MULTICODE VIBROTACTILE DISPLAYS TO SUPPORT MULTITASKING PERFORMANCE IN COMPLEX DOMAINS

A Dissertation

by

WIL-JOHNEEN ARDOIN WHITE

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Chair of Committee,	Thomas K. Ferris
Committee Members,	S. Camille Peres
	Steven M. Smith
	Tanya D. Wickliff
Interdisciplinary Program Director,	Timothy Jacobs

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ABSTRACT

The task sets for operators in many data-rich domains are characterized by high mental workload and the need for effective attention management, so the ability to effectively divide attention among multiple tasks and sources of task-relevant data is essential. With increasing technological advances, more and more sources of task-relevant data are being introduced in these already complex domains, thus introducing an increased risk of “data overload” – a cognitive burden which can lead to a substantial decline in operator performance. To combat this risk, it is important to consider how to best display the information for more efficient attention allocation and task management and thus improved overall multitask performance. A great deal of display design research has been centered around redundancy in multisensory information presentation, i.e., the presentation of identical information via two or more sensory channels, as a means to better support multitasking performance. One example is a display that delivers the same message via auditory speech and visual text. This redundant display of information may allow a multitasking operator to access the message via either channel, presumably the one less-loaded at the time. However, models of human information processing (such as multiple resource theory; MRT) as well as prior studies demonstrate a need for more than consideration of the sensory modality, but also consideration of the working memory functions engaged to interpret the encoded message.

This dissertation proposal expounds the concept of multi-processing code redundancy, which makes use of both spatial and nonspatial working memory functions to deliver information. The primary aim of this research is to investigate how the introduction of a multicode vibrotactile display (one that presents identical information using two dimensions of tactile display) will affect overall multitasking performance when processing demands for concurrent tasks vary over time. Three studies were performed to gain an understating of the benefits and limitations of a discrete and a continuously-informing multicode display when concurrent tasks have changing processing demands. Findings of this dissertation illustrate that *multicode* redundancy shows promise for combating processing code interference described by MRT (by allowing either processing code to be engaged in message interpretation) and may prove beneficial in complex domains that involve concurrent tasks with competing working memory resources.

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CHAPTER I

INTRODUCTION

The potential for information overload in data-rich domains such as aviation, medicine, military and even the car cockpit is ever increasing as more sophisticated technologies and sources of task-relevant data are made available. It is imperative that human operators in these environments effectually manage information while performing multiple tasks and maintaining a sufficient level of situational awareness for response to unexpected events. For example, an aircraft pilot must simultaneously control his aircraft, plan maneuvers, navigate, communicate with air traffic control, and monitor and manage other aircraft systems (Mavor, & Pew, 1998): all tasks that are dependent on an ongoing, continuously-changing analysis of the environment. Attention and working memory have been presented as critical limitations that may inhibit human operators from acquiring and interpreting information from their environment (Endsley, 1995; 2016). Therefore, it is important to consider how to best display relevant information to allow for efficient attention allocation and task management.

Multisensory displays – displays that present information via two or more sensory channels – have been widely proposed as a means to help operators divide attention between multiple tasks and sources of task-relevant data. In situations where there is heavy demand on one or few sensory channels (e.g., the visual channel of an automobile driver or aircraft pilot), dividing information between multiple senses may result in improved multitasking performance. This notion is based on Multiple Resource

Theory's (Wickens 1980; 2002) assertion that information can be processed more efficiently by distributing that information across multiple sensory channels (i.e., vision, audition, touch). These multisensory displays do offer a potential benefit in that they can be reliably processed in task environments where loads for individual processing resources vary and are difficult to predict. Often multisensory displays are used redundantly (relaying the same information as an alternate display via a different sensory channel), which can further improve the likelihood of a message being received. For example, presenting a voicemail message via auditory speech and visual text can support flexibility in receiving the message in environments that may at times impose high loads on either the visual or auditory resources.

Redundancy Gains, Costs and the Role of Multiple Resource Theory

A number of studies have provided empirical evidence for the benefits of redundant multisensory displays. Liu and Jhuang (2012), investigated visual, auditory, and redundant visual+auditory displays in a driving simulation and found that redundantly displaying warning information to participants supported increased speed and accuracy when responding to the warning. Similarly, Ho, Reed, and Spence (2007) found that the use of a multisensory in-car warning system was most effective for supporting speeded response to hazard warnings when compared to unisensory systems. Lastly, van Erp and van Veen (2004) found that participants responded faster when navigational messages were presented via the redundant bimodal display (vision and touch) than when they were presented unimodally. The results of these studies demonstrate that redundantly displaying a message via multiple sensory channels can lead to better performance, an advantage referred to as “redundancy gain” (Wickens et al., 2011).

Conversely, some studies have shown that redundant multimodal presentation might not always benefit performance and in fact at times may lead to a performance decrement, referred to as “redundancy cost” (Wickens et al., 2011). Stanley (2006) examined the use of haptic, auditory, and combined haptic+auditory cues as lane departure warnings and found that driving performance using the combined sensory warnings was the same or worse than that of the unisensory alerting cues. Additionally, in a dual-task patient monitoring simulation, Seagull, Wickens, and Loeb (2001) found that participant performance was poorer when patient parameters were presented both visually and auditorily, a redundancy cost, then when parameters were displayed either visually or auditorily alone.

Redundancy gain and cost effects are consequences that illustrate the need to carefully consider how task-relevant data are displayed in multitasking environments so information processing resources can be employed efficiently. This requires more than consideration of the sensory modality (e.g., vision, audition, or touch) – most often the dimension of interest for redundant displays – but also consideration of the working memory functions that must be engaged to interpret and respond to the encoded message.

Multiple Resource Theory of human information processing (MRT; Wickens, 2002; 1980; Wickens & Hollands, 2000) provides a framework for describing separable dimensions, and levels within those dimensions, of an individual’s limited mental resources. It asserts that multitask performance can be supported to the extent that concurrent tasks require different levels of three primary dimensions: *processing stage*, *sensory modality*, and *processing code* (where solid lines denote divisions of resources; see Figure 1-1). MRT is probably most often cited to justify distributing processing across multiple levels within the sensory modality dimension. According to the model, interference among tasks occurs if common processing resources are required for the completion of two or more tasks. For example, more interference is likely to occur between a driving and texting task (both relying heavily on visual perception) than between a visual and a tactile task, all else being equal. However, the model also shows that the benefit of distributing displays among sensory modalities primarily exists during the perceptual processing stage. In later stages (cognitive and response) it matters less which senses were engaged in perception. What matters more so are the working memory functions that must be engaged to decode and interpret displayed messages and to plan and activate responses. MRT describes the dimension that distinguishes these working memory functions as “processing code” and separates spatial/analog processing from nonspatial/verbal processing (see Figure 1-1).

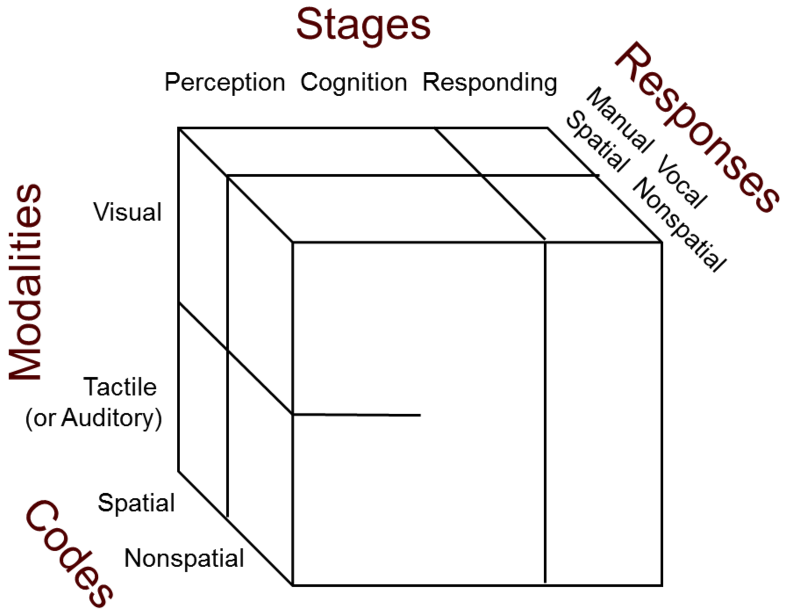

Figure 1-1: Adapted model of the structure of processing resources for a visual/tactile or auditory task set. Adapted from Wickens & Hollands, 2000 (see also Wickens, 2002; 2008).

This dichotomy of processing code resources is in accord with prominent theories and models of working memory such as Baddeley's (1992). In addition to a central executive coordinating function, Baddeley (1992) describes two primary working memory sub-systems: the visuospatial sketchpad responsible for processing visual and spatial information, and the phonological loop responsible for processing sounds and verbal information that you hear (i.e., aural speech) as well as create. The function of the phonological loop also extends beyond processing auditory sources of verbal information. An "inner speech" articulatory component can transform visually-displayed words, nameable images, and other symbolic content into verbal information. The two working memory components have separate but limited capacities (Baddeley, 2006), thus a person can perform a phonological task and a visuospatial task simultaneously without a substantial decline in performance. However, interference can arise when two tasks require the same working memory function, such as visualizing a sports broadcast while navigating a vehicle, two visuospatial tasks (Baddeley and Hitch, 1974), leading to a decline in performance of one or both tasks.

The role of processing codes in producing task interference has been thoroughly documented in the literature (e.g., Baddeley and Lieberman, 1980; Ferris & Sarter, 2009; Kinsbourne and Hicks, 1978; Wickens and Sandry, 1982; Wickens and Weingartner, 1985). MRT predicts that two tasks will have greater interference if they both demand spatial or verbal processes across any stage. For example, reading navigational instructions while listening to speech or providing vocal response engage separate sensory modalities, but require the same nonspatial/verbal processing code resources. Hence, the tasks are very difficult to effectively perform in parallel. This interference is further enhanced if within-code competition is also imposed within a stage (e.g., spatial perception and spatial memory) rather than between stages (e.g., spatial memory and manual response; Wickens & Liu, 1988).

Tactile Displays

In designing to reduce task interference and support multitasking performance in complex domains, one area of growing interest is the design of displays which communicate using the sense of touch. These displays are desirable in data-rich environments for two main reasons: (1) there are usually fewer competing demands for the sensory channel (Jones & Sarter, 2008) and (2) the tactile channel combines a number of unique affordances. Like audition, touch is omnidirectional, so signals can be perceived from any location or position. However, unlike audition, touch is also a proximal sense in that tactile devices must be in contact with the skin, allowing for privatization of displayed information. Touch is comparable to audition in its spatial discrimination capabilities and to vision in temporal discrimination (Geldard, 1960).

Vibrotactile displays, which present information through coded patterns of vibrations on the skin, have seen a major surge in both research and commercial development (e.g., Kern, Marshall, Hornecker, Rogers, & Schmidt, 2009; Ho, Reed, & Spence, 2007; Brewster, Wall, Brown, & Hoggan, 2008; Gallace, Tan, & Spence, 2007). When properly designed, tactile information can be processed while minimally competing with ongoing visual and auditory tasks, potentially reducing the overall attentional load and improving multitask performance (Wickens, 2008; 2002). Thus, these displays provide a promising means of communicating task-related information in complex environments where operators' visual and auditory channels are heavily loaded.

Tactile displays can be relatively simple, such as a pulse from a cellphone set to vibrate mode or a seat vibration to designate a lane departure warning (Fitch et al., 2007) or complex allowing a greater density of information to be communicated, such as in navigational instructions (Hogema et al., 2009). Structured, abstract messages known as "tactons" (tactile icons) are examples of tactile displays that have potential for greater degrees of complexity (Brewster & Brown, 2004) and are similar to icons in the visual domain and Earcons in the audio domain. Tactons can make use of several dimensions, such as intensity, frequency, waveform duration, rhythm, and spatial location, of a tactile display to encode an underlying message (Geldard, 1960; Brewster & Brown, 2004). These parameters can be combined redundantly (two or more parameters are manipulated together to encode the same information) or orthogonally (each parameter is manipulated independently to encode a different dimension of information; Brown, 2007). Furthermore, tactile displays can be used to communicate discrete event messages (e.g., lane departure warnings; Stanley, 2006) or can be used to present continuous or semi-continuous messages (e.g., patient physiological data; Ferris & Sarter, 2011).

Why Multicode Redundancy

To date, most tactile designs have been introduced in the form of multisensory interfaces and displays. The sense of touch is commonly used in conjunction with vision to either reinforce the same task or to support concurrent performance when operators must complete multiple tasks simultaneously. As previously mentioned, much of this work has demonstrated that multisensory redundancy can produce performance gains or costs and highlights the need for consideration of concurrent task demands beyond the engaged sensory modalities (Ardoin & Ferris, 2014; 2016; Ferris & Sarter, 2011). While tactile-visual redundancy of information provides an opportunity to offload visual resource demands, the dual mode of presentation may lead to an increase in mental load if the working memory operations needed to decode and interpret the tactile information compete for the same pool of processing resources as a concurrent task. For example, imagine following navigational instructions that can be accessed using a visual map or spatialized vibrations while also traversing an unfamiliar construction zone. The navigational instructions presented via two sensory channels may provide the driver flexibility to engage either the visual or tactile display of information, however, interpreting that information (whether visually or tactually) requires the same limited spatial working memory resources also needed to navigate the unfamiliar construction zone. This additional demand on spatial resources may lead to an increase in mental load. This dissertation expounds the concept of “multi-processing code” (or *multicode*) redundancy in a vibrotactile display as a way to combat competition for working memory and attentional resources among tasks, thus better supporting multitasking in complex environments. For the purpose of this research, the working memory functions (or processing codes) will be described here as either *spatial*, e.g., activities that require spatial processing such as judging the locations of presented stimuli, or *nonspatial*, e.g., activities that require processing content such as temporal properties or other symbolic/verbal qualities.

Similar to multi*sensory* redundancy, multi*code* redundancy also presents information using separable channels within a dimension described in MRT; however, the focus is now shifted from the sensory (modality) dimension to the processing codes dimension (see Figure 1-1). Multicode redundancy seeks to make use of both spatial and nonspatial processing codes to deliver information by simultaneously manipulating two parameters of a signal presented to a single sensory channel. One example is a traffic light, which uses both color (a visual, nonspatial property) and light position (a visual, spatial property) as ways of presenting the same information. Both signals are presented visually but utilize different processing codes. The idea of multicode redundancy is to design displays that support more flexibility in the way information can be processed in perceptual and cognitive stages (i.e., providing the ability to use *either* spatial *or* nonspatial working memory depending on concurrent task demands). Such flexibility should allow processing loads to be more efficiently distributed among working memory resources, thus better supporting multitask performance (Wickens 1980; 2002). Since perception via the sense of touch is reliable in processing both the spatial and nonspatial qualities of a signal (Geldard, 1957; 1960; Jones & Sarter, 2008), vibrotactile displays can serve as an effective instrument for multicode redundancy in complex domains that face problems with visual and auditory overload.

