the fact that intramodal transients are more effective in drawing attention to themselves than transients from another modality. This supports previous work from the literature that have shown that when transients share the same sensory modality, the transients have a more detrimental effect on change detection (Gallace et al., 2006).

The lack of a crossmodal effect may be explained by differences between the nature of cues and transients used in this chapter versus previous studies examining crossmodal change blindness. Recent research by Gallace et al. (2006) has shown that observers often fail to detect the presence of positional changes between two sequentially-presented vibrotactile patterns on the body surface not only when vibrotactile distractors are used to mask the change, but also crossmodally when visual distractors are used. In those studies, the tactile display was distributed across the body which required coding of the spatial position of the tactile stimuli – an important aspect missing from the present body of work where the change consisted of a modulation of intensity rather than location change.

Based on previous work, a crossmodal change blindness effect was expected since there was a one-to-one spatial mapping of the visual and tactile displays. The failure to find this effect may be attributed to the lower complexity of the cues used in this experiment, compared to previously published studies. Attentional and mental resources involved in processing spatial information may be shared between modalities, resource competition may be higher for more complex spatial information.

Effects of multitasking

The addition of a second task in the context of both visual and tactile change blindness have not been studied extensively in the literature, but is important because it replicates demands in most real world domains (aside from Ferris et al., 2010). In Experiment 3, there were no significant differences in change detection rates between single- and dual-task conditions. In fact, the majority of participants performed better or equally as well in the presence of the second task, which supports previous findings showing that tactile change detection rates were not adversely affected when the participants had to concurrently attend to the change detection task and an intubation task (Ferris, Stringfield, & Sarter, 2010). The second task did have a significant effect on correct rejection rates; however, it is worth noting that these rates were high for all cue-transient combinations in both single and dual task conditions, ranging between 92-97%.

One reason why multitask performance was unaffected may be that the indications associated with long range targets were global in nature and could be perceived in peripheral vision; in contrast, the short range targets were local and required foveal vision. According to Multiple Resource Theory (MRT), resource competition is avoided in this case. Attentional resources differ along four dimensions, one of which is the dimension of modality. The visual modality, in turn, can be further subdivided into ambient and focal vision, two subsystems which draw from separate pools of attentional resources. Thus, resource competition does not occur when a foveal and peripheral visual task are performed in parallel.

Another interesting finding from this experiment was that response bias was significantly lower when a second task was added. In other words, participants were more likely to indicate the presence of a change. One possible explanation for this finding is that, for the single task condition, several participants commented that it was difficult to remain focused on the long range change detection task for the entire 13-minute block. The addition of a second rather engaging task increased workload and thus may have prevented vigilance decrements.

Sensitivity was higher when participants had to attend to two tasks which may be due to the strategy some participants adopted. Some participants noted in the debrief that at the start of each trial they would immediately select “no change” and would stick with selection until they noticed a change in case they later became preoccupied with the second task. Thus overall, participants may have been more willing to err on the conservative side of saying “no target” to ensure they did not miss an indication from competing task demands with the second task.

Individual differences

To gain a better understanding of the role of inter-individual differences in change blindness, a number of variables, namely participants’ fatigue level, hours of video games played per week, and personality traits (extraversion level, conscientiousness level), were explored as potential predictors of change detection performance. The only variable that predicted visual change detection rates in the presence of a flicker (i.e. visual cue-visual flicker cue-transient combination) was extraversion. This supports previous findings which suggest that extroverts are better at dividing their attention between information from multiple sources (Oron-Gilad, Szalma, Thropp, & Hancock, 2005). Individual differences did not predict hit rates for any cue-transient combinations for the case of dual task performance.

Conclusion

Overall, the results from these experiments consistently demonstrate the existence of an analog of visual change blindness in the tactile modality. This finding highlights the need for developing countermeasures to the phenomenon to ensure the robustness of tactile and multimodal displays. Chapter 4 is dedicated to the development and evaluation of three such countermeasures.

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Chapter 4

Development and Evaluation of Countermeasures to Tactile Change Blindness

Introduction

The failure to detect a tactile change when it coincides with a tactile transient, occurred in all three experiments described in Chapter 3. These findings highlight that change blindness represents a significant concern for the effectiveness of tactile and multimodal interfaces. To address this concern, the following chapter focuses on the development and evaluation of three design-based countermeasures to tactile change blindness. These countermeasures relate to the cognitive steps involved in successful change detection, as outlined in the Introduction (Jensen, Yao, Street, & Simons, 2011). One of them is proactive in the sense that an alerting signal is presented in advance of a possible change to guide the operator's attention; the other two are reactive and adaptive in nature, i.e., signals change in response to the absence of detection by the software.

The first part of this chapter describes and details the design of the three countermeasures in some detail. Next, the expected effects of these countermeasures, in terms of detection rates and participants' preferences, are stated. Finally, an empirical study to test these hypotheses are described.

Proposed countermeasures to tactile change blindness

As described in the Introduction, successful change detection involves five steps: (Jensen et al., 2011):

1) Direct attention to the change signal/location.
2) Encode into memory what was shown at the target location before the change.
3) Encode what is presented at the target location after the change.
4) Compare the mental representations of the information at the target location before and after the change.
5) Consciously recognize the discrepancy.

The three countermeasures we developed as part of this line of research are intended to support various combinations of steps 1, 2, 3, and 4. Since attention is necessary for change detection (Simons, 2000), all three countermeasures were designed to direct attention to the change, thus supporting step 1. The first countermeasure, "attention guidance," is proactive: it consists of increasing the frequency (i.e., the pulse rate) of the tactile cue right **before** a potential change with the goal to support encoding of the pre-change cue intensity (step 2). The second and third countermeasures are reactive, i.e., they are triggered by an observed failure to notice a change. Countermeasure 2 – "signal gradation" – involves a further increase in the intensity of the tactile signal following a missed change. The third countermeasure – "direct comparison" – presents the participant with a tactile signal first at the low (pre-change) and then the high (post-change) intensity, with no interval separating the two, if a change was missed. This approach is expected to improve detection rates by supporting relative (as opposed to absolute) judgments and comparisons of cue intensities before and after a change.

The second and third countermeasure represent examples of context-sensitive or, more specifically, adaptive information presentation where the timing, form, is adjusted for the user in a context-sensitive fashion (Trumbly, Arnett, & Johnson, 1994; Scerbo, 1996; Sarter, 2007). The need for context-sensitive information presentation has been widely acknowledged (Bennet & Bennet, 2001; Dorneich, Whitlow, Ververs, & Rogers, 2003; Schmorrow & Kruse, 2002). However, no consensus has been reached on the most appropriate and effective approach to, and implementation of, flexible information presentation. Two important questions in this context are the appropriate type and driver (in this case: an observed breakdown in detection performance) of the adaptation.

Gradation – the type of adaptation used for the second countermeasure – consist of signals that differ, or vary over time, in terms of their salience or intensity to reflect differences or changes in the urgency of the underlying task or event. This approach has been shown to be much more effective than binary alarms (such as the change events in our earlier experiments) for supporting operator performance. For instance, Lee, Hoffman, and Hayes (2004) contrasted graded and single-stage tactile warnings in the context of a driving task as part of a collision warning system. The intensity of three tactile warnings (vibrations of the seat) changed over time and corresponded to the severity of the required braking action, i.e., high, medium, or negligible. The authors found that graded warnings led to an increased minimum time to collision, indicating a greater margin of safety compared to the single-stage warnings. We adopted a similar approach here by further increasing the intensity of the signal following a missed change (the equivalent of a driver not braking in response to the first seat vibration in the Lee et al., 2004 research). The findings from the earlier experiments highlight that simply repeating the tactile signals (after the change) at the same intensity is not sufficient.

Countermeasure 3 is adaptive also in the sense that it is triggered by a failure of the participant to notice a change in signal intensity. In this case, however, the tactile signal following the change is applied first at the low (pre-change) and then the high (post-change) intensity, with no interval separating the two. The goal here is to support step 4 (in addition to step 1) – the comparison of the information before and after the change – but to do so without requiring a prolonged retention of a mental representation of the initial signal. Instead, the participant can make a relative judgment of the two signals presented side-by-side.

Hypotheses

We expected the three countermeasures to have the following effects on participants' performance and preferences:

1) All three countermeasures are expected to lead to improved performance, compared to no countermeasure in terms of higher hit rates and better multitasking performance.
2) Correct rejection rates will be higher with 'attention guidance' because this countermeasure is triggered in advance of a change and prepares the participant for making a decision.
3) Of the three countermeasures, the two adaptive displays – signal gradation and direct comparison – will be preferred over 'attention guidance' because the latter will result in some false alarms.
4) The overall response bias will be higher with the two adaptive countermeasures as participants can rely on the system to alert them if they miss a change.

Methods

Participants

Twenty undergraduate and graduate students from the University of Michigan participated in this study (13 males and 7 females; mean age = 22.8, stdev = 2.8). Participants were required to possess normal or corrected-to-normal vision, have no known disorders or injuries that may impair their sense of touch, and have no history of epilepsy (flickering displays may trigger epileptic seizures).

Tasks and countermeasures

As in Experiment 3, participants had to timeshare between the long range and short range target detection tasks described in those sections. However, in this study, the tactile cues indicating the presence of a long range target could take the form of either the baseline version or one of the three countermeasures described in the previous section. The three countermeasures were pilot tested to ensure that they could be reliably detected and accurately interpreted by participants.

Countermeasure 1: Attention guidance

The first countermeasure – 'attention guidance' – was proactive and occurred across all tactile cues, for both change and 'no-change trials'. The cue consisted of pulses at a rate of 1 pulse/150 msec for two seconds to prepare the participant for a potential change. Figure 4-1 provides a depiction of the attention guidance cue and its relation to when an intensity change occurred (see Figure 4-2 for 'no-change trials').

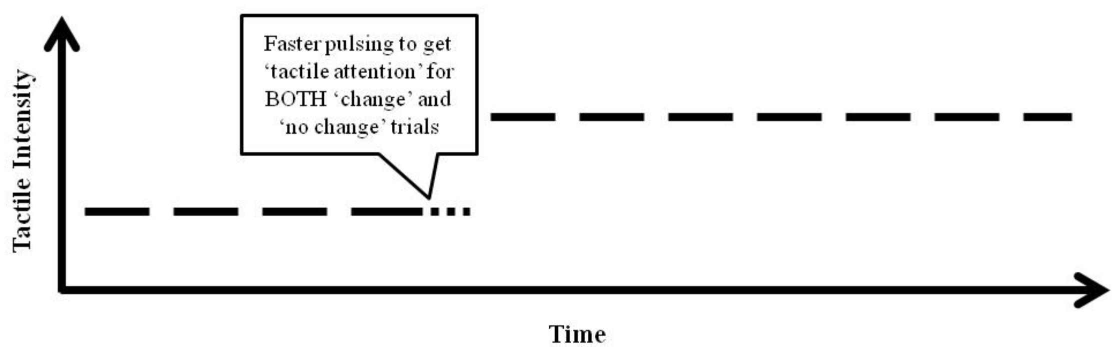


Figure 4-1: Attention guidance for one 'change trial' (dashed lines represents onset and duration of the tactile vibrations)

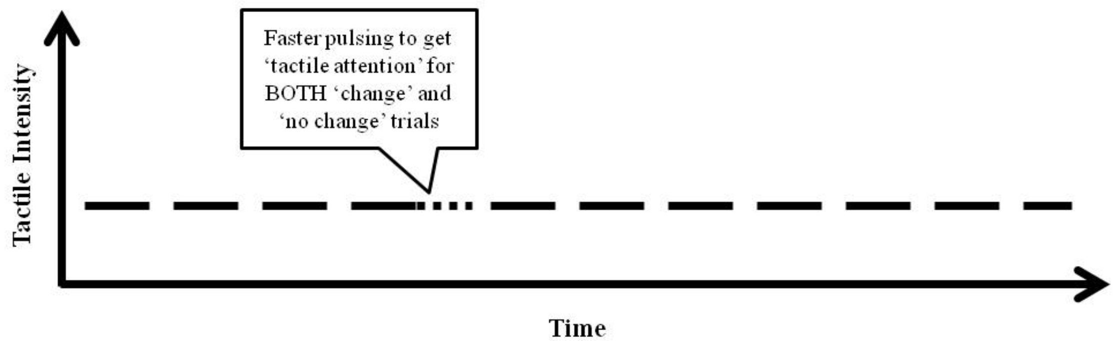


Figure 4-2: Attention guidance for one 'no-change trial' (dashed lines represents onset and duration of the tactile vibrations)

Countermeasure 2: Signal gradation

The signal gradation countermeasure was adaptive in nature, i.e., it was triggered 1.5 sec after a change if the participant responded incorrectly by indicating that there was no change or by not responding yet. The increased intensity cue was presented at 250 Hz with a gain of 16.2 dB, which was close to the maximum gain possible for the C-2 tactors used in this experiment. Figure 4-3 provides a depiction of the signal gradation and its relation to the three tactile intensity levels.

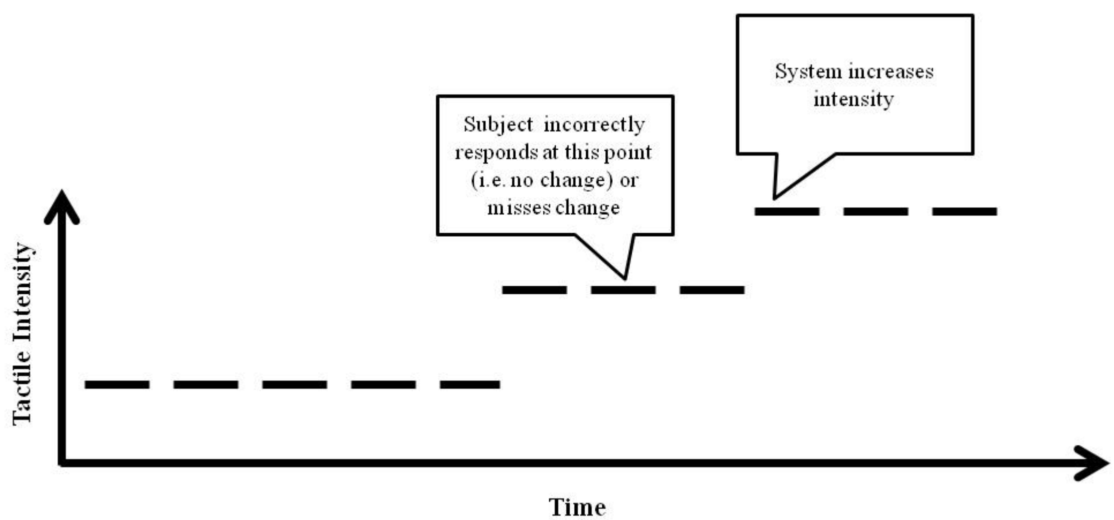


Figure 4-3: Signal gradation for a 'change trial' (dashed lines represents onset and duration of the tactile vibrations)

Countermeasure 3: Direct comparison

Like signal gradation, the direct comparison countermeasure was adaptive and occurred 1.5 sec after a change if the participant responded incorrectly by indicating that there was no change, or by not responding at all. Figure 4-4 provides a depiction of the direct comparison and its relation to the two tactile intensity levels.