To date, very few studies have utilized tactons to present *identical* messages via multiple dimensions of the tactile channel (e.g., use of both spatial location and frequency to communicate a change in state). Much of the research in the area of tactile displays has focused on solely presenting either spatial or nonspatial signals to convey task-relevant information (Ho, Reed & Spence, 2007; Ho, Tan, & Spence, 2005; Hogema, De Vries, van Erp, & Kiefer, 2009; van Erp & van Veen, 2004). However, in a study performed by Ferris & Sarter (2011), a novel vibrotactile display designed using spatial (e.g., orientation of blood pressure) and nonspatial (e.g., intensities for respiratory measures) signals was investigated in an anesthesia simulation. The display showed promise for effective communication of task-relevant information in support of attention management and multitasking. Though a multi-processing code display was employed in this study, a multicode redundancy gain was *assumed* but not explicitly *tested*, and it remains an open question whether this novel type of display produces better performance (redundancy gains) or performance decrements (redundancy cost) in comparison to a unicode display, which utilizes a single processing code dimension to communicate information.

While the benefits and limitations of multimodal redundancy are well documented, the concept of “multicode” redundancy and its effects on multitask performance have not been thoroughly explored. This thesis will investigate how discrete and continuously informing multicode displays designed using tactons (structured, abstract tactile messages; Brewster & Brown, 2004) ultimately affect multitask performance and whether these types of display produce better or poorer overall performance than a unicode display.

Research Questions

The primary research goal of this dissertation work is:

To investigate how the introduction of a multicode vibrotactile display (one that presents identical information using two dimensions of tactile display) will affect overall multitasking performance when processing demands for concurrent tasks vary over time.

Investigating this gap is important when considering the safety implications of processing code interference in data-rich, event-driven domains, such as aviation, medicine, military, or the car cockpit, and may aid in the prevention of incidents that affect operator safety or the safety of those under their care. This research will investigate whether and to what extent redundant encoding methods for vibrotactile displays (both discrete and continuous) support multitasking when concurrent tasks have changing processing demands. This can be decomposed into the following two research questions:

1. *What are the performance benefits and limitations of a multicode vibrotactile display in multitask scenarios when concurrent tasks have changing processing demands?* This question is addressed in Chapter II using a discrete set of tacton displays encoded with spatial location and/or vibration pulses. The tacton messages were presented to participants while they were engaged in driving tasks.
2. *What are the effects of a task-relevant multicode display on multitask performance in a monitoring task under various workload demands?* This question is addressed in Chapter IV using continuously-informing tactons encoded via spatial location and/or pulse frequency mapped to a simulated monitoring task. The design of the monitoring task was informed by the findings of an observational study described in Chapter III and incorporates both multimodal and multicode redundancy.

The research efforts described in this dissertation contribute to theories of tactile and multimodal information processing and the structure of cognitive resources. Although Multiple Resource Theory is often cited to justify distributing processing across multiple senses, the model illustrates that the benefit of distributing displays among sensory modalities exists mainly during the perceptual processing stage (Ardoin & Ferris, 2014; 2016; Ferris & Sarter, 2011; Wickens, 2002; 1980). In the later cognitive and response stages what matters more so are the working memory functions (processing codes) engaged to decode and interpret displayed messages and to plan and activate responses (see Figure 1-1). It can be inferred that when task-related workload is high and one processing resource is more heavily loaded than others, the risk of cognitive overload can be reduced by engaging the relatively available channels to offload those with higher demand. Thus, if a message is encoded redundantly using both spatial and nonspatial rules, an operator should be able to interpret it by engaging the processing resources that are relatively available, so that processing interference is minimized. However, it may also be found that the increased complexity of the redundantly encoded signal could impose a heavier processing load resulting in a decline in multitask performance.

The main objectives of this dissertation are to investigate the effects of multicode redundancy and to inform the development of a multicode vibrotactile display that may support decoding a message by attending to either the spatial locations or a nonspatial component in the displayed pattern. The present research is important for the design of both multimodal and tactile displays intended to support multitasking in complex, data-rich domains. Findings will provide insight into a fundamental question of human information processing regarding whether humans can effectively select which processing code/working memory functions they engage when interpreting a redundantly-encoded message.

CHAPTER II

A FIRST INVESTIGATION OF REDUNDANT ENCODING METHODS FOR TACTILE MESSAGING IN MULTITASK SCENARIOS*

Previous research has shown that humans can interpret moderately complex tactile messages and gain performance benefits when tactile displays are introduced in multitasking domains where visual resources a heavily utilized. The benefits are assumed to stem from a reduced competition for visual attention; however, multitasking performance can also be affected by competition for cognitive processing resources, such as spatial or symbolic working memory. Thus, when selecting tactile signal dimensions for encoding messages (e.g., in spatial or temporal patterns), multitasking can be best supported when the cognitive processing demands of concurrent tasks are considered. This chapter describes a study which was the first investigation determining whether the use of multicode redundancy in a tactile display would better support performance in a dual-task scenario. The study investigated discrete tactile messages that were encoded redundantly (using both spatial location and waveform duration) and thus could be fully interpreted by engaging either spatial or symbolic *processing resources.* Because of the recent surge in research and commercial development of in-vehicle tactile displays, this experiment was conducted in a highly-controlled driving simulation.

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Introduction

Recognizing the high demand for visual (and to a lesser extent, auditory) resources in the driving domain, there has been a surge in the interest and development of tactile displays for use in the car cockpit. Examples include whole-seat vibrations that serve as lane departure warnings (Stanley, 2006) and vibrations presented to individual locations on the seat to indicate the direction of a pending collision (Fitch, Kiefer, Hankey, & Kleiner, 2007). Seat-based directional vibrations have also been used to communicate navigation instructions or other directional information (Hogema, De Vries, van Erp, & Kiefer, 2009; van Erp & van Veen, 2004). Other in-vehicle vibration presentation locations include the steering wheel (Kern, Marshall, Hornecker, Rogers, & Schmidt, 2009), on the torso as if via a seatbelt (Reed & Spence, 2007), and through the throttle or brake pedals (Lee, Hoffman, & Hayes, 2004). Vehicle manufacturers have begun including vibrotactile displays, such as seat-based directional collision warnings, as standard or optional features in their new models.

As discussed in Chapter I, tactile displays can be simple, such as a vibrating pulse from a cellphone or more complex, such as in navigational instructions. More complex displays can increase the density of information being communicated but may also increase processing load. Tactons are examples of tactile patterns that range broadly in complexity and make use of several dimensions of tactile display to encode an underlying message (Brewster & Brown, 2004; also see Chapter I).

When introducing more complex tactons to multitask environments, previous research has demonstrated how the dimension(s) used to encode the message can greatly influence their interpretability, as well as performance on concurrent tasks. Multiple resource theory (MRT; Wickens 1980; 2002) provides a framework that describes separable dimensions of an individual's limited information processing resources that can be allocated to tasks. In general, crossmodal multitasking (e.g., visual and auditory, or visual and tactile tasks) has been shown to support better performance than intramodal multitasking (e.g., two visual tasks; Kieras & Meyer, 1997). However, MRT shows that the benefit of distributing displays among sensory modalities primarily exists during the early perceptual stages of information processing. After displayed data have been perceived, processing moves to the cognitive stage, and later to the response stage. In these later stages, it matters less which senses were engaged in perception; what matters more so are the working memory functions, namely processing codes, that must be engaged to decode and interpret displayed messages and to plan and activate responses (see Figure 1-1; Wickens, 2002).

This chapter considers human performance under conditions when there is competition for working memory resources between tasks that engage the visual and tactile senses. The study investigated whether tacton displays could be designed to support flexibility in the interpretation of information with regard to the required processing resources. Such flexibility would allow processing loads to be more efficiently distributed among working memory resources, thus better supporting multitask performance. Previous work (e.g., Ferris & Sarter, 2010) suggests that multitask performance for a task set that includes tacton interpretation suffers considerably more when primary processing code requirements (e.g., spatial or nonspatial processing codes) are the same between tasks versus when separate codes are required between tasks. Therefore, when processing demands for concurrent tasks vary over time (from primarily spatial to primarily nonspatial), redundantly encoded tactons may best support load distribution by allowing the tacton message to be decoded by attending to either the spatial locations of presented vibrations or a nonspatial property such as rhythm.

While more efficient load distribution may improve multitask performance – an advantage referred to as "redundancy gain" (see Chapter I) – a tacton that encodes its message in multiple dimensions is more complex than a unidimensional tacton. The added complexity in the signal may impose additional processing load during tacton interpretation and can negatively impact multitask performance (a "redundancy cost;" Chapter I).

Because of the considerable interest in research and commercial development of in-vehicle tactile displays, this experiment tested the benefits and limitations of redundantly encoded tactons in a dual-task experiment (tacton interpretation+ visual tasks) set in a controlled driving simulation. Simple visual tasks were used to convey navigation instructions to the driver and were designed to emphasize either spatial or nonspatial information processing. Tactons – which provided spatial and/or nonspatial messages – were presented to the driver's back. Dual-task scenarios were designed such that the visual task stimuli and the tactons were presented simultaneously requiring concurrent processing of the encoded information in both displays.

It was expected that redundancy gains would be observed; that is, participants would be able to shift attention between the spatial and non-spatial dimensions of the redundantly encoded tactile messages and thus better balance loads during multitasking. However, the added complexity of the redundant tacton signals may limit this benefit, illustrating redundancy cost. It was expected that redundant tactons would support equivalent or better performance than the worst-case dual-task pairing: unidimensional tactons and concurrent visual tasks that share the same processing requirements. A second prediction was that the redundant tactons would support equivalent or worse performance than the best pairing: unidimensional tactons and visual tasks that require separate processing codes.

Related Work

In a series of studies set in driving simulators, Ferris and Sarter (2010) investigated the role of processing code on the ability to perform a multitask set which included a visual task and a tacton-interpretation task. Each type of task was designed to isolate cognitive processing to either the spatial or nonspatial processing code as much as possible. For example, spatial tactons required identifying the sequence of locations on the body where vibrations were presented, while nonspatial tactons required recognizing the presentation rhythm or number of pulses presented to a single location. Similarly, the visual tasks required interpreting and acting on sequentially presented visual stimuli which carried information either in their presentation location (visual-spatial task) or in a nonspatial dimension such as the hue of the presentation (visual-nonspatial task). As expected (and in concurrence with MRT extended to the tactile channel), dual-task performance decrements that were significantly and substantially larger when decoding the tacton message and processing the images for the visual task required the same processing code (see Table 2-1). The current experimental design was modeled loosely after Ferris and Sarter (2010) in order to compare performance results.

Table 2-1: Decrements in Performance in Dual-Task Conditions Relative to Performance in Single-Task Conditions for Concurrent Visual and Tacton-Decoding Tasks (adapted from Ferris and Sarter, 2010).

		Visual-spatial task	Visual-nonspatial task
Tacton encoding method	spatial	15.9%	5.4%
	nonspatial	7.0%	11.7%

As mentioned in Chapter I, redundantly displaying the same message via multiple sensory channels in multimodal displays can lead to better performance in multitask environments, which illustrates redundancy gain. When task-related workload is high and one sensory channel is more heavily loaded than others, relatively available sensory channels can be engaged to process a redundant message. Conversely, studies have also shown how redundant multimodal presentations can negatively impact performance, illustrating redundancy cost. Wickens et al. (2011) asserts that this cost may reflect that the presentation of redundant information can require more time to process than a single modality, which seems to challenge the basic MRT assumption of independent and parallel processing for separate sensory channels. Another potential reason for the cost is that the individual sensory components of the redundant message may not “fuse” and thus impose additional processing. In other words, instead of getting one message, the person attempts to process both streams separately and concurrently. This is similar to when lip movements do not synchronize with the sound track in an overdubbed foreign film (Wickens et al., 2011). While the benefits and costs of multimodal redundancy are well documented, the effects of “multicode” redundancy within a single modality are not well known.

With limited data, a study performed by Ardoin & Ferris (2014) demonstrated that redundant tactile messages can show either redundancy gain or cost in dual-task settings. The research discussed in this chapter further develops the previous study controlling for ordering effects and quantifying multitasking performance in a manner that accommodates differences in task strategy. This allows broader conclusions to be drawn about the performance effects of employing redundantly encoded tacton displays. Understanding the benefits and limitations of redundant encoding is useful for the design of complex tactile displays that are informative yet minimally interfere with concurrent task processing in multitask environments. The research also provides insight into whether and to what extent humans can effectively select and/or switch between engaged working memory functions when decoding a redundantly encoded message.

Methodology

Thirty-six students (28 males and eight females, ages 18–32) participated in this study. All possessed a valid driver’s license for at least one year and had normal or corrected-to-normal visual acuity and no known conditions limiting the tactile sensitivity of the back. They drove a simulated vehicle in scenarios created in STISIM Drive, a PCbased driving simulator, with a force feedback steering wheel and floor-mounted throttle and brake pedals. A pair of adjustable suspenders and an adjustable neoprene support belt were worn over participants' clothing, securing four pairs of C-2 "tactors" (solenoid-based vibrating devices developed by Engineering Acoustics, Inc.) to the four corners of the upper and lower back (see Figure 2-1). The tactors, approximately 30 mm in diameter, were affixed to the suspenders with Velcro. The neoprene belt was secured over the suspenders. Vibrotactile stimuli were displayed with a frequency of 250 Hz and at the maximum gain, resulting in a sensation that was similar in intensity to that of a cell phone set to vibrate mode. Noise-canceling earbuds were used to play scenario-related sounds and mask the audible tactor activation.

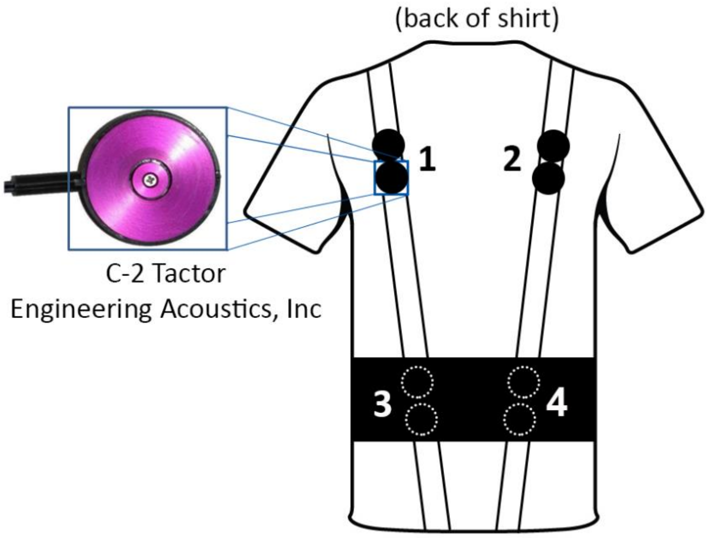


Figure 2-1: Arrangement of C-2 tactors for the tactile display.