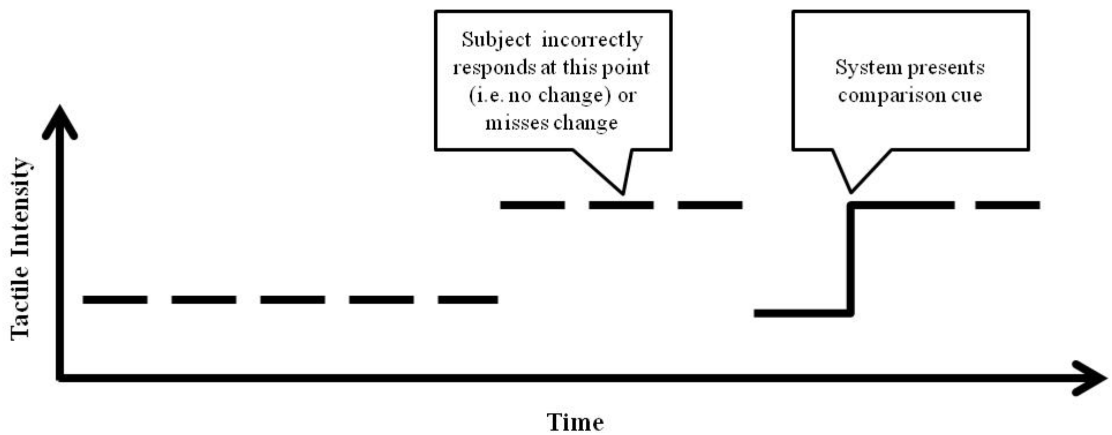


Figure 4-4: Direct comparison for one 'change trial' (dashed lines represents onset and duration of the tactile vibrations)

As in the earlier experiments, when changes in brightness in the UAV background or intensity of tactile cues were detected, participants were instructed to press the "Target" button on the top right hand corner of the respective UAV feed to indicate to Command Central the presence of a long range target. During a trial, if there was no change in brightness/intensity, participants were instructed to press the "No Target" button. If, at any time, participants were unsure whether or not there was a change, they were instructed to press the "?/Unsure" button. Participants could make their selection any time during the 8.5 sec trial, with the final response being used for data analysis (See Figure 4-5 for each of the buttons).

Since the attention guidance countermeasure was proactive, participants were instructed to press the target button after a change in tactile cue intensity was actually detected. In the signal gradation (countermeasure 2) trials, participants were instructed to respond by pressing the 'target' button if they noticed either the initial change from low to medium tactile intensity or the further increase from medium to high intensity in case of a miss. Similarly, in the direct comparison trials (countermeasure 3), participants were told to press the ‘target’ button if they noticed either the original tactile change or the subsequent direct comparison in case of a miss.

Figure 4-5: One of the nine UAV feeds with associated response buttons

Procedure

As in the earlier experiments, upon arrival, participants read and signed the consent form and, after a brief explanation describing the reason for conducting the study, the experimenter described the visual and tactile cues, the participant’s tasks, and guided the participants through an interactive training session. Next, participants completed two 8-minute training sessions which allowed them to practice the visual and tactile baseline combinations, i.e. the long range target change detection task without the presence of transients. By the end of the second training session, participants were required to achieve at least 90% hit rate accuracy in determining whether a brightness or intensity change had occurred in the tactile and visual baseline combinations. Upon successful completion of the training sessions, participants were shown a demonstration of the transients. Participants were asked to wear headphones playing white noise to mask the sound of tactor activation. The participants then completed four blocks of 8.5 sec trials in randomized order:

1) 70 trials with no countermeasure
2) 70 trials with attention guidance,
3) 70 trials with signal gradation, and
4) 70 trials with direct comparison.

For each block with a countermeasure, participants were given a demonstration of the countermeasure before the start of the respective block. For the direct comparison block, participants were also asked to draw how they perceived the direct comparison and the intensity change after the demonstration (see Appendix 3 for handout). The information was collected because there were some concerns during pilot testing that not all participants may have perceived the direct comparison like they were intended and this perception may have differed between individuals. The order of these four blocks were randomized and counterbalanced between subjects. At the conclusion of each block, participants filled out a survey which asked the participants to rate how difficult it was to complete their tasks in the block they had just completed. Each block lasted about 13 minutes during which participants had to respond either to a visual or tactile indication every 11.5 sec.

After completing all four blocks, participants filled out a debriefing questionnaire which was similar to the one used in the experiments reported in Chapter 3, with the same questions asking about their fatigue level, the number of video games played per week, and a personality assessment (See Appendix 1 and 2). However, the debrief for this study also included a question asking participants to rank in order each of the four tactile displays in terms of the following cue attributes: supporting change detection, minimizing annoyance, comfort, and overall preference. The debrief also asked about how difficult it was to complete the long range target detection task under the different cue-transient combinations and also included open ended questions about any strategy that may have been adopted. In total, the experiment lasted about two hours.

Experimental design

This study employed an unbalanced nested design. The two main factors were cue-transient combination (six cue-transients combinations with tactile transients) and countermeasure type (no countermeasure, attention guidance, signal gradation, and direct comparison). The design was unbalanced in the sense that there was an unequal number of trials for each cue-transient combination. Since this study was interested in overcoming change blindness, there were more 'change trials' (56% of all trials), compared to 'no-change trials' (44% trials) in each scenario. A short range target appeared in 22% of the trials.

Dependent measures

The main dependent measures in this study were accuracy (detection of a change or correct rejection when there was no change), sensitivity and response bias, multitasking performance, and participant preferences.

Results

Repeated measures linear models (General Linear Model formulation in SPSS 16.0) were used to identify main and interaction effects and for significant effects, two-tailed Fisher's LSD post-hoc tests were performed to determine differences between means. Performance data for each participant were first analyzed using Signal Detection Theory. Using hits, misses, correct rejections, and false alarms, sensitivity (d`) and response bias (c) were calculated for each participant under each cue-transient combination. The rank data were analyzed using a nonparametric Friedman test; a Bonferroni correction was performed for multiple pairwise comparisons.

Note that, for all analyses, the three crossmodal combinations ('visual cue, baseline,' 'visual cue, tactile flicker,' 'visual cue, tactile mudsplash') did not differ significantly in terms of performance and approached a ceiling for hit rates and correct rejections. Thus, the performance data and Signal Detection Theory analysis will focus on the findings for the intramodal tactile combinations (‘tactile cue, baseline,’ ‘tactile cue, tactile flicker’ and ‘tactile cue, tactile mudsplash’).

Hit rate

Figure 4-6 shows the hit rates for each of the countermeasures under the different cue-transient combinations. There was a significant effect of countermeasure type ($F(3, 17) = 18.263$, $p < .001$), with hit rates being the highest for signal gradation (hit rate = 95%) and direct comparison (hit rate = 91%), followed by attention guidance (hit rate = 81%, $p < .029$ for both pairwise comparisons. Performance was worst with no countermeasure (hit rate = 66%; $p = .004$). This replicates and confirms the findings from Experiment 3. There was also a significant effect of cue-transient combination ($F(2, 18) = 8.626$, $p = .002$), with hit rates being significantly higher in the ‘tactile, baseline’ combination compared to the other intramodal tactile combinations. Finally, there was a cue-transient combination*countermeasure type interaction ($F(6, 14) = 3.273$, $p = .032$), such that for the cue-transient combinations with tactile transients, signal gradation and direct comparison had the highest hit rates, followed by attention guidance, and lastly no countermeasure.

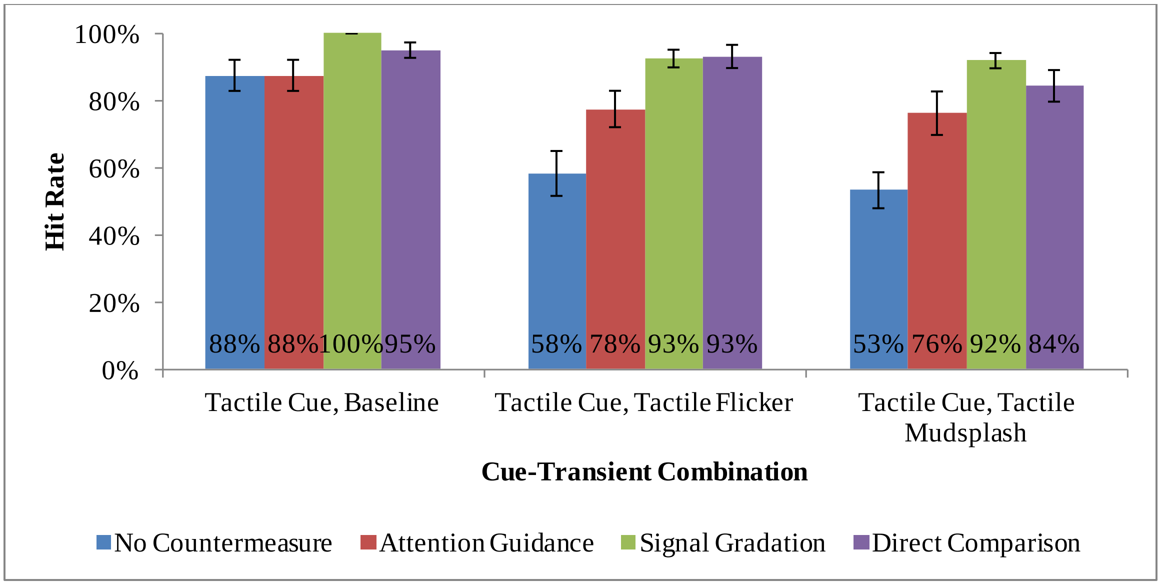


Figure 4-6: Hit rate for the intramodal tactile cue-transient combinations for 'change trials' (errors bars represent standard error)