Driving Scenario

Each scenario consisted of a four-lane road with alternating open stretches and “obstacle zones” (32 trials per task condition). The obstacle zones included longitudinal parallel barriers so lane changes were not possible while within the zone (Figure 2-2). During tactile single-task conditions (for which visual task stimuli were not presented), all four obstacle zone lanes were unobstructed, and participants could choose to enter the zone from any lane. During visual single-task and dual-task (tactile+visual tasks) conditions, three of the four lanes were obstructed, and participants were instructed to pilot the vehicle into the unobstructed lane. The location of the unobstructed lane was randomized and balanced across trials and could be inferred only by correctly interpreting the visual task stimuli. If participants entered an incorrect (obstructed) lane they encountered a barrier, causing a mild crash sound but allowing the car to continue unabated. Visual and tactile stimuli for trial N+1 were presented within the latter half of the obstacle zone for trial N. This allowed participants to observe the stimuli when the steering wheel was in the “home” position so that the embedded but-tons were properly mapped to tactile task stimuli. Participants driving at the maximum governed speed of 30 m/h experienced trials approximately every 10 s.

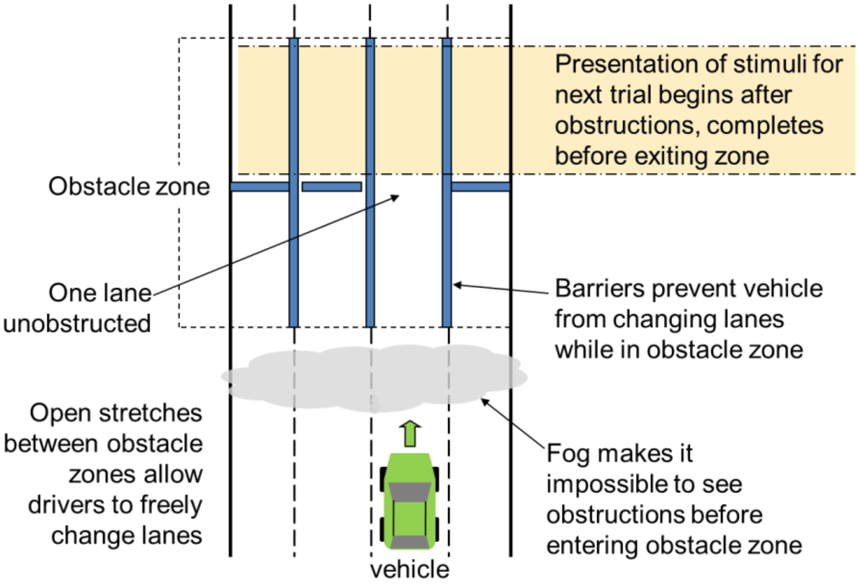


Figure 2-2: Schematic of an “obstacle zone” in the driving scenarios.

Visual Tasks

Visual tasks required combining information from three successive images to determine which lane was unobstructed in the upcoming obstacle zone. These images were presented 1000 ms apart as if on a head-up display (see Figure 2-3) and coincided with tacton vibrations in dual-task conditions.

Images for the visual-spatial task were overhead views of the obstacle zone, each showing the spatial location of one of four obstructed lanes (in randomized order), leaving one to be identified as unobstructed. The images for the visual-nonspatial task were three numbers (1, 2, 3, or 4, in randomized order) and participants determined which number was not displayed. After exiting the obstacle zone, a randomized “key” that consisted of an image of four lanes labeled with the four numbers was displayed on the screen until shortly before the next obstacle zone. The unobstructed lane was labeled with the number that had not been displayed. The performance measure was the accuracy of lane choice, i.e., the percentage of trials in which the participant entered the unobstructed lane.

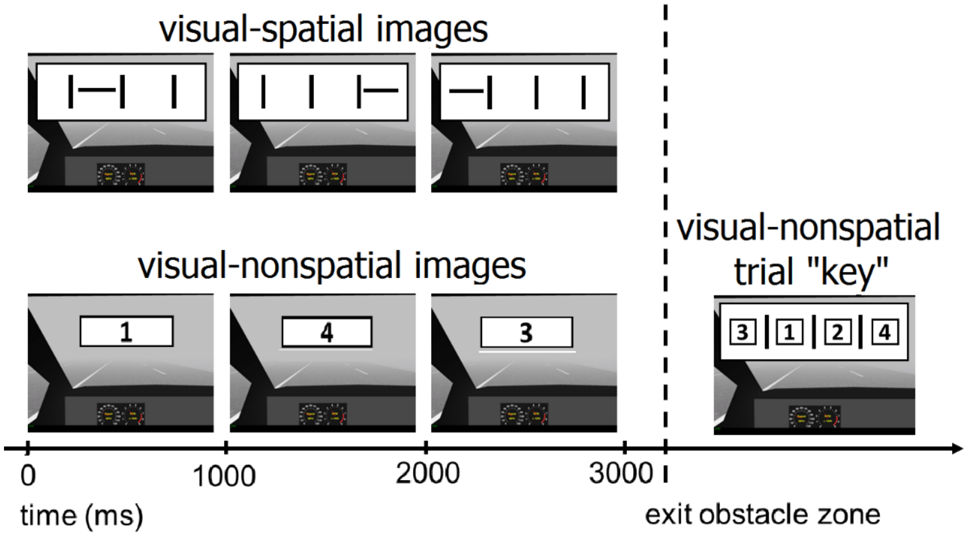


Figure 2-3: Visual task images. Each image sequence indicates the third lane from the left as unobstructed.

Tacton Identification Tasks

Participants were told that the vibrations they received were tactons providing generic information such as the logging of various engine performance metrics. Three types of tactons were created to require similar processes for interpretation but differ in encoding methods: *spatial, nonspatial, or redundant* encoding. The tactons were defined by two 1000-ms presentation "segments" separated by an equivalent off-time so that the entire presentation lasted 3000 ms. For dual-task conditions, the tacton presentations were synchronized with the display of visual task images.

While gripping the steering wheel, three buttons aligned vertically on each side could be reached by the thumbs. The middle buttons were covered with foam tape to distinguish them haptically from the other buttons. Each *tactile-spatial* segment consisted of a 1000-ms vibration pulse presented to one of four body locations (see Figure 2-1), which spatially mapped to the four corner buttons on the steering wheel. If the first and second segments were from differing corners, participants were instructed to press, in order, the corresponding buttons on the steering wheel. If the segments were presented at the same location, participants were instructed to press both middle buttons simultaneously. The different response types required participants to receive the entire tactile message before responding, rather than initiating the response after the first segment.

Each *tactile-nonspatial* segment was a sequence of pulses evenly divided over 1000 ms with a straight cadence: one 1000-ms pulse, two 400-ms pulses, three 250-ms pulses, or four 150-ms pulses (see Figure 2-4). The off-times between pulses varied between 133 and 200 ms so that the conclusion of each message ended at the same time. Segments were presented via all four tactor locations, activated simultaneously. Participants responded by pulling paddles behind the steering wheel reached by the fingers of either hand while gripping the wheel. If the two vibration segments were a different number of pulses, participants pulled the left then right paddle, respectively, a number of times that corresponded to the number of pulses in the first and second segment. For example, if the first segment was four pulses and the second segment was one pulse, the participant pulled the left paddle four times then the right paddle once. If the two segments were the same number of pulses, participants were instructed to pull both paddles simultaneously one time. This method was designed to minimize the amount of spatial processing that was required in the response activity, since nonspatial processing was to be emphasized.

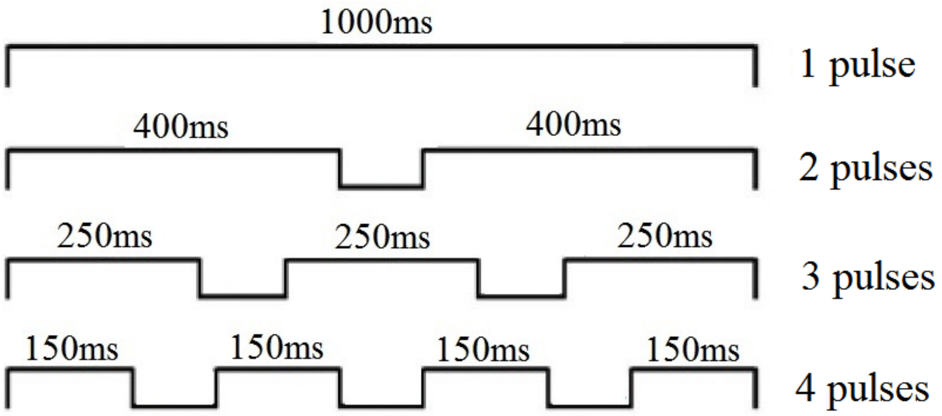


Figure 2-4: Pulse patterns that could be presented for a vibration segment of nonspatial and redundant tactons (adapted from Ferris and Sarter, 2010).

Tactile-redundant segments were defined by the spatial location of the presentation as well as pulse count at that location (e.g., one pulse at the top left corner, two pulses at the top right corner, three at the bottom left, four at the bottom right) (see Figures 2-1 and 2-4). Participants could receive the complete tactile message by attending to *either* the spatial location *or* the number of pulses. They responded to the tactile-redundant cues via either response method, i.e., buttons or paddles, which were used for the *tactile-spatial* or *tactile-nonspatial* tasks, respectively.

Performance measures for tactile tasks were tacton identification accuracy, i.e., the percentage of correct button/paddle responses, and response time (RT), measured from the beginning of pattern presentation until the first paddle or button activation. Only RT data from correct responses were considered. Participants were not given feedback regarding the accuracy of their tactile-task performance during the experiment.

In dual-task conditions, since the visual task response (changing lanes) could not begin until after exiting the obstacle zone, participants were encouraged to respond to the tactons before initiating a response to visual task stimuli to minimize tactile task RT. Participants were told that both tasks were equally important, but that they could adopt any strategy to prioritize the tasks to achieve the best overall multitasking performance.

Experimental Procedures

A 30-min training session comprised of five single-task scenarios (*visual-spatial, visual-nonspatial, tactile-spatial, tactile-nonspatial,* and *tactile-redundant* task conditions) and six dual-task scenarios (each combination of the visual and tactile tasks) introduced participants to each task condition and allowed practice responses. The scenarios included five trials for each task condition.

The experimental session consisted of 11 task scenarios, each of which was five and a half minutes and consisted of 32 trials. Participants first completed the three single-task tactile conditions, with order balanced between participants, followed by the two single-task visual conditions, also with order balanced. Then, they completed the six dual-task scenarios. Those involving the same tacton were always completed in back-to-back paired "sets" in order to minimize confusion about required responses. The order of dual-task conditions within each tacton set (i.e., the order of the visual tasks paired with a given tacton) was balanced.

Between scenarios, participants rated the perceived level of difficulty for the immediately completed condition on a ten-point scale ranging from 1 (*very easy*) to10 (*very difficult*) and also explained any notable strategies employed. Then, they were reminded of instructions and required responses for the next task condition to minimize performance costs attributable to task-switching between scenarios (Monsell, 2003). After completing the first five scenarios, participants were required to stop for a break. The entire experiment took approximately 2 hours, and participants received $15 as compensation.

Results

For simplicity, task conditions will be further abbreviated in the text with notations listed in Table 2-2. Data were analyzed using repeated-measure ANOVAs formulated in IBM SPSS Statistics 22 with $\alpha = 0.05$. Marginal effects are reported for p values less than 0.1. Fisher's LSD posthoc tests were used to determine differences between means and a Huynh–Feldt correction was applied when data failed the assumption of sphericity. Datasets from three participants were removed due to simulator failures that interfered with data collection and task performances that were more than three standard deviations outside of the mean. Additionally, subjective ratings data for one participant were removed for a failure to comply with survey instructions.

Table 2-2: Summary of Task Conditions and Notations.

Notation	*Task Condition*	*Description*
V_S	Visual-Spatial	Overhead view shows 1 of 4 obstructed lanes, leaving one to be identified as unobstructed (Figures 2-2 & 2-3).
V_N	Visual-Nonspatial	Overhead view shows 3 of 4 numbers, successively. Use "key" to determine unobstructed lane, labeled with number not previously displayed (Figure 2-3).
T_S	Tactile-Spatial	Tactons presented to one of four body locations (Figure 2-1). Response method: button press
T_N	Tactile-Nonspatial	Tactons presented as sequence of pulses via all four locations, activated simultaneously (Figures 2-1 & 2-4). Response: paddles
T_R	Tactile-Redundant	Tactons presented via spatial location and pulse count at that location (e.g., 1 pulse at the top left corner) (Figures 2-1 & 2-4). Response: buttons or paddles
T_S+V_S T_N+V_S T_R+V_S	Dual-task combinations involving visual-spatial task	Combination of visual-spatial task and tactile-spatial, tactile-nonspatial, or tactile-redundant task as described above.
T_S+V_N T_N+V_N T_R+V_N	Dual-task combinations involving visual-spatial task	Combination of visual-nonspatial task and tactile-spatial, tactile-nonspatial, or tactile-redundant task as described above.

Tacton Identification Performance

Identification Accuracy

Overall, accuracies in the T_S, T_N, and T_R conditions did not differ significantly (see Figure 2-5). However, within each of the three tacton types, task condition impacted identification accuracy: *spatial* ($F(1.630,52.170) = 17.36$; $p <0.001$); *nonspatial* ($F(2, 64) = 9.17$; $p < 0.001$); and *redundant* ($F(1.533,49.070) = 2.92$; $p = 0.076$). Posthoc tests showed that accuracy was better in the T_S condition than in both the $T_S + V_S$ condition ($p < 0.001$) and the $T_S + V_N$ condition ($p = 0.004$; see Figure 2-5). Additionally, accuracy in the $T_S + V_N$ condition was significantly higher than in the T_S+V_S condition ($p = 0.002$).

Similarly, for conditions involving T_N identification accuracy, the single-task condition (95.5%) was significantly higher than both $T_N + V_S$ ($p = 0.001$) and $T_N + V_N$ dual-task conditions ($p = 0.002$). Accuracies for $T_N + V_S$ and $T_N + V_N$ did not differ significantly (see Figure 2-5).

Finally, identification accuracy in the T_R condition did not differ from $T_R + V_S$ ($p = 0.136$) but was marginally higher than the $T_R + V_N$ condition ($p = 0.063$). As in the T_N dual-task conditions, accuracies in $T_R + V_S$ and $T_R + V_N$ did not differ significantly (see Figure 2-5).