Correct rejection rate

Figure 4-7 shows the correct rejection rates for each of the countermeasures under the different cue-transient combinations. There was a significant effect of countermeasure type ($F(3, 17) = 4.302$, $p < .001$), with correct rejection rates being the highest for signal gradation (correct rejection rate = 97%), and significantly higher than direct comparison and no countermeasure, but not attention guidance (92%; $p < .029$ for both pairwise comparisons). There was also a significant effect of cue-transient combination ($F(2, 18) = 8.023$, $p = .003$) as correct rejections rates for the 'tactile cue, tactile mudsplash' combination were significantly lower than for the 'tactile cue, tactile flicker' combination (94%, $p = .001$). Finally, there was a cue-transient combination*countermeasure type interaction ($F(6, 14) = 10.246$, $p < .001$). Post hoc tests showed that for the 'tactile cue, baseline' combination, the rejection rates for signal gradation (98%) was significantly higher than no countermeasure (91%; $p = .021$) and for the 'tactile cue, tactile mudsplash' combination, rejection rates were significantly lower for the direct comparison compared to all other countermeasures ($p < .001$ for all pairwise comparisons).

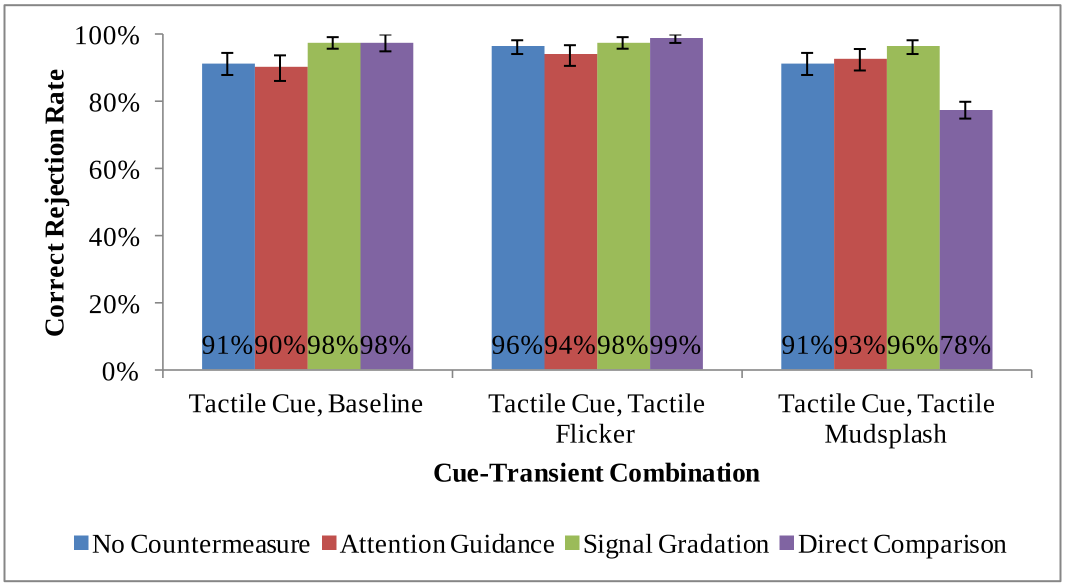


Figure 4-7: Correct rejection rate for the intramodal tactile cue-transient combinations for 'no-change trials' (errors bars represent standard error)

Sensitivity (d`) and response bias (c)

For the Signal Detection Theory analysis, misses were calculated by subtracting the hit rate percentages from 100%, and false alarm rates were calculated by subtracting the correct rejection percentages from 100%. The option to select the '?/Unsure' button or not to respond at all was chosen in only 0.1% of all cases. Instances where the '?/Unsure' button was chosen or no response was made were included in the 'miss' category for 'change trials' or the 'false alarm' category for 'no-change trials.'

Figure 4-8 shows the sensitivity data (d`) and Figure 4-9 shows the response bias data (c) for the three intramodal cue-transient combinations. For sensitivity, we found a significant effect of countermeasure ($F(3, 17) = 24.005$, $p < .001$), such that sensitivity was the highest in case of signal gradation (d` = 2.80), followed by the direct comparison (d` = 2.48), attention guidance (d` = 2.20), and no countermeasure (d` = 1.79). All four countermeasures differed significantly from each other ($p < .039$ for all pairwise comparisons). Sensitivity was also significantly affected by cue-transient combination ($F(2, 18) = 22.328$, $p < .001$), with post-hoc tests showing that sensitivity was the highest in the 'tactile cue, baseline' combination (d` = 2.63), followed by the flicker (d` = 2.34) and mudsplash combinations (d` = 1.98). The three combinations all differed significantly from each other ($p < .006$, for all pairwise comparisons).

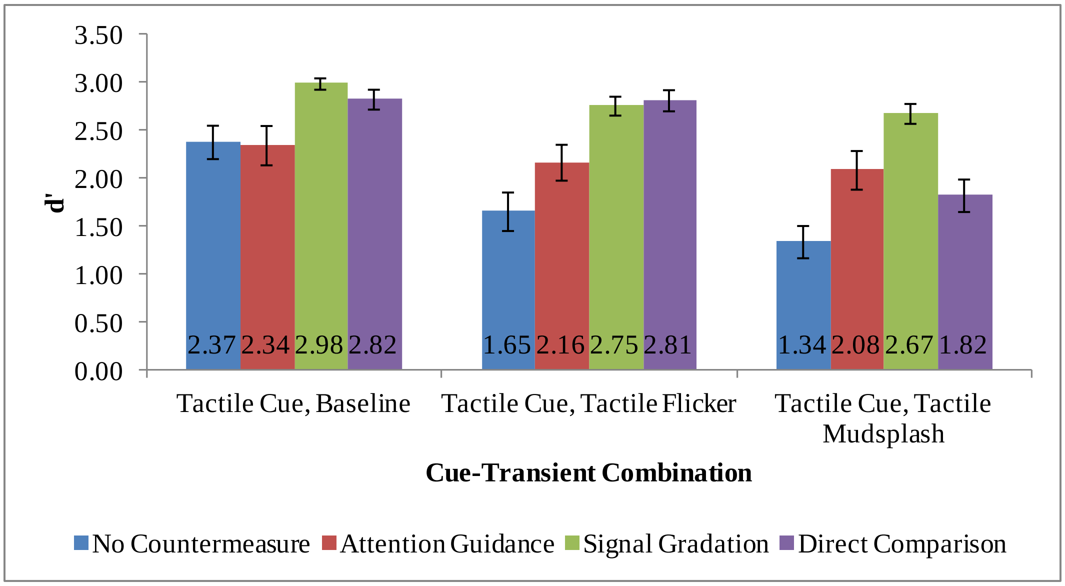


Figure 4-8: Sensitivity (d`) for the intramodal tactile cue-transient combinations (bars respresent standard error)

For response bias, there was also a significant effect of countermeasure type ($F(3, 17) = 11.527$, $p < .001$), with the response bias being significantly higher in the absence of a countermeasure, compared to all three types of countermeasures ($p < .015$ for all pairwise comparisons). Response bias was also affected by cue-transient combination ($F(2, 18) = 6.797$, $p = .006$), with a higher c value for the 'tactile cue, tactile flicker' combination (c = .245) compared to the 'tactile, baseline' (c = .024; p = .003).

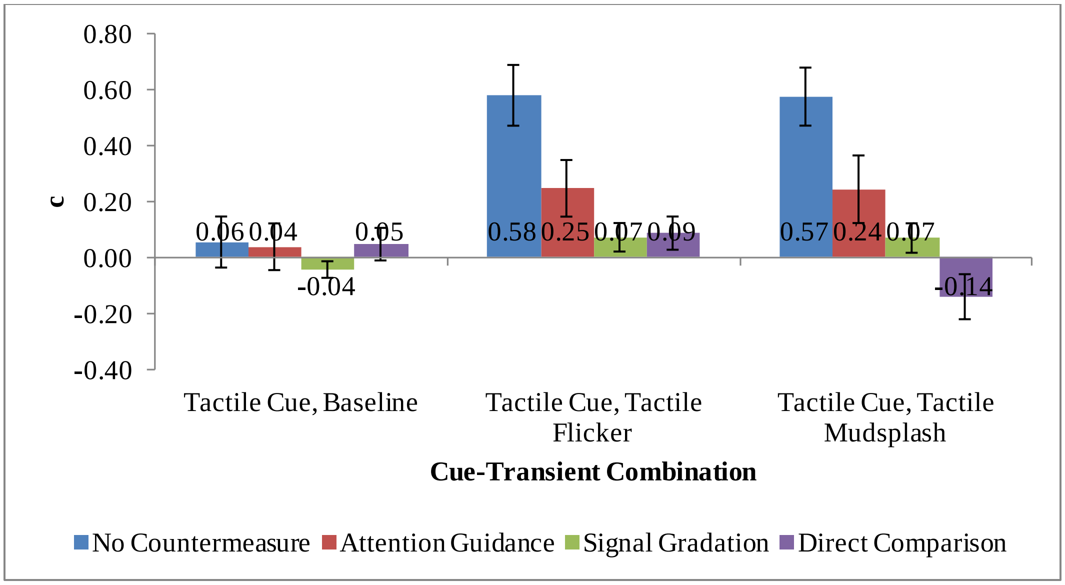


Figure 4-9: Response bias (c) for the intramodal tactile cue-transient combinations (bars respresent standard error)

Multitasking performance

Figure 4-10 shows participants' performance for the tactile and visual 'change' and 'no-change' trials when a potential change coincided with the appearance of a short range target[7]. There was a significant effect of countermeasure type on hit rates for visual, but not tactile, cues when participants were required to attend to both tasks ($F(3, 17) = 6.727$, $p = .003$). Post hoc tests showed that hit rates for 'change trials' were significantly higher with no countermeasure (mean = 91%), compared to the direct comparison (mean = 84%; $p = .045$) and attention guidance (mean = 78%; $p < .001$), but not to signal gradation (mean = 86%; $p = .088$). There was no effect of cue type or countermeasure, nor was there a cue type*countermeasure interaction for the 'no-change trials' as correction rejection rate reached a ceiling (correct rejection accuracy: 88-99%). Figure 4-11 shows that attention guidance and signal gradation resulted in significantly higher short range detection rates compared to when there was no countermeasure and with the direct comparison countermeasure ($p < .05$ for both pairwise comparisons).

[7] These cases were independent from the trials discussed in the 'hit rates' and 'correct rejection rates' sections.

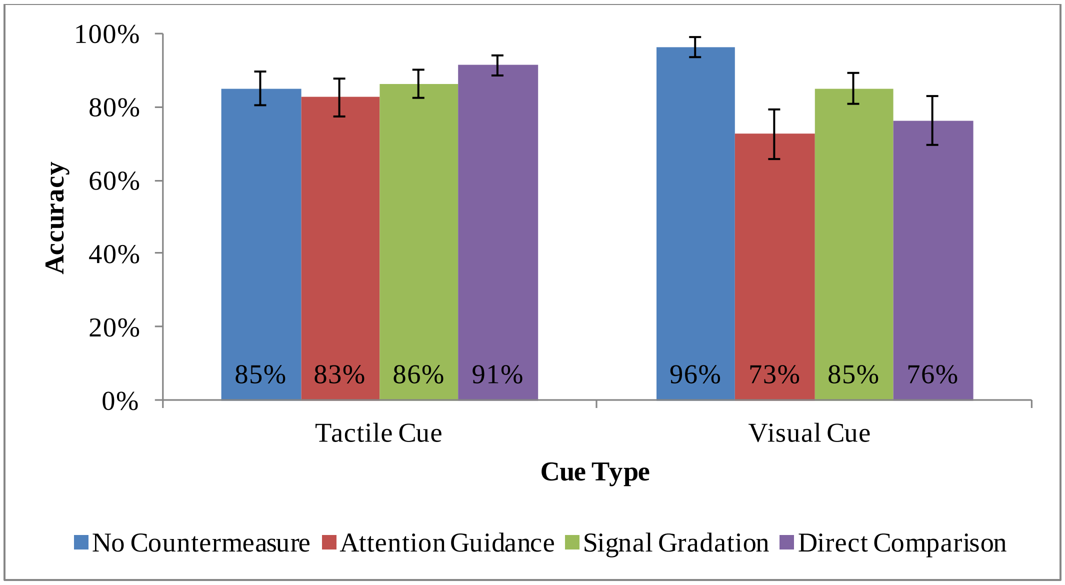


Figure 4-10: Performance for 'change trials' when a short range target was present (bars respresent standard error)

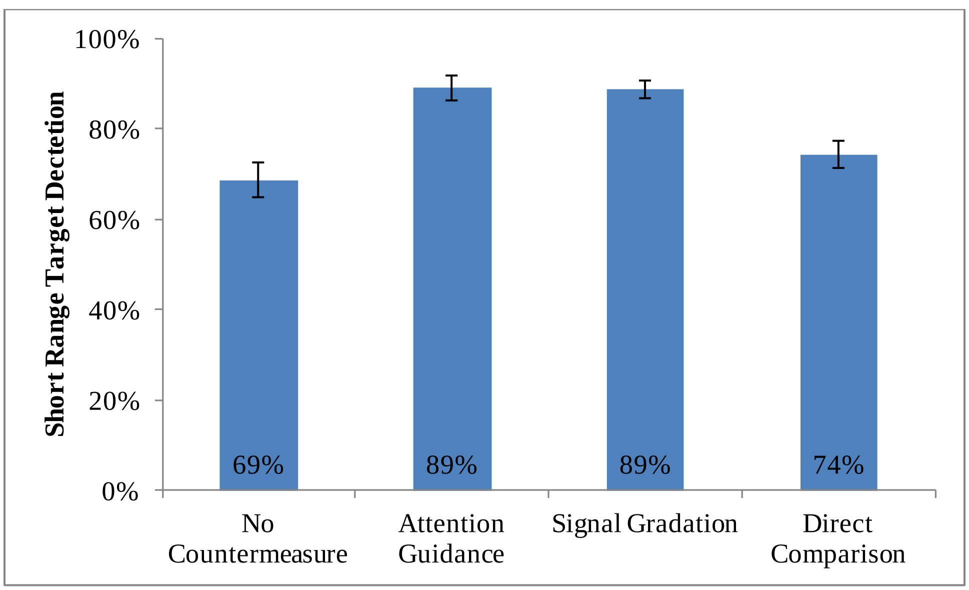


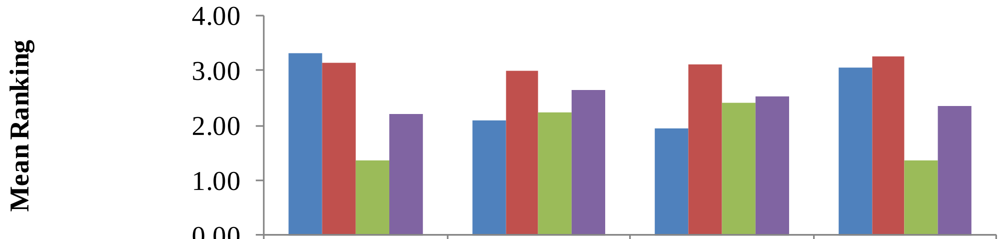
Figure 4-11: Short range target detection rates for each tactile display type (bars respresent standard error)

Subjective rankings of tactile displays

Figure 4-12 shows the mean rankings of each of the countermeasures in terms of the following attributes: (1) support for change detection, (2) annoyance, (3) comfort, and (4) overall preference.