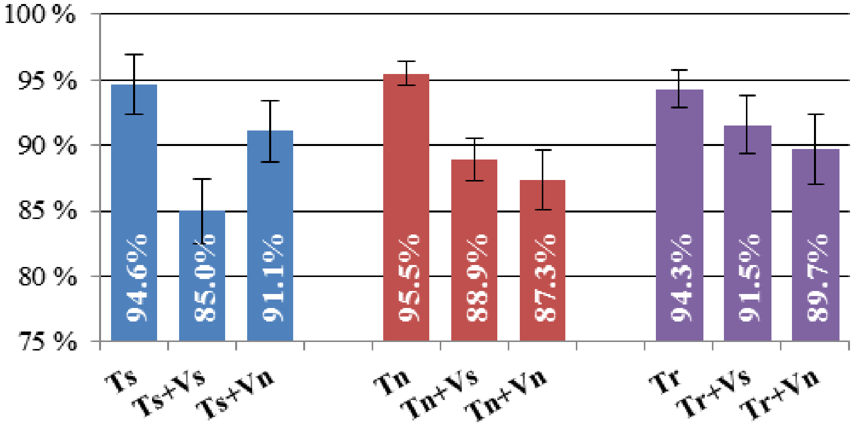


Figure 2-5: Tacton identification accuracy for conditions involving each type of tacton encoding method (Ts: spatial; Tn: nonspatial; Tr: redundant). Error bars represent standard error.

Response Times

Shown in Figure 2-6, mean RTs differed significantly across single-task conditions ($F(1.698,54.332) = 20.161$; $p < 0.001$). Participants responded significantly faster in the T_S condition than in the T_N ($p < 0.001$) and T_R conditions ($p = 0.001$). RTs were also significantly faster in the T_R condition than in the T_N condition ($p = 0.009$).

RTs were compared across task conditions within each tacton type. Among conditions involving the T_S task ($F(2,64) = 7.765$; $p = 0.001$), posthoc tests showed RTs in the single-task condition were significantly faster than those in dual-task conditions ($T_S + V_S$, $p = 0.004$; and $T_S + V_N$, $p = 0.003$). No difference was found between $T_S + V_S$ and $T_S + V_N$.

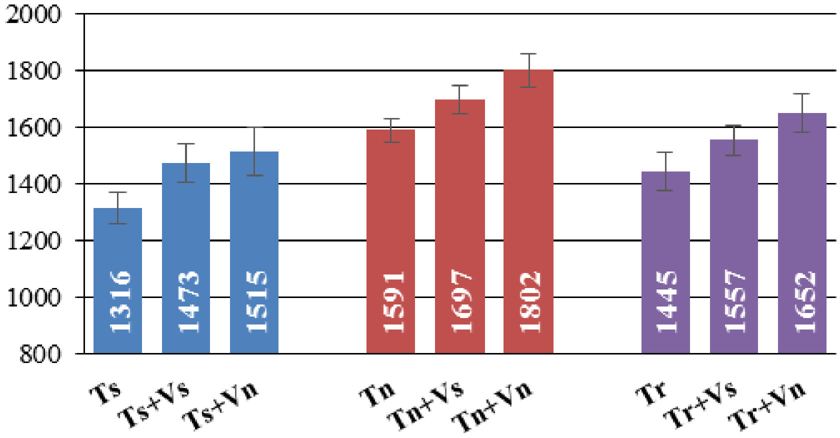


Figure 2-6: RTs in ms to correctly identified tactons for conditions involving each type of tacton encoding method (Ts: spatial; Tn: nonspatial; Tr: redundant). Error bars represent standard error.

RT also differed significantly among conditions involving the T_N task ($F(2,54.116) = 14.553$; $p < 0.001$). RTs for the T_N condition were significantly faster than the $T_N + V_S$ ($p = 0.001$) and $T_N + V_N$ conditions ($p < 0.001$), and RTs for the $T_N + V_N$ condition were significantly longer than those for $T_N + V_S$ ($p = 0.016$; see Figure 2-6).

Significance was also found across T_R task conditions ($F(2,64) = 7.039$; $p = 0.002$). Similar T_S and T_N, posthoc tests showed that participants responded faster in the single-task condition than the dual-task conditions ($T_R + V_S$, $p = 0.024$; and $T_R + V_N$, $p = 0.002$). No difference was found between $T_R + V_S$ and $T_R + V_N$ (see Figure 2-6).

Visual Task Performance

Lane choice accuracy was very high in the single-task conditions and did not differ statistically: V_S and V_N (see Figure 2-7). Task condition significantly affected lane accuracy within V_S conditions ($F(2.253,72.094) = 9.813$; $p < 0.001$), with accuracies in the V_S condition higher than in the dual-task conditions ($T_S + V_S$, $p < 0.001$; $T_N + V_S$, $p < 0.001$; and $T_R + V_S$, $p < 0.001$, see Figure 2-7). Lane choice accuracies were also significantly worse in the $T_S + V_S$ condition than the $T_N + V_S$ condition ($p = 0.027$) and marginally worse than the $T_R + V_S$ condition ($p = 0.088$). No difference was found among $T_R + V_S$ and $T_N + V_S$ conditions.

Shown in Figure 2-7, accuracy also differed across V_N conditions ($F(2.332,74.624) = 17.525$; $p < 0.001$). Accuracies in the single-task condition V_N were again higher than each dual-task condition ($T_S + V_N$, $T_N + V_N$, $T_R + V_N$, $p < 0.001$ for each comparison), but the magnitudes of these differences were greater than those observed between the V_S single- and dual-task conditions. Accuracies in the $T_S + V_N$

condition were considerably higher than in both $T_N + V_N$ ($p = 0.011$) and $T_R + V_N$ ($p = 0.043$). No difference was found between $T_N + V_N$ and $T_R + V_N$ conditions.

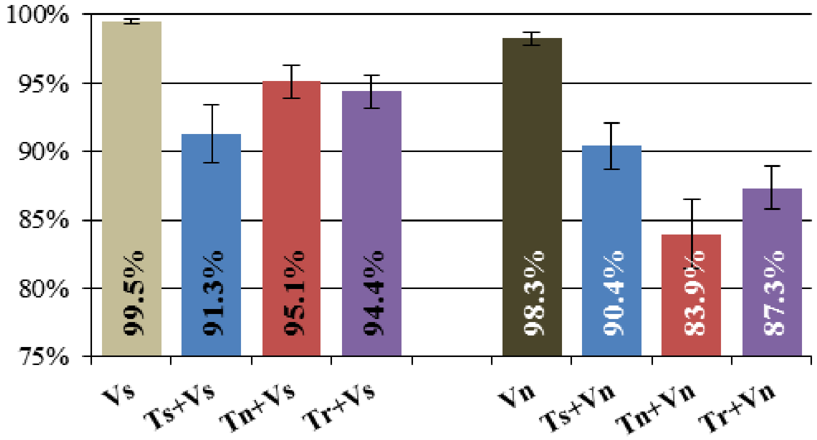


Figure 2-7: Visual task accuracies for visual-spatial (Vs) and visual-nonspatial (Vn) conditions in each respective single- and dual-task condition. Error bars represent standard error.

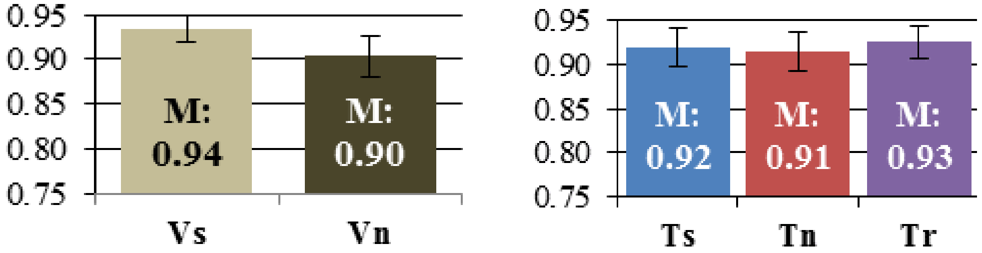
Multitask Performance Metric

Some variance in the performance data could be attributed to differences in participants' chosen strategies in dual-task conditions. Several participants reported prioritizing one of the two concurrent tasks to perform best overall on both tasks. As a result, dual-task performance decrements were expressed primarily in the tactile task for some participants and in the visual task for others. Thus, a metric was created to combine performance on both tasks into one measure of overall multitasking performance (*M*, see Equation 2.1). The metric normalizes each participant's dual-task performance according to single-task performance and assigns weightings to each dependent measure based on instructions (e.g., each equally important task represents ½ of the metric). Higher *M* values indicate better relative dual-task performance, and a value of 1.0 indicates equal performance in single- and dual-task conditions. Metrics were calculated for each participant and compared in a two-way repeated-measure ANOVA.

$$M_{i,j} = \left[{}^{1}\!/_{2} \left(\frac{L(T_i V_j)}{L(V_j)} \right) + {}^{1}\!/_{2} \left(\frac{1}{2} \frac{A(T_i V_j)}{A(T_i)} + \frac{1}{2} \frac{RT(T_i)}{RT(T_i V_j)} \right) \right]$$

Equation 2-1: Metric for multitask performance in conditions that paired visual task V_j (j = spatial or nonspatial) with tactile task T_i defined by encoding method i (i = spatial, nonspatial, or redundant). $L(X)$ = visual task lane choice accuracy in scenario X; $A(X)$ = tacton identification accuracy; $RT(X)$ = mean tacton response time.

Analysis of the *M* metrics showed a significant effect for visual task ($F(1,32) = 11.975$; $p = 0.002$), in which performance was worse for dual-task conditions involving the visual-nonspatial task (V_N conditions) than those involving the visual-spatial task (V_S) [see Figure 2-8(a)]. Tacton encoding method did not significantly affect multitask performance [see Figure 2-8(b)].



(a) (b)

Figure 2-8: Multitask performance metric (M) comparison for (a) dual-task performance in conditions involving the visual-spatial task (Vs) vs. visual-nonspatial task (Vn); and (b) dual-task performance for conditions involving each type of tacton encoding method (Ts: spatial; Tn: nonspatial; Tr: redundant). Error bars represent standard error.

As expected, a strong interaction effect was found between visual task and tacton encoding method ($F(1.634,52.298) = 10.618$; $p < 0.001$) (see Figure 2-9). Comparing dual-task conditions involving the visual-spatial task, posthoc tests showed a significant difference between $T_S + V_S$ and $T_N + V_S$ ($p = 0.023$), which reflects the expected pattern that performance is worse when tasks require the same spatial processing code ($T_S + V_S$). Furthermore, performance in the $T_R + V_S$ condition was also found to be significantly better than $T_S + V_S$; however, it did not differ from the $T_N + V_S$ condition (see Figure 2-9).

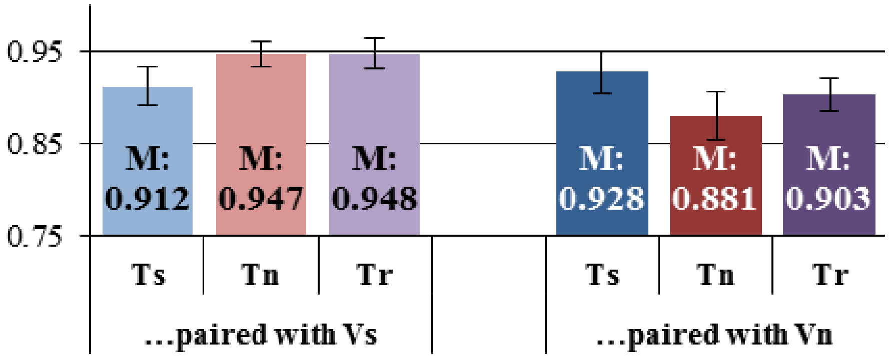


Figure 2-9: Multitask performance metrics for all dual-task scenarios. Error bars represent standard error.

Comparing within *visual-nonspatial* task conditions, posthoc tests again revealed that multitask performance was significantly worse when the concurrent tactile task required the same nonspatial processing code ($T_N + V_N$) than when the task required spatial processing ($T_S + V_N$; $p = 0.014$). Performance in the $T_R + V_N$ condition did not differ from either $T_S + V_N$ or $T_N + V_N$.

Analyzing the interaction within each type of tacton, multitask performance with the *tactile-nonspatial* task was significantly worse when it was paired with the *visual-nonspatial* task ($T_N + V_N$) than the *visual-spatial* task ($T_N + V_S$; $p < 0.001$). A significant difference was also found for the *tactile-redundant* task, showing better performance in $T_R + V_S$ than in $T_R + V_N$ ($p = 0.002$). No difference was found when pairing T_S with either visual task.

Subjective Ratings

When completed in isolation, the V_N task was rated significantly more difficult than the V_S task ($F(1, 34) = 12.850$; $p = 0.001$), and a marginal difference was found among tactile tasks ($F(2,68) = 5.576$; $p = 0.084$; Table 2-3). Posthoc analysis showed that participants perceived both T_S and T_R to be less difficult to perform than the T_N task ($p = 0.092$; $p = 0.063$, respectively); however, no difference was found between T_S and T_R.

Furthermore, dual-task conditions were rated significantly higher than single-task conditions (mean rating of five single-task conditions: 2.43; of six dual-task conditions: 5.71; $F(1,34) = 171.713$; $p < 0.001$). Due to an unexpected difference in ratings of V_S and V_N, dual-task difficulties were compared by calculating the increase in difficulty over the single-task condition which involved the same visual task (see Table 2-3).

Analysis of the difficulty increases revealed a significant visual task by tactile task interaction ($F(2,68) = 9.25$; $p < 0.001$). Dual-task conditions involving the *visual-nonspatial* task (mean increase: 3.810) increased in difficulty to a greater extent than those involving the *visual-spatial* task (mean increase: 3.390). Within the visual tasks, simple effect analyses showed that when paired with the V_S visual task, the increase in difficulty did not differ statistically among paired tactile tasks (T_S: 3.57; T_N: 3.23; T_R: 3.37). When paired with the V_N task, the increase in difficulty by adding the T_S task (3.09) was significantly less than the increase when adding the T_N (4.46; $p = 0.011$) or the T_R (3.89; $p = 0.008$) tasks. No difference was found between T_N and T_R.

Table 2-3: Summary of Subjective Ratings of Difficulty.

Condition	*Mean rating (SD)*	*Dual-task increase in difficulty over visual single-task rating*
V_S	1.77 (1.46)	--
V_N	2.46 (1.50)	--
T_S	2.51 (2.06)	--
T_N	2.97 (1.90)	--
T_R	2.43 (1.90)	--
T_S+V_S	5.34 (2.33)	3.57 (2.05)
T_N+V_S	5.00 (1.93)	3.23 (1.73)
T_R+V_S	5.14 (2.32)	3.37 (2.06)
T_S+V_N	5.54 (2.24)	3.09 (1.83)
T_N+V_N	6.91 (2.55)	4.46 (2.66)
T_R+V_N	6.34 (2.14)	3.89 (1.88)

Discussion

Previous work demonstrated how competition for the same processing code resources can lead to larger dual-task decrements when a tactile-visual multitask set engages the same processing codes than when the set engages separate processing codes (Ardoin & Ferris, 2014; Ferris & Sarter, 2010). MRT is one model that helps to explain performance decrements as due to interference arising when concurrent tasks require the same processing code resources (Wickens et al., 2002). The main goal of this study was to determine if processing interference between concurrent visual and tactile tasks could be minimized with the introduction of redundantly encoded tacton displays. Ideally, this type of display would allow decoding of the tactile message by engaging *either* spatial or nonspatial processing code resources, supporting better load balancing under changing demand imposed by concurrent tasks. While it was expected that the performance benefits of redundancy gain would be observed, it remained a possibility that redundancy costs (Wickens et al., 2011) resulting from higher processing loads in interpreting a more complex signal could offset the benefits.