There was a significant difference between the countermeasures with respect to supporting change detection ($\chi(2) = 29.700$, $p < .001$). Signal gradation was ranked the highest (mean ranking = 1.35), followed by the direct comparison (2.20), attention guidance (3.15), and no countermeasure (3.30). Signal gradation was also ranked significantly higher than the attention guidance ($p < .001$), and both the signal gradation and direct comparison were ranked significantly higher than the baseline condition ($p < .001$ and $p = .042$, respectively). There was no difference in ranking between the countermeasures in terms of minimizing annoyance ($\chi(3) = 5.940$, $p = .115$) and comfort ($\chi(3) = 7.737$, $p = .052$).

However, there was a significant difference in overall display preference ($\chi(3) = 26.520$, $p < .001$). Signal gradation was ranked the highest (mean ranking = 1.35), followed by the direct comparison (2.35), no countermeasure (3.05), and direct comparison (3.25). The signal gradation was also ranked significantly higher than the attention guidance and baseline ($p<.001$ for both pairwise comparisons). The no countermeasure condition did not differ significantly from attention guidance.



	Support Change Detection	Minimize Annoyance	Comfort	Overall Preference
No Countermeasure	3.30	2.10	1.95	3.05
Attention Guidance	3.15	3.00	3.11	3.25
Signal Gradation	1.35	2.25	2.42	1.35
Direct Comparison	2.20	2.65	2.53	2.35

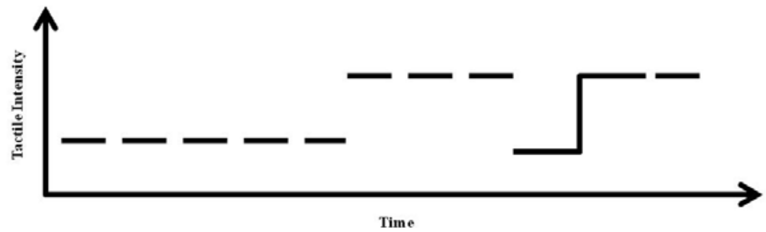
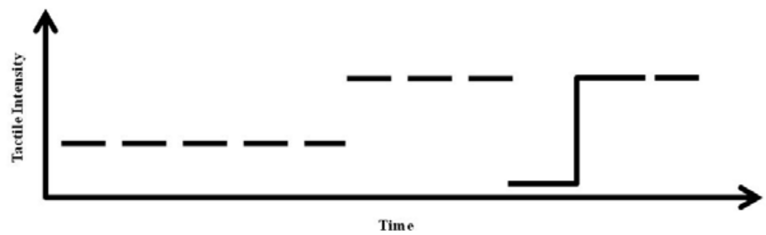
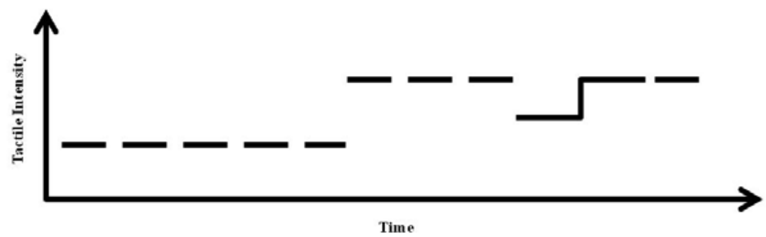
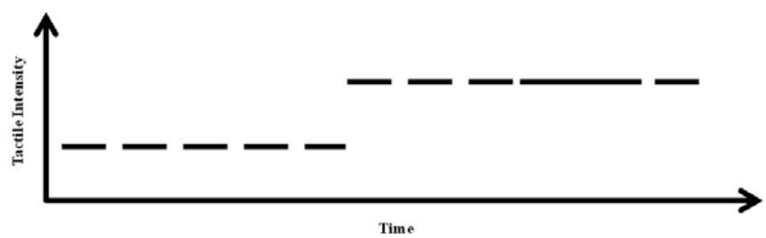
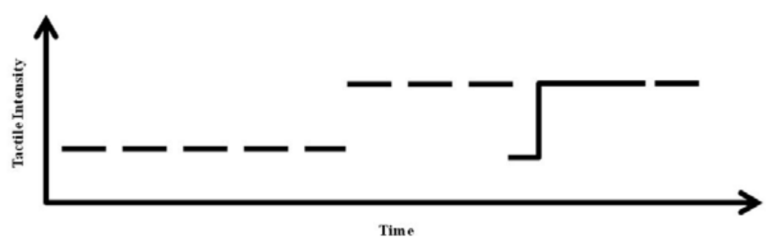
Attribute

Figure 4-12: Mean rankings of each countermeasure for each attribute (with a ranking of 1 being the most favored and 4 being the least favored)

Direct comparison drawings

As mentioned earlier, the debrief questionnaire asked participants to capture, in visual form, their perception of a comparison cue. The direct comparison was programmed to last two seconds, with the first half of the cue presented at the lower intensity (frequency = 250 Hz, gain = 5.4 dB), immediately followed by the higher intensity (frequency = 250 Hz, gain = 10.8 dB) for the latter half of the cue. The intended perception of the cue would look like row one of Table 4-1. All 20 participants indicated they could reliably detect the presence of the comparison cue, but only half of the participants drew their perception of the direct comparison the way it was intended be perceived. Table 4-1 provides a description and depiction of how the remaining participants perceived the comparison cue including the number of participants for each.

Table 4-1: Perceived direct comparison descriptions and depictions based on the participant's debrief responses

n	**Perceived Description**	**Perceived Depiction**
10	Intended perception of direct comparison	
4	First half of the direct comparisons lower in intensity than the tactile cue's low level intensity	
2	First half of the direct comparisons higher in intensity than the tactile cue's low level intensity	
2	No difference in intensity, except it was perceived to be a longer pulse	
2	First half of the direct comparison at the lower intensity was significantly shorter than the latter half of the cue at the higher intensity	

Discussion

The findings from the previous chapter confirmed that intramodal tactile cue-transient combinations adversely affect tactile change detection (Auvray, Gallace, Hartcher-O'Brien, Tan, & Spence; Ferris, Stringfield, & Sarter, 2010; Gallace, Tan, & Spence, 2007). Thus, the goal of this study was to design and evaluate three countermeasures to intramodal tactile change blindness. The design of these countermeasures focused on supporting four of the five steps required for change detection and was found to significantly improve performance compared to when there was no countermeasure in place. Overall, the adaptive countermeasures, i.e. signal gradation and direct comparison, were the most beneficial in terms of aiding change detection and thus increasing hit rates.

Attention guidance, on the other hand, resulted in an increase in correct rejections. This can be explained by the fact that it was the only countermeasure that provided support in no-change trials. However, there was not a significant difference in correct rejection rates between attention guidance and signal gradation. Signal gradation may have also effectively supported correct rejection rates because a number of participants indicated that the strategy they adopted was to press the 'no target' button for every trial and then switch their selection when they detected a change or one of the countermeasure. Participants could leave their initial response until the extremely salient signal gradation countermeasure was triggered.

Direct comparisons were not as effective for supporting correct rejections, especially in the tactile cue, tactile mudsplash combination. As discussed in Chapter 3, the randomness of mudsplashes may have been distracting and diverted attention away from the tactile change. Also, only half of the participants perceived this countermeasure as intended (equal duration at low and high intensity) which may have led to an increased number of false alarms. This is supported by the fact that response bias was also higher (negative c value) for this condition, i.e. participants were more inclined to respond that there was a change.

Combining hit rates and correct rejections, overall accuracy as well as sensitivity were highest with signal gradation, followed by direct comparison. One likely reason for the success of these adaptive measures is that they served as error feedback to participants. While countermeasure 1 – attention guidance – prepared them for a potential change but left the final decision to the participant, while signal gradation and direct comparison indicated that an actual change had been missed and thus served as a safe recovery mechanism from an incorrect response or no response.

Another reason that a performance benefit was seen with the countermeasures was that it addressed specific and distinct steps required for change detection (Jensen et al., 2011). The effectiveness of the three countermeasures may be the result of their ability to garner attention and supports previous findings which has shown that attention is necessary for change detection. However, attention alone may not be sufficient as changes to attended objects can still go unnoticed (Williams & Simons, 2000; Triesch et al., 2003), and is shown with the finding here as change detection was not 100% for any of the countermeasures.

The superior performance benefits of the two adaptive measures may also suggest that the various steps involved in change detection are not equally likely to be missed or are not of equal importance. One reason is that attention guidance, which addressed step 2 (encoding the target before the change), may have been less effective compared to the adaptive measures. This may be because this step is not likely affected by or is subject to breakdowns. Therefore supporting this step is less critical compared to the latter change detection steps addressed by the adaptive countermeasures. Another reason that attention guidance was less effective than the other countermeasures may be due to how it was implemented. Attention guidance effectiveness drastically decreased in the presence of tactile flicker and mudsplash, although it was effective in the absence of any transients. This may imply that the design of the attention guidance may have distracted participants from the change.

Although signal gradation was found to be an effective measure in countering tactile change blindness overall, one important question is whether the sense of touch may become desensitized over time using the 3x3 tactile display. Each of the four blocks only lasted 13 minutes, but it will be critical to ensure that the effectiveness of this countermeasure be tested for longer durations.

The direct comparison was also successful in preventing tactile change blindness. Previous work has indicated the need for absolute judgments for conveying certain types of information (Hameed, Ferris, Jayaraman, & Sarter, 2009). The finding supports their conjecture: presenting a reference stimulus and thus requiring relative (rather than absolute) judgments could improve the interpretability of different parameters, such as tactile intensity. However, to ensure that comparison cue is effective, its implementation needs to be improved to ensure that the cue itself is perceived consistently, which had high false alarm rates. This may be attributed to the fact that there were five different and distinct interpretations of the direct comparison. As a result, participants may have been less certain about whether or not a change may have occurred, which may explain the issues with the lower accuracy for correct rejections for the ‘tactile cue, tactile flicker’ cue-transient combination.

The superior performance observed with signal gradation, followed by direct comparison, is also reflected in participants’ overall preference for these two countermeasures which was based almost exclusively on how much each measure supported change detection. Comfort and annoyance seem to have had little impact on which countermeasure participants liked, although the rankings were similar to the overall preference. Subjective rankings of the adaptive measures showed that attention guidance was the least preferred means of presentation. This may be due to the fact that 30% of the participants indicated that it was more difficult to attend to the tactile cues because attention guidance presented an overload of tactile information. Another 15% of participants noted that although attention guidance was better than the baseline with assisting in tactile change detection, its benefit was nullified in the presence of tactile transients. The attention guidance may have contributed to tactile clutter – which previous literature has indicated can reduce the effectiveness of tactile signals and that sometimes a simpler display is preferred (van Erp, 2002; van Erp, Veltman, van Veen, & Orving, 2003).

Conclusion

The adaptive countermeasures were best in maximizing the probability that tactile changes were detected, especially in the presence of tactile transients. Overall, signal gradation was the best in terms of hit rate, correct rejection rate, led to the highest sensitivity and the lowest response bias. It was also the most preferred countermeasure in terms of supporting change detection and overall preference. It is recommended that increasing the saliency of the tactile signal be used as a means to counter tactile change blindness; however, one major concern is whether or not people will experience cue fatigue from the highest intensities of the signal gradation over longer periods of time. The other countermeasures fared well in improving change detection rates in the intramodal tactile cases, but were not as effective as signal gradation. Further work needs to explore more effective designs and implementations of these countermeasures. For the direct comparison, it is critical to ensure that people perceive the signal the same and for attention guidance, measures need to be taken to minimize the tactile “clutter.”

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Chapter 5

Conclusion

The introduction of tactile displays in various data-rich environments can benefit performance by offloading the visual and auditory channels; however, to ensure that tactile displays are appropriately designed and thus effective, they need to take into consideration perceptual and attentional limitations, such as change blindness. To date, this phenomenon has been studied and documented primarily in vision, but there is limited empirical evidence that the auditory and tactile modalities may be subject to change blindness as well (Eramudugolla et al., 2005; Vitevitch, 2003; Gallace, Tan, & Spence, 2006). The goal of this body of work was to investigate whether an analog of change blindness exists in the tactile modality and whether or not change blindness can occur crossmodally between vision and touch. That is, whether change detection in one modality is poor when a coincident event is perceived in the other modality, which is suggested by recent studies that have shown that modalities are, to some extent, linked to one another (Spence & Driver, 1997a, 1997b, 1998, 2001; Ward, McDonald, & Lin, 2000). Most studies that investigated tactile and crossmodal change blindness to date focused on change detection in the context of pattern recognition tasks or very simple detection tasks in single task conditions that are not representative of real world domains. In contrast, the body of work described in Chapters 3 and 4 seeks to examine change blindness in the context of search and detection tasks in a real world domain – simulated Unmanned Aerial Vehicle (UAV) control. UAV control was selected as the application domain for this work because of the expected sharp increase in the amount of data and the highly dynamic displays that operators have to cope with. The combination of these two factors will likely lead to frequent co-occurrence of events and, consequently, a high likelihood of change blindness.

The first important finding from this research is related to crossmodal matching, a procedure which is critical to avoid confounds in any research on multimodal information processing. The two studies reported in Chapter 2 show considerable variability in crossmodal matches not only between participants – an expected finding and the one that necessitates the use of the procedure to begin with – but also high within-subject variability. This highlights that a single unidirectional match, which is employed by most studies to date, is likely insufficient to yield reliable stimulus sets. The studies also highlight that the specific implementation of the matching task (e.g., with or without a visible sliding scale) has a major impact on variability.

The experiments described in Chapter 3 consistently demonstrated intramodal tactile change blindness, i.e. the failure to detect tactile changes in the presence of tactile transients. This finding confirms the results from very limited earlier research (Gallace et al., 2006; Ferris, Stringfield, & Sarter, 2010). Not surprisingly, tactile change detection was best in the absence of any type of transient. Intramodal tactile change detection did not deteriorate further with an added visual search task. Since UAV control could benefit from the introduction of tactile displays, the design of tactile displays need to take into account and minimize environmental vibrotactile noise that could interfere with tactile encoding. Not only does this apply to UAV control, but could also have implications for other complex environments including aviation (i.e. turbulence from aircraft) and driving (i.e. vibrations with an automobile from the road).

Intramodal visual change blindness was observed as well, but to a much lesser extent than found in earlier studies. This may be explained by that the fact that the visual changes employed in this research were global (as opposed to local) in nature. Such global changes can be perceived in peripheral vision and therefore tend to be detected faster and more reliably. Their detection in peripheral vision may also account for the fact that the addition of a focal visual search task did not result in performance decrements. This suggests that important visual changes should be presented in a global fashion to ensure their detection in data-rich and multitask environments (see also Nikolic & Sarter, 2001).

The findings from Chapter 3 also suggest that the mechanisms underlying change blindness in the two modalities – vision and touch – differ. Specifically, transient duration was shown to have an effect on intramodal visual change blindness, with longer transients resulting in lower change detection rates, possibly due to the limitations of visual short term memory. However, tactile change detection did not vary as a function of transient length. This finding adds to the knowledge base on how information is encoded and retained in the two sensory channels.

Across all three studies in Chapter 3, crossmodal change blindness between vision and touch was not observed. This may be attributed to the fact that our experimental set up was different from previous studies where the visual and tactile displays were distributed across different parts of the body (Auvray, Gallace, Tan, & Spence, 2007; Gallace, Auvray, Tan, & Spence, 2006), and participants were required to detect not only that but also where changes occurred on the body. In our studies, stimulus intensity was varied while change location was highlighted in advance for the participants.