The five individual tasks (three tactile and two visual) were designed to be similar in difficulty and show similar levels of performance in single-task conditions. With a few exceptions, this is what was observed. V_S and V_N tasks showed high lane choice accuracies that did not differ; however, subjective ratings showed V_N was perceived to be significantly more difficult than V_S. This difference may have been due to the additional step in the V_N task that required matching the missing number to its corresponding lane presented in the "key" (see Figure 2-3). This additional step was necessary so that the response mechanism (steering into the proper lane) would be the same between the two tasks but still allow working memory to be loaded only with nonspatial/symbolic information (numbers 1–4) during the time window in which dual-task processing code interference was designed to occur.

As with the visual single-task conditions, the tactile single-task conditions showed comparable and very high identification accuracy; however, participants perceived the T_N task as more difficult than the T_S and T_R tasks, which were similarly rated. This may be attributable to the differences in response method associated with the tasks. Many participants anecdotally reported that response using the paddles (nonspatial response) was more difficult than using the buttons (spatial response). Furthermore, a difference was found in tacton RT data that showed the T_N (nonspatial) tactons took significantly longer to respond to than both the T_S (spatial) and the T_R (nonspatial+spatial) tactons. This may reflect that for the T_N tactons, participants likely counted the number of pulses in each segment as opposed to attending to their duration. This technique required waiting until the entirety of the second segment was completed before interpreting the overall tacton and initiating response. Spatial and redundant tactons, on the other hand, could conceivably be interpreted shortly after the onset of the second segment. Although participants were instructed to wait for the entire tacton presentation to be completed before initiating a response, the decision about how to respond could be made earlier for T_S and T_R than T_N, which may be the reason for the difference in RTs. Another consequence of needing to count pulses for the T_N task is that this activity requires more sustained attention over longer periods of time (nearly the entire 1000-ms segment) than does location recognition. Thus, there may be a greater opportunity for dual-task interference with the nonspatial tactons because of this longer time window.

As expected, dual-task conditions showed performance decrements and increased difficulty ratings over the component single-task conditions. This reflects general capacity effects in mental resources (Kahneman, 1973). Furthermore, the decrements and increased difficulty ratings associated with dual-task conditions involving the same processing codes ($T_S + V_S$ and $T_N + V_N$) tended to be greater in magnitude than those that required different codes (T_S + V_N and T_N + V_S). These findings confirm our expectation and reflect the MRT claim that processing interference is greater when concurrent tasks require the same processing code resources (Wickens, 2002).

While the pattern of multitask performance concurred with the results of previous studies (see Ardoin & Ferris, 2014; Ferris & Sarter, 2010), it is interesting to note that the in the current study, the V_S (spatial) task appeared to have been less affected by dual-task requirements than the V_N (nonspatial) task, although the V_S task was identical to that in previous studies. Findings showed that participants performed significantly better overall in dual-task conditions with the *visual-spatial* task [see Figure 2-8(a)] and also rated it as less difficult (see Table 2-3). This may be partially attributable to design changes made to the *visual-nonspatial* task. Although the experimental design was modeled after (Ferris and Sarter, 2010), an attempt was made in the current study to improve the previous design by creating “nonspatial” visual tasks that had a greater degree of similarity with the nonspatial tactile tasks. Instead of using colored rectangles to convey task-relevant information for the *visual-nonspatial* task, as done in the previous studies, numbers were used to convey the task information. Since the *tactile-nonspatial* task involved counting pulses, participants had to mentally keep track of numbers for both nonspatial tasks and thus there was a greater degree of task similarity in the T_N + V_N pairing. In addition to the processing code competition, confusion due to this task similarity likely impacted dual-task performance negatively (Fracker & Wickens, 1989; Wickens, 2002).

Furthermore, in the current study, greater consideration was given to spatial and nonspatial processing in the response methods associated with each tactile task. For the *tactile-spatial* and *tactile-nonspatial* tasks, respectively, responses were designed to maximally emphasize spatial (pressing buttons at specific locations) or nonspatial (pulling paddles a specific number of times) activities, whereas previous studies used spatialized button press responses for both types of tasks (Ferris & Sarter, 2010). It can be assumed that after decoding the tactons to determine the "answer," generating the motor program needed for tactile task response more clearly stressed nonspatial processing resources in the current study compared with previous studies. Altogether, these task modifications may have increased dual-task interference in the $T_N + V_N$ conditions by increasing the overall difficulty of the tactile task as well as creating more confusion due to a greater degree of task similarity. Indeed, the $T_N + V_N$ condition suffered the largest dual-task decrements overall and was rated as the most difficult.

In single- and dual-task conditions involving the redundant tactons, performance measures and subjective ratings consistently fell between those associated with the most challenging conditions (those involving competition for the same processing code resources) and those associated with the least challenging conditions (those involving opposite processing codes). This pattern might be interpreted as illustrating how spatial+nonspatial redundant tactons offer a *redundancy gain* compared with the most challenging conditions and a *redundancy cost* compared to the least-challenging conditions, thus confirming both hypotheses tested in this research. These results reflect each type of effect that has been observed with multi*sensory* redundancy in communicating task-relevant information (Wickens et al., 2011) and illustrate that these effects can be observed with *multicode* redundancy as well.

Generally, single-task and dual-task performance for the *tactile-redundant* task more closely align with the pattern of the spatial tactons than the nonspatial tactons. This suggests that participants tended to pay attention to the spatial nature of the signal rather than the nonspatial pattern even when the nonspatial information was more readily available (see Figures 2-5, 6, and 8(b)). Confirmed in the postexperiment questionnaire, participants tended to simplify their multitasking strategy to attend to the more “natural” or “familiar” dimension, which was more often the spatial location of the tactile signal rather than the number of vibrations felt. This strategy also extended to the chosen response method (buttons or triggers, as each was equally valid in responding to redundant tactons). Although participants were encouraged to respond with the method that mapped to the attended component, it would appear that many, but not all, participants responded to the redundant tactons with the spatial method. It is unclear if there were any strategies adopted in which one aspect of the redundant signal (such as the nonspatial component) was attended to, while the opposite response method (spatial button-presses) was employed.

It is also interesting to note that although participants seemed to attend to the spatial component of the redundant message, when paired with V_S, performance in the dual-task condition involving redundant encoding was similar to the least challenging condition (T_N + V_S) but significantly better than the most challenging condition (T_S + V_S), a clear redundancy gain. However, when paired with V_N , the condition involving T_R

was either similar to the most challenging task condition ($T_N + V_N$) and significantly worse than the least challenging condition ($T_S + V_N$) or showed no difference at all (see Figures 2-7 and 9). One possible explanation for this also incidentally helps explain the possible observance of redundancy cost. It could be that a similar amount of cognitive resources is required to decode the nonspatial content of the message as is needed to suppress the nonspatial component when attending to the often-preferred spatial dimension of redundant tactons. This would explain why, when paired with the V_N task, subjective ratings of difficulty with the T_R tactons increased almost as much as with the T_N tactons. This result may also be attributable to a higher degree of task similarity like that experienced in the $T_N + V_N$ pairing.

One limitation of this study is that participants were allowed to form their own processing strategies with the redundant tactons and thus did not universally attend to the aspects of the redundant signal associated with the relatively available processing code. Another possible limitation involved task-switching effects, specifically the possibility that participants engaged the same processing code of the previous task condition when beginning *tactile-redundant* conditions. However, to reduce task-switching costs (Monsell, 2003), participants were given mini tests between each scenario (single- and dual-task) in order to refamiliarize them with task instructions and response methods. In looking at participants' response patterns and reported response strategies, there did not appear to be a "carry-over" effect in which the response type for an immediately preceding condition tended to be used in the *tactile-redundant* conditions.

Summary

This study demonstrates how a relatively overlooked dimension for the design of displays – processing code – can be used to redundantly encode information in a discrete tactile display. Results demonstrated that the added complexity of a multicode display may lead to performance costs when cognitive loads of concurrent tasks are high (a potential limitation of the display). However, results also suggest that these costs are outweighed by the performance benefits due to redundancy gain, as dual-task conditions with T_R produced better performance than both conditions that required direct competition for the same processing code ($T_N + V_N$ and $T_S + V_S$). It can be inferred that *multicode* redundancy shows promise for combating the processing code interference described by MRT (by allowing either processing code to be engaged in message interpretation) and may prove beneficial in complex domains that involve concurrent tasks with competing working memory resources.

It is important to note that real-world multitask environments often impose higher baseline levels of cognitive workload than those evaluated in this study. Thus, before multicode displays can be introduced into more complex domains, future work is needed to investigate the cost they impose under various workload conditions. Chapter III details an observational study of four separate but related remote monitoring systems currently in use by a large Midwest Tertiary Care Hospital. The findings of this study served to inform the design of the test environment and vibrotactile display discussed in Chapter IV of this dissertation.

CHAPTER III

OVERVIEW PATIENT MONITORING: AN OBSERVATIONAL STUDY

Researchers at a large Midwest Tertiary Care Hospital developed a remote monitoring system that supports 24-hour real-time physiological monitoring of multiple noncritical care patients from a central remote monitoring station. Although remote patient monitoring has the potential to transform the healthcare industry, it is not fully-understood how some of its characteristics may interact to affect qualities of interest such as worker efficiency and patient care. This chapter summarizes the findings of an observational study of four remote patient monitoring systems currently in operation at the hospital. Goals of the study included gathering input about the human and technological components of the systems as well as identifying potential sources of monitoring task workload with respect to technological components that could be redesigned to better support overall monitoring efficiency. The findings of this study served to inform the design of the test environment and vibrotactile displays used in the experimental described in Chapter IV. They also served to ensure that the study adequately addressed some of the real-world challenges faced by operators in the task of remote patient monitoring.

Introduction

In recent years, remote patient monitoring systems have been widely proposed as an option for economizing healthcare resources, and providing efficient, quality patient care (Sneha & Varshney, 2009). These monitoring systems provide continuous, reliable monitoring of patient physiological information independent of physical location allowing for prompt medical care as and when needed. One such system was developed by a large Midwest Tertiary Care Hospital to support 24-hour real-time physiological monitoring of multiple noncritical care patients by teams of trained technicians. Since its introduction, the remote monitoring operation (termed “overview” monitoring) has expanded from a single monitoring station to multiple monitoring stations each capable of displaying physiological data (e.g., cardiac rhythms, pulse oximetry, blood pressure, etc.) for 15-120 in-hospital patients, concurrently. The additional set of “trained eyes” monitoring patients can provide numerous benefits, including early recognition of deterioration in patients’ condition, faster response to patient care, and a reduction in workload per patient for on-site caregivers (e.g., nurses on staff in the patients’ units), as there is less of a need for them to closely monitor the physiology of patients under their care.

Overview monitoring systems show potential to revolutionize the healthcare industry, and soon may be expanded to include monitoring additional off-site patients from other hospital systems and support continuing care in nontraditional settings such as the home. However, before broader application and/or expansion can occur, it is imperative to understand the roles and interactions of the human and technological components of the current monitoring systems as well as the sources, or “drivers”, for monitoring task workload, such as the manner in which patient physiological data are displayed. Human cognitive resources – attention, working memory, and general information processing functions – are limited (Wickens, 2002), and therefore only so many data sources or task activities can be attended to and processed with sufficient depth at any given time. Performance can break down when overall cognitive workload gets too high and workload demand exceeds the capacity of available resources (at the theoretical “red line” of workload; Grier et al., 2008), thus introducing patient safety risks.

It is important to note that the overview monitoring system not only includes the monitoring technologies (i.e., wireless communication technology, patient worn devices for medical telemetry, console displays, alarms, etc.), but it also includes patients, physicians, nurses, console technicians (certified rhythm technicians monitoring patient data at the station), other clinical personnel, and the environment in which the overview monitoring takes place (Carayon et al., 2006). However, for the purposes of this chapter, the “system” will be characterized by console technicians interacting with tools and technology (namely console displays and alarms) to perform patient monitoring tasks.

Console technicians are highly trained, certified rhythm analysis technicians (CRATs) working independently under the direction of nursing staff. In addition to monitoring patient physiological parameters and evaluating cardiac rhythms, they are trained to identify false alarms generated by the technology due to poor signal quality and patient movement as well as interpret detailed patient information. As such, the technicians often act as aids to nurses and a liaison in responding to patients' direct care needs and patients' outcome. The console technician works in conjunction with a paired CRAT referred to as a "runner." The runner performs care tasks characterized by direct interaction with nurses or patients, as directed by the console operator. Additionally, runners have the responsibility of communicating critical information to nursing staff, namely irregularities in patient physiology as reported to them by their partnering console operators. They are also the point of contact for electrode placement and troubleshooting and maintenance for monitoring devices (Ardoin et. al, 2016).

In order to gain a comprehensive understanding of the overview monitoring system as defined above, investigators conducted an observational study of five separate but related overview monitoring stations currently in operation. In a previous analysis, researchers grouped the five monitoring stations and developed descriptions for three distinct Remote Monitoring Paradigms (RMPs) based on the make-up of the healthcare team (console operators, runners, and nurses), performed tasks, physical location, and technological components of each system (Ardoin et. Al, 2016). This chapter builds upon that analysis evaluating RMPs 1 and 2 with the goal of gathering input about the human (more specifically the console technicians) and technological components of the "systems" as well as identifying potential sources of monitoring task workload with respect to technological components that could be redesigned to better support overall monitoring efficiency.

This chapter summarizes the current study's findings with the following aims:

1) Describe the overview monitoring system with respect to the needs of console technicians as they perform different tasks that contribute to the overall system goal of quality patient monitoring
2) Discuss human operator challenges related to technological components that may affect patient safety and console technician ability to provide quality patient care.

These efforts are important in identifying overview monitoring system elements that can be used in the construction of a fundamental model as well as some challenges of the current system that must be managed in current and future operations. They also inform the ongoing development of guidelines for integrating remote monitoring into existing care facilities, and for supporting patient care and safety inside a traditional clinical setting.

Methodology

To gain an understanding of the needs of console technicians in the system and identify ways that monitoring activities could be better supported, investigators utilized various observational and ethnographic methods such as think-aloud verbal protocol, observations with questioning, and Hierarchical Task Analysis (HTA).

Participants

Two investigators interacted with 20 console technicians (12 males, 8 females) while they performed monitoring tasks. The participants' experience in the current or previous iterations of the patient monitoring system ranged from 3 to 26 years, with an average of 7.75 years. Informed consent was obtained from all technicians prior to their participation in the study.

Procedures

Data collection took place onsite over the course of one week. Investigators conducted all questioning and observations in the participant’s work area and staggered them so that they occurred during the three different work shifts (8-hour shifts beginning at 6 AM, 2 PM, and 10 PM). The following methods were employed for this study: observations with questioning, think-aloud verbal protocol, and a hierarchical task analysis.

Observations of the monitoring technicians were conducted while they were doing their work and the researchers would periodically ask the technician questions about what activities they were currently conducting (including mental activities that were not directly observable) and why they were doing them (referencing task goals, constraints, and strategies). Precautions were taken to ask questions only during gaps in workflow or relatively low periods of workload, as observed, to minimally interfere with monitoring and other task performance.

Think-aloud verbal protocols involved technicians speaking aloud their intended actions and reasoning as they were performed. During particularly high-workload periods it was necessary for workers to remain silent and focus on the task at hand; however, because the researchers were present for an extended period of time, they were able to review these periods with the console technicians afterward to identify new insights.

The hierarchical task descriptions were developed via in situ observational analyses and follow up questioning. First, fundamental tasks of the console technician's monitoring duties were noted by the investigators. From there, an initial template of the task analysis was constructed then divided into subtasks (see Appendix). For the purpose of this study, HTA will be used when referencing the hierarchical task descriptions discussed in this chapter. The final HTA was constructed to a level that described the tasks and subtasks that had to be completed to achieve the duty of monitoring, but it did not describe any actions directly involving patients (e.g., adjusting limits for physiological alarms). This was done so that individual needs of the patient did not affect the task analysis across the four monitoring systems. The HTA was then used to provide insight about how and why activities associated with the overview monitoring tasks of interest were performed, and ultimately identify potential challenges in the display technology that could be addressed with changes in task activities and/or technological support for the activities.

Investigators were also able to use their experience of being in the central overview monitoring station to gain deeper insight into the roles and needs of the console technicians as well as how they interacted with tools and technologies to perform necessary tasks in monitoring patients. Investigator interactions and conversations were digitally recorded and/or recorded in field notes written during the time of the observation. All recordings were transcribed during the data collection phase and typed up along with the field notes.

Findings

This section first briefly introduces findings from data collection and analysis that focused on the components of interest in the monitoring system: console technicians, their tasks, and tools and technology. We then provide details of the display technology and associated challenges of the current system informed by analysis results.

Each console technician concurrently monitors 15-32 noncritical patients at one of the four stations located in the hospital’s central overview monitoring station (see Figure 3-1). The technicians rotate monitoring duties with their (paired) runner every hour for the duration of their 8-hour shift to reduce vigilance decrement and fatigue (R. Kaplan, personal communication, September 8, 2015).

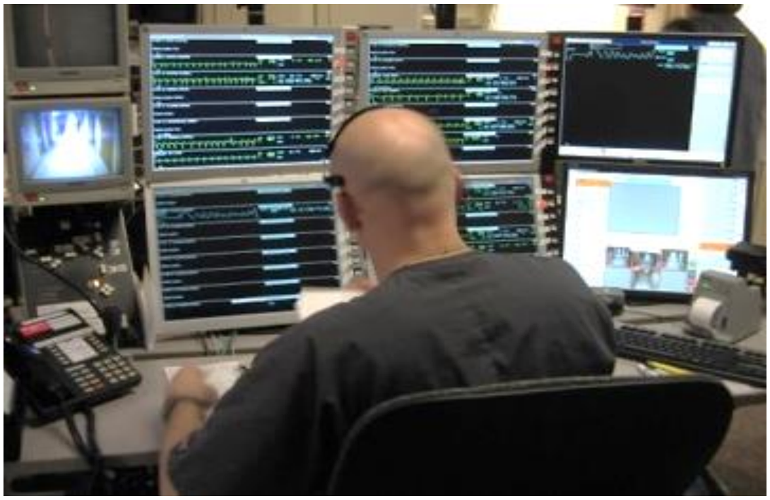


Figure 3-1: Image of a console technician performing regular monitoring activities at designated station.

Tasks

Table 3-1 below outlines examples of the console technicians' tasks and their needs as provided by a well-functioning monitoring system. Investigators noted fundamental tasks, such as those listed in Table 3-1, then divided them into subtasks that had to be performed to successfully complete the task with regard to monitoring (also see HTA in Appendix). Investigators did not describe any actions directly involving patients (e.g., adjusting physiological parameters) to maintain applicability of the task analysis across the remote monitoring paradigms.

Table 3-1: Examples of a Console Technician's Tasks and Their Needs as Provided by a Well-Functioning Monitoring System.

Example tasks in monitoring system	*Example needs provided by monitoring system*
Monitoring physiological state	Display of physiological parameters
Monitoring and evaluating cardiac rhythms	Arrhythmia detection
Managing alarms	Instant alarm review
Documenting patient health information and communicating with nurses	Adjustable alarm parameters
	Real-time audio/visual contact with patients
	Direct audio/visual contact with nurse stations

Table 3-2 is a modified excerpt taken from the final HTA (see Appendix). The excerpt gives a sample view of the sequence that must be completed as part of evaluating a displayed alarm with its first level subtasks.

Table 3-2: Example Detailing First Level Subtasks Associated with the 'Evaluate Alarm' Task.

No.	*Task*	*Plan*	*No.*	*Subtasks*
3	Evaluate alarm	Do subtasks 3.1, 3.2 in order	3.1	Interpret the type of alarm
		Do subtask 3.3 if required	3.2	Determine the severity of the alarm
			3.3	Get additional information

Tools and Technology

Both RMPs described in this chapter provide 24-hour real-time physiological monitoring of multiple in-hospital patients via wireless communication technology and patient worn devices for medical telemetry. Patient physiological data is communicated to the console technicians through visual displays such as those shown in Figure 3-1. Displayed parameters include heartrate, blood pressure, arterial oxygen saturation, electrocardiogram data, cardiac waveforms, pulse oximetry, ST, and QT monitoring with a substantial focus on two health events: asystole (a state of no cardiac electrical activity) and premature ventricular contractions (PVCs; extra, abnormal heartbeats that begin in one of the heart's two lower pumping chambers). The two main input controls are a desktop mouse and keyboard.

To signal changes in a patient’s health state, the alarm systems utilize redundant visual and auditory alarms and can be characterized as threshold-based (activated when the level of a parameter surpasses a designated high or low threshold value) and binary (only two states: on and off) in nature. Depending on the severity of the alarm, the console technician will notify the nursing staff via telephone, audio and visual display, or face to face contact according to established protocol guidelines or document the event on an “ectopy sheet” (a written document used to record important patient health events and provide a snapshot of each patient’s health state during each shift)(see “Interpret (evaluate) alarms” section in Appendix).

Visual and Auditory Alarms

Visual alerts appear as messages in an alarm box at the top of a patient’s window (see Figure 3-2). If there are multiple alarms for a patient, an arrow appears which allows the technician to view the list of alarms sorted by recency. The alerts are displayed as blue, yellow, or red depending on the severity of the event: a blue alert is a general notification, usually low priority, and indicates events such as a low telemetry battery or one or more of a patient’s electrodes have loosened; a yellow alert is a warning and often requires immediate attention or action (e.g., a patient experiences three PVCs in a row); and a red alert indicates an emergency and takes precedence over all other events (e.g., a patient experiences asystole of 5 secs or greater). Each alarm box remains displayed in the “patient’s window” until the event is either corrected or dismissed by the console technician (see Figure 3-2 and "Multiple alarms for a patient" section in Appendix).

SpO2T Unavailable

7:51 CANNOT ANALYZE QT

9:18 Tele Battery Low

9:18 SpO2T Unavailable

SOME ECG ALRMS OFF

Figure 3-2: A sample view of multiple visual alerts appearing as messages in a displayed alarm box at the top of a patient's window.

The system also uses auditory alarms to signal the console technician of an event. Each auditory tone is associated with a visually-displayed alarm as follows: a blue alert is accompanied with a low volume, soft tone; a yellow alert with a medium volume, soft tone; and a red alert with a high volume, urgent and repeating tone. The type of tone indicates the severity of a displayed alarm but provides no information regarding which patient requires attention or the type of event (e.g., whether a patient's electrodes have loosened or low telemetry battery). All auditory alarms continue until the associated visual alarms are addressed.

Visual Displays

Visual displays are the primary source in which patient physiological data are presented to the console technicians. Each station consists of six computer screens as shown in Figure 3-1. Four of the screens communicate patient physiological data and can display up to eight patient windows per screen. Since multiple patients are being monitored, console technicians must visually scan each display to manage and evaluate alarms as well as maintain a true mental model of their patients' health state (see "Monitor and manage patients" section in Appendix). A fifth display is used as an additional information screen for activities such as deeper analysis of patient cardiac rhythms or to display historical physiological data. The final monitor is an audio and visual (A/V) display (see Figure 3-3) that allows input via touch or the desktop mouse. This technology is used to communicate directly (bedside) with nursing staff and patients and also allows console technicians to view into the patient's room in the event of a problem or emergency via camera feed linked to the monitoring console. Nurses and patients also have the ability to communicate with the console technician from the room using the display.

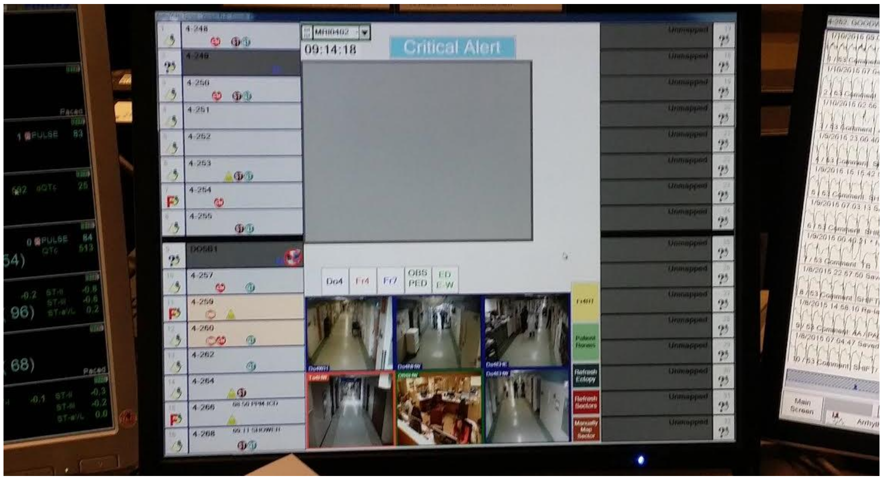


Figure 3-3: Snapshot of the A/V display used to communicate (bedside) with nurses and patients and view a patient’s room.

Key System Challenges

Findings from the task analysis and observations highlight two potential challenges contributing to monitoring task workload with respect to how patient physiological data and alarms are displayed: sensory overload and processing code interference.

Sensory overload in this context refers to the likelihood that some visual and auditory sensory stimulation cannot be processed perceptually, thus critical events may be missed or overlooked. Overview patient monitoring relies heavily on the use of visual displays and auditory alarms to communicate important patient information, which can present several challenges. The volume of information alone in complex environments such as this can create a situation where it is challenging to quickly determine where to look in the “data field,” and it can become easy to miss critical information or difficult to determine which situation requires the most immediate attention (Patterson et al., 2001). As previously mentioned, visual attention is a critical resource for the console technician. He or she must monitor a series of parameters related to blood pressure, cardiac waveforms, respiration, and more for 15-32 patients simultaneously and thus divide attention between multiple sources of physiological and other task-relevant data. In the current system design, methods for the display of this data requires considerable visual scanning of multiple patient windows and other visual displays and alarms distributed across multiple locations (see Figure 3-1; also see “Monitor and Manage Patients” section in Appendix). Observation of console technicians revealed that this resource competition becomes even more apparent during periods when there is an even greater demand for visual attention such as when a patient’s condition is declining. A common approach during these periods is for the technician to offload parallel visual monitoring demands to some degree by ignoring relevant but less-critical tasks to focus on that patient’s physiological display. This requires orienting visual resources to a single patient window. If the display is attended too frequently (at the expense of others) or infrequently, there is an increased likelihood that critical information will be missed, potentially introducing a risk to patient safety.

The auditory alarms that redundantly accompany visually-displayed alerts can also be problematic. There were five overview monitoring stations located in the central monitoring station, where an excessive number of auditory alarms can be an annoyance for the console technicians and may also lead to alarm fatigue (a desensitization to an excessive number of alarms due to sensory overload), which has been identified as a major health hazard (Blake, 2014; Keller, 2012). The problem of excessive alarms may also be a potential source of confusion. Warning tones for the monitoring systems are identical and thus can make it difficult at times for console technicians to quickly determine which station is sounding. Additionally, excessive or more salient alarms from surrounding stations can mask others when heard together. It is also important to note that the periods of heaviest auditory alarms are also likely to be the time periods of highest cognitive load and task management for technicians (when multiple patients experience health events), and alarms are just as likely to distract and disrupt problem-solving activities as they are to serve as an aid during these most critical periods (Cook & Woods, 1996; Woods, 1995).

Another key challenge is the processing interference that can occur due to the way patient data and alarms are presented to the technicians. Although the data displays and alarms allow for distribution of information across multiple modalities – a method primarily beneficial during the first phase of information processing – there remains potential for a great deal of processing interference in the later cognitive and response stages (Wickens, 2002; 1980). The physiological data and alarm displays used in overview monitoring systems are represented with both nonspatial (e.g., text, numbers, and sounds) and spatial (e.g., rhythm analog representations) patterns which then require the planning and activation of responses that are also nonspatial (e.g., speech responses) and spatial (e.g., mouse and keyboard manipulations) in nature (see Figure 3-1; also see “Silence/process alarm” section in Appendix). Consequently, there are different ways in which processing code interference can arise among concurrent tasks: between processing stages (e.g., spatial memory and manual response) and within processing stages (e.g., spatial perception and spatial memory; Wickens & Liu, 1988). For example, interference between stages could occur when the spatial processing required to generate and execute a manual response to displayed alarms coincides with ongoing processing of visual-spatial task stimuli, such as cardiac rhythms. Furthermore, interference due to within-code competition will arise when concurrent tasks require the same processing resources to interpret displayed information, such as reading visual alarm messages and monitoring multiple numeric parameters (Wickens, 2008; 2002).

Previous research has shown the extent to which processing code interference can affect performance in event-driven environments and can contribute to an overall higher cognitive load (Ferris, 2010; also see Chapter 2); therefore, in order to better support multitasking in this system, it is important to consider how to best display task-relevant data to allow for more efficient attention allocation and task management.

Discussion

This chapter summarizes the findings in continued analysis of an observational study of four 24-hour remote patient monitoring systems developed by researchers at a large Midwest Tertiary Care Hospital. Goals of the study included gathering input about the human and technological components of two RMPs as well as identifying potential design challenges with respect to technological components of the systems contributing to the overall workload of console operators. Findings from the analyses highlighted two potential challenges: sensory overload and processing code interference.