Overall, all three experiments in Chapter 3 confirm that the relative timing of changes and transients is critical. Specifically, to avoid change blindness, display designers should make every effort to ensure that simultaneous masking is prevented or minimized through context-sensitive stimulus presentation. In Chapter 4, three additional countermeasures to change blindness were developed and tested: attention guidance, signal gradation, and direct comparison. These countermeasures supported various combinations of two each of the five steps involved in successful change detection (Jensen et al., 2011). The two adaptive displays – signal gradation and direct comparison – led to the greatest improvements in performance, compared to when there was no countermeasure in place. Thus, for changes that require an overt operator response and thus provide an opportunity for assessing performance in real time, these adaptive measures that are triggered in case of miss represent effective means to ensure tactile change detection.

Of the two adaptive measures, signal gradation was the most successful intervention, supporting higher hit rates, correct rejections, higher sensitivity (participants could better discern signal from noise) and bringing response bias close to the ideal of zero (no response bias). Also, this measure did not affect multitasking performance and was preferred by participants. All of these attributes make signal gradation the ideal candidate for the design of UAV control displays where operators are increasingly required to timeshare and where both misses and false alarms can lead to catastrophic outcomes.

Direct comparison ranked second behind signal gradation for hit rates, but it was less effective for correction rejections. One of the open-ended questions in the debrief showed that participants perceived the signal in five different ways which suggests that its implementation needs to be improved to avoid confusion and minimize false alarm rates.

Attention guidance was surprisingly the least preferred approach. Participants indicated in the opened-ended debrief questions that they felt that it resulted in an overload of the tactile channel. This suggests that, similar to the direct comparison countermeasure, a modified version of this type of intervention should be developed and tested. Perhaps presenting the signal earlier, or presenting a slightly less salient tactile signal, would still prepare the participant for a potential change without being overwhelming. Attention guidance still resulted in higher hit rates compared to having no countermeasure at all. If redesigned and improved, this countermeasure offers a promising means of improving change detection in cases where no overt operator response is available to trigger error recovery mechanisms, such as signal gradation or direct comparison.

Overall, all three countermeasures were found to increase hit rates compared to when there was no countermeasure in place. However, detection rates did not reach 100% across all participants. This finding is somewhat surprising since participants could have relied on signal gradation or direct comparison as an error detection tool. Possible reasons for the finding of less than perfect performance may be participants' limited familiarity with the task and controls prior to the start of the study. The training sessions lasted at most 10 minutes and this may have not been adequate for the participants to be fully trained on the task and, even more importantly, the novel tactile stimuli.

Future work

The research that is reported in this document enhances our understanding of tactile and crossmodal information processing and change blindness but it also highlights outstanding questions and direction for future research. The following are some of my future research plans when I start my faculty career as an assistant professor of industrial engineering at Clemson University in the fall of 2014.

One change blindness paradigm that has not been included in this thesis research, and which has, in general, been investigated to a lesser extent, is gradual changes, especially in the tactile modality. Gradual changes often take the form of a slow appearance or disappearance of an object or signal (pattern). Sonification, the successful use of presenting non-speech audio to convey information in the auditory modality (Kramer, 1993), suggests potential benefits of presenting information in the tactile modality in a similar fashion, but empirical studies are needed to establish gradual change detection for vibrotactile stimuli (i.e., tactification).

Second, I will seek to understand change blindness in the context of concurrent processing of information in all three modalities – vision, hearing, and touch. To my knowledge, only one study has examined change blindness involving all three modalities (Auvray, Gallace, Hartcher-O'Brien, Tan, & Spence, 2008), and this study was not conducted in the context of a real-world application. Previous work has identified spatial and temporal links between modalities, and therefore more controlled investigations are needed to understand crossmodal three-way change blindness.

Finally, since adaptive measures were successful in preventing change blindness in this research, I hope to continue work along these lines. One promising means of developing effective countermeasures is the use of eye tracking which can provide a real-time trace of attention allocation and information search. Using eye tracking data, one may be able to develop fixation-based interventions that are triggered when a user fails to attend to the relevant change location. Ultimately, the goal is to develop adaptive, real-time countermeasures that can be individualized since performance varied across participants in our studies.

Overall, this body of work and future work contributes to a deeper understanding of tactile and crossmodal information processing. The findings from this work and future work will inform multimodal information presentation in complex data-rich domains, not only UAV control and military operations, but also the aviation industry, the medical domain, military operations, and the automotive industry. These research efforts will ultimately benefit joint system performance and thus safety in these complex environments.

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Appendices

Appendix 1: UAV debrief questions for Chapter 3

Q1 What is your subject number?

Q2 What is your gender?

☐ Male

☐ Female

Q3 What is your age?

Q4 On a scale of 0-10, please rate how alert or sleepy you feel right now.

_______ How alert and/or sleepy are you?

Q5 Do you think the distractors (static and blackouts) affected your performance on the visual/tactile change detection task?

☐ Yes

☐ No

Q6 Rate how difficult it was to complete your task with the following cue/distractor combinations

	Very Easy	Easy	Somewhat Easy	Neutral	Somewhat Difficult	Difficult	Very Difficult
Visual cues with visual static	❍	❍	❍	❍	❍	❍	❍
Visual cues with visual blackouts	❍	❍	❍	❍	❍	❍	❍
Visual cues with tactile static	❍	❍	❍	❍	❍	❍	❍
Visual cues with tactile blackouts	❍	❍	❍	❍	❍	❍	❍
Tactile cues with visual static	❍	❍	❍	❍	❍	❍	❍

Tactile cues with visual blackouts	❍	❍	❍	❍	❍	❍	❍
Tactile cues with tactile static	❍	❍	❍	❍	❍	❍	❍
Tactile cues with tactile blackouts	❍	❍	❍	❍	❍	❍	❍

Q7 Please feel free to comment on any of the above selections you've made.

Q8 Describe any strategy you adopted to complete the visual/tactile change detection task.

Q9 (If applicable) Describe any strategy you adopted to complete both the primary visual/tactile change detection task and target search task.

Q10 (If applicable) Describe any strategy you adopted to complete the gradual visual/tactile change detection task.

Q11 Here are number of characteristics that may or may not apply to you. For example, do you agree that you are someone who 'likes to spend times with others'? Please make a selection for each statement to indicate the extent to which you agree or disagree with that statement. There is no right or wrong answer, so please be as truthful as possible.

Q12 I see myself as someone who …

	Disagree strongly	Disagree a little	Neither agree nor disagree	Agree a little	Agree strongly
Is talkative	❍	❍	❍	❍	❍
Does a thorough job	❍	❍	❍	❍	❍
Is reserved	❍	❍	❍	❍	❍
Can be somewhat careless	❍	❍	❍	❍	❍
Is full of energy	❍	❍	❍	❍	❍
Is a reliable worker	❍	❍	❍	❍	❍
Generates a lot of enthusiasm	❍	❍	❍	❍	❍
Tends to be disorganized	❍	❍	❍	❍	❍

Tends to be quiet	❍	❍	❍	❍	❍
Tends to be lazy	❍	❍	❍	❍	❍
Has an assertive personality	❍	❍	❍	❍	❍
Perseveres until the task is finished	❍	❍	❍	❍	❍
Is sometimes shy, inhibited	❍	❍	❍	❍	❍
Does things efficiently	❍	❍	❍	❍	❍
Is outgoing, sociable	❍	❍	❍	❍	❍
Makes plans and follows	❍	❍	❍	❍	❍

through with them					
Is easily distracted	❍	❍	❍	❍	❍

Q13 During an average week, how many hours do you spend playing different types of video games?

_______ Play PC based video games

_______ Play console video games (e.g. Playstation 3, Xbox, etc.)

_______ Play online java-script games (e.g. like those on Facebook)

Q14 This study is a work in progress. Please feel free to provide any comments and suggestions for us to take into account for the future. Thank you again for your participation in our study!

Appendix 2: Additional question for the debrief for Chapter 4

Q5 Please rank order the four tactile cue designs - baseline, intensity increase cue, comparison cue, warning cue - with respect to the following criteria:

(*Note the online form will allow to drag each of the options according to their preference: *baseline, intensity increase cue, comparison cue, warning cue)*

- Support change detection
- Minimize annoyance
- Comfort
- Overall preference

Appendix 3: Direct comparison handout