One way to address the issue of sensory overload is to reduce the burden on the technicians' visual and auditory resources by employing an alternate modality, namely touch, to convey information directly or help capture and direct attention to the appropriate display. This is in line with the MRT assertion that distributing the presentation of some task-relevant information to other channels can reduce the competition for perceptual resources and thus the threat of sensory overload (Wickens, 2002; 2008). Furthermore, alarm-like vibrotactile displays have already shown promise in other clinical settings that involve patient monitoring, such as the OR (Ferris & Sarter, 2011). Previous research suggest that these displays can be as effective as visual and auditory displays in supporting the detection, identification of, and response to patient health events in visually- and auditorily-demanding medical environments (Ferris & Sarter, 2009; Ford et al., 2008; Ng, Man, Fels, Dumont, & Ansermino, 2005; Ngo & Spence, 2010; Shapiro, Santomauro, McLanders, Tran, & Sanderson, 2015). Results from these studies demonstrate the potential for tactile displays to better support non-visual overview monitoring and management of patient physiology.

Likewise, tactile displays – more specifically multicode displays – have also shown promise as a way to minimize processing interference, demonstrated in Chapter 2. A multicode tactile display utilizes separate methods (e.g., spatial location and rhythm) to redundantly encode information, each of which requires a separate processing code. This allows the engagement of either processing code – whichever faced less interference – in interpreting the tactile message.

Summary

This chapter summarized the details an observational study of four separate but related remote monitoring systems currently in operation. The findings of this study provide a model task context for investigating the continuously-informing vibrotactile displays described in Chapter IV, and also served to ensure that the study more adequately addresses some of the real-world challenges faced in complex environments than the dual-task scenarios employed in Chapter II.

CHAPTER IV

INVESTIGATING NONVISUAL INFORMATION DISPLAYS: DESIGNING TO SUPPORT MONITORING EFFICIENCY

As outlined in Chapter I, the ultimate goal of the research described in this dissertation proposal is to investigate *how* redundant encoding methods used to design vibrotactile displays affect multitasking performance when the demands of concurrent tasks vary over time. The research activities described in Chapters II and III contributed input to the designs for the displays and task context of the multitasking environment employed in this study. This chapter describes the final experiment in which three continuously–informing displays, a spatially-encoded vibrotactile display, a nonspatially-encoded vibrotactile display, and a multicode vibrotactile display, are evaluated in a multitasking environment under different workload levels.

Introduction

Vibrotactile displays have been represented as a promising approach to supporting multitasking performance in supervisory control tasks such anesthetic monitoring when visual and auditory resources are in high demand (Ngo & Spence, 2010; Ferris & Sarter, 2009). By reducing some of the load on visual (and auditory) channels, this underutilized channel can be employed to keep clinicians more continuously aware of developments in the patient's health status, thus improving performance in physiological monitoring tasks, while minimally distracting them from concurrent tasks. In particular, tactons have been explored for communicating fairly rich information (see "Tactile Displays" in Chapter I).

Although these displays may improve multitasking performance, previous research has demonstrated the potential for processing code interference when consideration is not given to how the dimensions used to encode the tactile messages can influence performance on concurrent tasks (Ardoin & Ferris, 2016; Ferris & Sarter, 2009; 2010; also see Chapter II). One possible way to address this issue is through the utilization of "multi-processing code" (or multicode) redundancy which employs both the spatial and nonspatial dimensions to encode information in displayed messages allowing participants to decode the message using whichever resources are available based on demands of concurrent tasks. Ferris and Sarter (2011) developed a novel continuously-informing vibrotactile display that employed this type of redundancy to present multiple health parameters in a supervisory control setting. Findings demonstrated potential for the display to support multitask performance over customary visual and auditory displays; however, a multicode redundancy gain was *assumed* in their display but not explicitly *tested*, and it remains an open question whether this novel type of display produces better performance (redundancy gains) or performance decrements (redundancy cost) in comparison to a unicode display, which utilizes a single dimension to communicate information.

The experiment described in Chapter II was the first investigation in determining whether the use of multicode redundancy in a tactile display would better support performance in a multitasking environment. This was tested using three discrete tactile displays: a spatially-encoded display, a nonspatially-encoded display, and a multicode display. Findings suggested that the added complexity of a multicode display may lead to performance costs when cognitive loads of concurrent tasks are high, though these costs appeared to be outweighed by the performance benefits due to redundancy gain, as dual-task conditions with multicode display produced better performance than conditions that required direct competition for the same processing code (see Chapter II). The study demonstrated that multicode redundancy shows promise for combating the processing code interference described by MRT, and hence may prove beneficial in complex domains where concurrent tasks compete for working memory resources. However, before multicode displays can be introduced into more complex domains, additional work is needed to examine the mental cost they impose under various workload conditions that are more representative of real-world domains.

The observational study of two overview monitoring systems discussed in Chapter III served to inform the context and design of the multitasking environment used in this experiment. Overview patient monitoring requires continuous observation of multiple patients and a number of physiological data displays by trained console technicians. During a follow-up interview, it was found that premature ventricular contractions (PVCs; extra, abnormal heartbeats) are considered priority health events when monitoring cardiovascular patients (R. Kaplan, personal communication, May 20, 2015). PVC events may occur singly, consecutively, every other beat (bigeminy) or interpolated (occurring between two normal beats). Two or more consecutive PVCs are referred to as PVC "runs." For cardiovascular patients, these events can indicate a decline in heath state and if not attended to can prove fatal. As discussed in Chapter III, it was observed that the high visual demand of concurrent tasks that are performed in overview patient monitoring may make continuous monitoring for these events more challenging.

The present study explored whether a multicode continuously-informing tactile display can provide aid to operators in a monitoring task performed in parallel with other visually- and attentionally- demanding tasks under two different levels of workload. A comparison of task performance was also performed between the multicode and unicode (spatial and nonspatial) displays. As in many clinical settings, overview patient monitoring requires console technicians to be continuously informed of the health state of their patients in order to decide whether and when it is most appropriate to shift attention from one task to address patient alarms or changes in a patient's health parameters (see Chapter III). Previous research has demonstrated the benefit of continuously-informing tactile displays in these types of settings in support of operator performance during monitoring tasks of parameters (Ferris & Sarter, 2009; 2011), thus a continuously-informing display was chosen for this experimental design.

It was expected that the conditions involving the multicode display would show similar or better monitoring performance than spatial display conditions under both workload levels. Findings from Chapter II of this dissertation revealed that participants tended to pay more attention to the spatial component of the multicode signal regardless of concurrent task demands; however, performance was significantly better with the multicode display than the spatially-encoded display when the concurrent visual task also required spatial resources. This suggests that the multicode display better supported multitasking performance than the spatial display when concurrent task demands were also spatial. Similar results were expected in this study given the simulated test environment is made up of tasks represented with both spatial (e.g., rhythm analog representations) and nonspatial (e.g., text, numbers, and sounds) patterns which then require the planning and activation of responses that are also spatial (e.g., mouse and keyboard manipulations) and nonspatial (e.g., speech responses) in nature.

It was also expected that the multicode display conditions would show similar or worse monitoring performance than the nonspatial display under both workload levels. Previous findings showed that multitasking performance with the multicode display was slightly poorer than the best nonspatial case (concurrent tasks required difference processing resources) and slightly better than worst nonspatial case (concurrent tasks required the same processing resources) (Ardoin & Ferris, 2016; also see Chapter II). Since it was found that participants tended to pay more attention to the spatial component of multicode signal, it remained a possibility that the multicode display could produce more task interference than the nonspatial display given the design of the test environment.

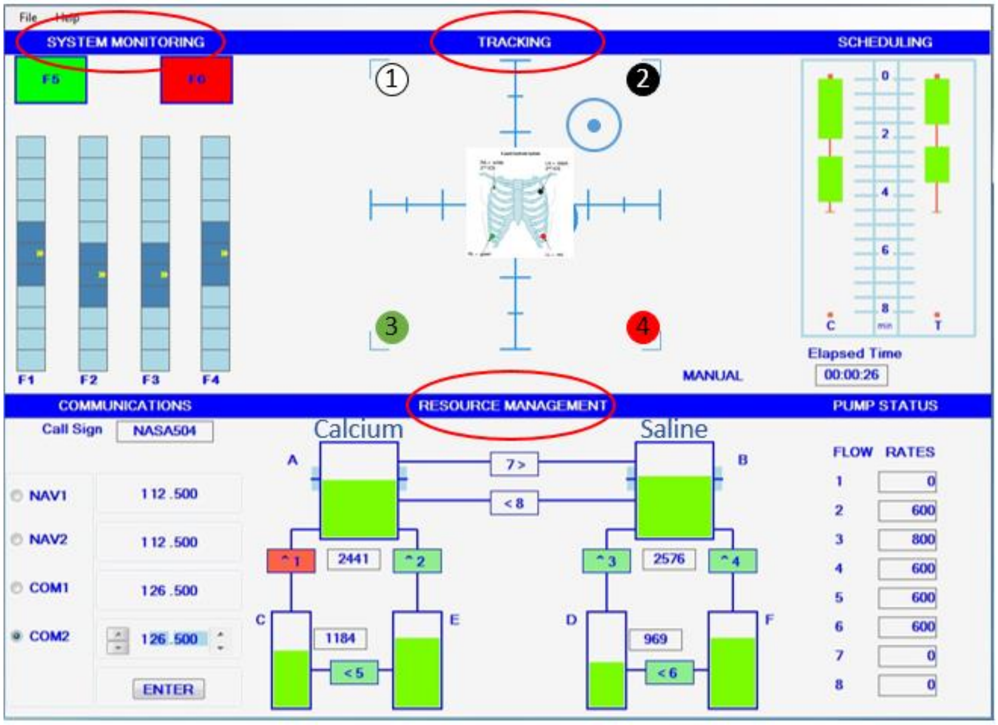
In summary, the aim of this study was to investigate the performance effects of multicode redundancy within a continuously-informing display under two different levels of workload demand, as well as how these effects compare to that of unicode displays. Expectations were that the conditions involving the multicode display would show similar or better monitoring performance than spatial display conditions and similar or worse monitoring performance than the nonspatial display under both workload levels. The present research is important for the design of redundantly-encoded displays intended to be informative and support multitasking in complex, data-rich environments. It will also provide additional insight into a fundamental question of human information processing regarding whether humans can effectively select which processing code/working memory functions they engage when interpreting a redundantly-encoded message.

Methods

Fourteen participants (seven males and seven females, average age 30.5) with normal or corrected-to-normal visual acuity and no known conditions limiting the tactile sensitivity of the back took part in this study. Informed consent was obtained from all participants prior to their participation in the study.

Test Environment

Two tasks in the NASA Multi-Attribute Task Battery-II (MATB-II; Santiago-Espada et al., 2011) were used to generate task scenarios that loosely model the displays and alarms that characterize an overview monitoring station. Those tasks included: system monitoring (SYSMON) and resource management (RESMAN; see Figure 4-1).



Elapsed Time 00:00:26

Call Sign NASA504

○ NAV1 112 .500
○ NAV2 112 .500
○ COM1 126 .500
● COM2 126 .500

2441
2576
1184
969

FLOW	RATES
1	0
2	600
3	800
4	600
5	600
6	600
7	0
8	0

Figure 4-1: Screenshot of the MATB-II program display.

The SYSMON task consists of two subtasks: warning lights (a visual-nonspatial task) and parameter scales (a visual-spatial task). Both tasks required responses using a desktop mouse or keyboard (manual-spatial responses). In this study, the parameter scales represented blood pressure readings for four cardiovascular patients who required overview monitoring. Each scale has a moving segment bar that fluctuates slightly around the scale center, which indicates normal patient readings. If one of the four patients has a blood pressure reading that is outside of the acceptable range (i.e., a scale fault occurs), the corresponding segment bar will shift its position all the way up or down away from center. If this occurs, the participant was to either press the corresponding button on the desktop keyboard (F1-F4) or click on the scale using the desktop mouse.

The second monitoring task involved two warning lights – that turn on and off – presented in the upper left portion of screen (see Figure 4-1). This task can be equated to the low and high priority visual alarms used to notify a console technician of an event such as a low telemetry battery or a malfunctioning lead. If the green light turned off and/or the red light turned on the participant was to respond by pressing F5 or F6 on the desktop keyboard depending on which light needed to be attended to. Participants were also allowed to use the desktop mouse to respond. Additionally, the onset of a red warning light (F6) signaled participants to visually “check” the TRACK display for a malfunctioning lead indicated by the appearance of a blue target (see Figure 4-1). The location of the blue target indicated which lead required attention. For example, in Figure 4-1 the blue target is in quadrant 2 of the TRACK window. This communicates that the black lead (or lead 2) needs to be attended to. Once the faulty lead was identified, the participant would then verbally communicate to the researcher (acting as the paired runner) that a lead had malfunctioned and needed to be checked. The TRACK task was mainly visual-spatial in nature but required a verbal-symbolic response.

Participants were given 10 seconds to respond to the SYSMON displays before they would “reset” to their original states.

The final task in MATB-II was the RESMAN task. This task represented a monitored patient’s calcium intravenous (IV) infusion. Calcium is often given in conjunction with sodium chloride (saline) when treating patients that require treatment with a calcium IV (personal communication with the Director of Nursing for a local Rehabilitation Long-Term Care Facility, June 7, 2018). Participants were instructed to monitor the calcium and saline levels displayed in tanks (IV bags) A and B with the goal of maintaining their levels within ±500 units of the target indicated by the dark blue lines on the side of the tanks (see Figure 4-1). The tank levels were communicated with both spatial and nonspatial visual messages: spatial in the increasing or decreasing volume levels within the tanks themselves and nonspatial in the increasing or decreasing numbers that represented the volume levels of each tank. Similar to the SYSMON warning light and scale tasks, the RESMAN task required manual-spatial responses.

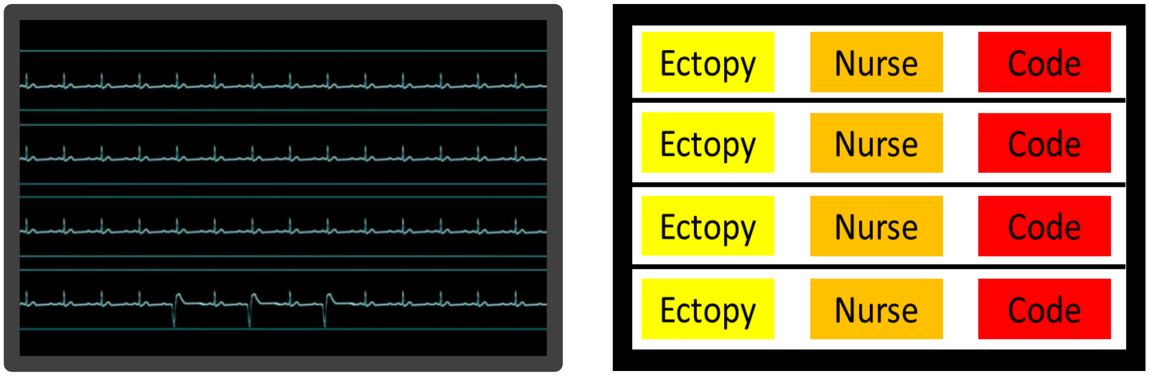
Two experimental levels of MATB-II were created to represent high and low workload conditions modeled loosely after the low and difficult levels designed by Rodriguez Paras et al. (2015). Table 4-1 provides a breakdown of incidences by task that will occur in each high and low workload scenario.

Table 4-1: Summary of Tasks and Number of Occurrences Within the High and Low Workload Levels Designed in MATB-II.

Workload Level	SYSMON: Warning Lights		SYSMON: Parameter Scale	RESMAN
	Green	Red		
Low	2	1	3	10
High	16	15	44	20

To complete the patient-monitoring task set, a physiological display was created to simulate cardiac rhythms for four patients requiring overview monitoring (see Figure 4-2a). A continuously-playing audio file of ambient hospital sounds as well as periodic, distant-sounding alarms served to improve the realism of the simulated environment and mask the sound of tactor activation.

Each patient's cardiac rhythm display was monitored by participants for occurrences of PVC events. In addition to the visual display of PVCs, auditory tones were created to alert participants each time a PVC occurred. The volume of the tone increased with each successive PVC starting at a moderate level gradually increasing to a measured severe level. The loudness of the auditory tones, ambient hospital sounds, and distant alarms were recorded in a local clinical setting: severe level 73dB, moderate level and ambient hospital sounds 64dB, and distant-sounding alarms 60dB.



(a) (b)

Figure 4-2: Examples of (a) simulated cardiac rhythms for four monitored patients and (b) the charting display used to respond to PVC runs.

A touchscreen “charting” display was used to record participants’ detection of more critical PVC health events or runs as defined in Table 4-2. The display contained twelve large buttons (three per patient) color-coded to represent severity of the event: a yellow “Ectopy” button, an orange “Nurse” button, and a red “Code” button (see Figure 4-2b). The *ectopy* button simulates the action of documenting a health event on a console monitor’s ectopy sheet, the *nurse* button simulates the action of calling a nurse, and the *code* button simulates the action of coding the patient. The patient monitoring task was both spatial and nonspatial in nature. To successfully perform the task, participants were required to visually gauge which patient was experiencing a PVC, i.e., where on the monitor the event was occurring, and also “count” the number of event PVCs to make the appropriate response. The response buttons on the charting display were encoded using both spatial (location of buttons) and nonspatial (words and colors) cues (see Figure 4-2b).

Table 4-2: Description of Consecutive PVC Events and How Participants Responded to the More Critical Events Enclosed in the Red Rectangle.

No. of PVCs	*Event Name*	*Event Definition*	*Charting Response*
2	Couplet	2 Beat Run of PVCs	-
3	Triplet	3 Beat Run of PVCs	Press yellow, Ectopy button
4	Salvo 4	4 Beat Run of PVCs	Press orange, Nurse button
5	Salvo 5	5 Beat Run of PVCs	Press red, Code button

The final task included in the study simulated a "rogue patient" roaming the halls of the hospital. This task was meant to mimic the additional tasks of a console technician and visual displays present at a monitoring station (see Figure 3-1 in the "Findings" section of Chapter 3). Participants were to monitor simulated security footage on a computer screen modeling camera feeds of four adjourning hospital wings in a constructed medical center for the wondering patient (a visual-spatial task). Whenever the patient was seen on screen, participants would verbally report to the experimenter (acting as the paired technician) when and in what wing the patient was spotted.

Vibrotactile Display

Vibrotactile displays were used to redundantly communicate information regarding the PVC events of a single monitored patient. An adjustable arm sleeve was used to secure five C-2 tactors (Engineering Acoustics, Inc.; http://www.atactech.com/PR_tactors.html). The sleeve was worn over the participant's clothing on the left upper arm (see Figure 4-3). The apparatus was described to participants as a display of PVC events designed to aid the overview monitoring of one patient (patient three) who was reported as having more PVC runs than the other monitored patients. Whenever patient three experienced a PVC event, the participant received corresponding tactons (spatial, nonspatial, or multicode) depending on the vibrotactile display condition (described in the *Tacton Encoding* section below).

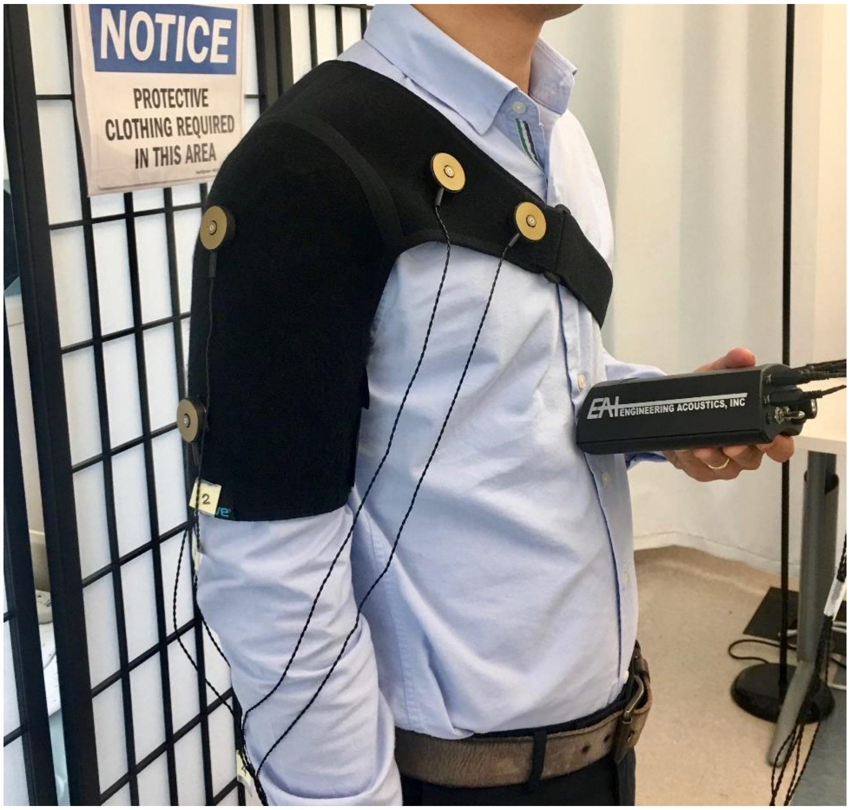


Figure 4-3: Arrangement and approximate location of the vibrotactile devices on the upper arm.

Tacton Encoding

Similar to the experiment described in Chapter II, the tactons that will be used for this study are designed to be as similar as possible (e.g., same intensity) so that they only differ in the encoding methods – spatial patterns, nonspatial patterns, or both – used to communicate information. Each vibrotactile signal, regardless of display configuration, lasted 500 ms with 500 ms off-times between signals, which coincided with the PVC occurrences experienced by patient three.

For the *spatially-encoded* display, PVC runs will be communicated by a series of tacton segments felt at one of the five tactor locations depending on the number of PVCs. For example, if a couplet occurs (i.e., two consecutive PVCs), the tactor second from the bottom began to vibrate; if a triplet occurs, then the 3rd tactor from the bottom began vibrating. An increasing number of back to back occurrences caused the vibrations to move to higher locations on the arm employing a metaphorically accurate natural mapping for the displayed messages (see Figure 4-3).

The *nonspatially-encoded* display was defined by different haptic beat patterns presented via *all* tactor locations. Haptic beats are created when vibrotactile stimuli of different frequencies are presented simultaneously to one or multiple locations (Yang, Tippey, & Ferris, 2014). For example, the simultaneous presentations of a 250-Hz and 248-Hz vibrotactile signal would form a new signal with a 2-Hz beat frequency (see Figure 4-4). One PVC event was represented by a single 250-Hz signal. However, as an increasing number of consecutive PVCs occurred, an increasing beat frequency was employed, doubling with each event. For example, if a couplet occurred, participants received a vibrotactile signal with a beat frequency of 2 Hz. If a triplet occurred, participants received a signal with a beat frequency of 4 Hz. Pilot testing was performed prior to data collection to ensure that all patterns could be distinguished. This display configuration also used metaphorically accurate natural mapping in that an increasing number of back to back occurrences causes an increase in the beat frequency of presented vibrations.

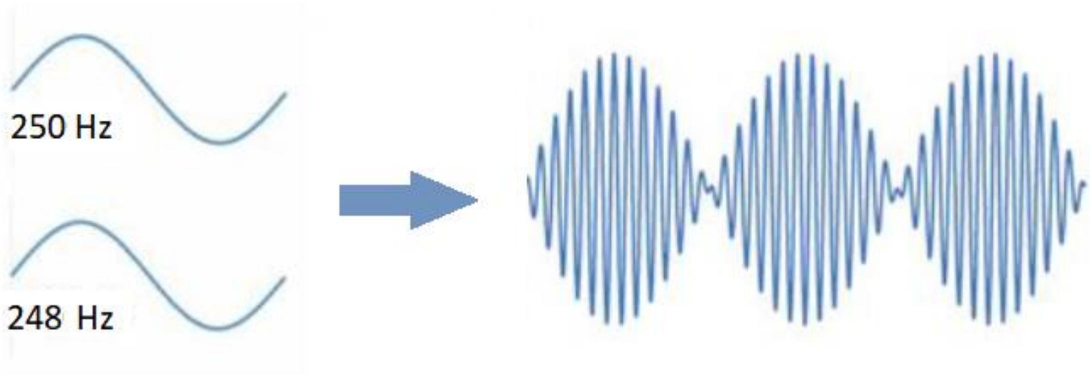


Figure 4-4: Graphical representation of the haptic beats phenomenon where a 250 Hz and 248 Hz signal are combined to form a beat frequency of 2 Hz (adapted from Yang, Tippey, & Ferris, 2014).

Finally, the *multicode* display will communicate information by combining the tacton messages and metaphorical mapping of the *spatial* and *nonspatial* displays, i.e., the spatial location of the presentation as well as a beat frequency at that location. For example, a couplet event was represented by a 2-Hz beat frequency at location two (the second tactor from bottom) and a triplet by a 4-Hz beat frequency at location three (the third tactor from bottom).

Experimental Procedures

Training

After consent was obtained, participants were given a “training binder” created by the experimenter to explain their role and tasks as overview monitor technician in the

Ardoin White Medical Center (a simulated hospital environment; see Figure 4-5). The binder also served to familiarize participants with the vibrotactile display, MATB-II tasks, and required responses). Participants were also presented with a “shift change report” created to provide detail about the (simulated) patients being monitored as if reported by the previous technician. After training was completed, participants were fitted with the vibrotactile display. Next, participants were presented with each tacton that they would encounter during the experiment to familiarize them with each display configuration and to ensure that there was no discomfort experienced by the vibrations. Participants then began the experimental training sessions which were one-minute mini versions of each experimental trial.

Figure 4-5: The simulation setup, distributed across three separate desktop monitors and a touchscreen tablet. Left to right: simulated surveillance video of the constructed Ardoin White hospital wings, the MATB-II display, the simulated physiological data display, and the charting display (touch screen).

Experimental Trials

After being given an opportunity to ask any remaining questions, participants began the six experimental blocks alternating between high and low workload conditions (see Table 4-5 under *Results*). A total of 6 script files (3 per workload level) were designed to drive to occurrences of warning lights, parameter scale faults, and RESMAN tasks (see Table 4-1 in the *Test Environment* section of this chapter).

Each scenario lasted a duration of 4 minutes, with a 2-minute "rest period" between to lessen the likelihood that mental workload from one condition would carry over to the next condition. Noise-cancelling headphones were worn by participants to play auditory alerts and hospital sounds as well as to mask the audible tactor activation assuring that detecting changes in the signal could only be done via tactile (and not auditory) perception (Brown, 2007).

Experimental Design

To investigate the performance effects of multicode redundancy under high and low workload levels, as well as how these effects compare to that of the unicode (spatial or nonspatial) displays, a number of repeated-measures ANOVAs were completed with respect to the monitoring performance of PVC events correctly identified with aid of the vibrotactile display. As previously discussed, it was expected that the conditions involving the multicode display would show similar or better monitoring performance than spatial display conditions and similar or worse monitoring performance than the nonspatial display under both workload levels. The three display conditions were counterbalanced to reduce the learning effect (Prinzel et al., 2000) with half of the participants receiving trials with a low workload level first and half receiving trials with a high workload level first (see Table 4-3).

Additionally, a comparison of monitoring performance between PVC events identified with aid of the vibrotactile display and those identified with aid of redundant visual-auditory displays alone was also performed to determine if accuracy of detection as well as response time would be better supported with aid of the vibrotactile display.

Table 4-3: Order of Display Conditions.

Spatial		Nonspatial		Multicode	
Low	**High**	**Low**	**High**	**Low**	**High**
1	**2**	**1**	**2**	**1**	**2**
2	**1**	**2**	**1**	**2**	**1**
Spatial		Multicode		Nonspatial	
Low	**High**	**Low**	**High**	**Low**	**High**
1	**2**	**1**	**2**	**1**	**2**
2	**1**	**2**	**1**	**2**	**1**
Nonspatial		Spatial		Multicode	
Low	**High**	**Low**	**High**	**Low**	**High**
1	**2**	**1**	**2**	**1**	**2**
2	**1**	**2**	**1**	**2**	**1**
Nonspatial		Multicode		Spatial	
Low	**High**	**Low**	**High**	**Low**	**High**
1	**2**	**1**	**2**	**1**	**2**
2	**1**	**2**	**1**	**2**	**1**
Multicode		Spatial		Nonspatial	
Low	**High**	**Low**	**High**	**Low**	**High**
1	**2**	**1**	**2**	**1**	**2**
2	**1**	**2**	**1**	**2**	**1**

Table 4-3 Continued.

Multicode		**Nonspatial**		**Spatial**	
Low	**High**	**Low**	**High**	**Low**	**High**
1	**2**	**1**	**2**	**1**	**2**
2	**1**	**2**	**1**	**2**	**1**

Results

Data were analyzed using repeated-measure ANOVAs formulated in IBM SPSS Statistics 22 with α = 0.05[†]. Fisher's LSD posthoc tests were used to determine differences between means. For simplicity, display conditions will be further abbreviated in the text with notations listed in Table 4-4.

Table 4-4: Summary of Display Conditions and Notations.

Notation	*Condition*	*Description*
S	Spatial	Tactons presented to one of five tactor locations (Figure 4-3). Metaphorical mapping with vibrations closer to a participant's heart indicating greater number of PVC events.
N	Nonspatial	Haptic beat patterns presented via *all* tactor locations (Figures 4-3 & 4-4). Metaphorical mapping with increasing beat frequencies indicating greater number of PVC events.
M	Multicode	Tactons presented via spatial location and haptic beat patterns at that location (e.g., 4-Hz beat frequency at the 2nd tactor location; Figures 4-3 & 4-4).

[†] Order effect was tested as a between-subjects variable in all analyses. No significance was found in any case; thus, the variable was removed from the model.

The primary performance measures for this study were event detection rate and time in response to patient PVC events. Performance for the surveillance, SYSMON, and RESMAN tasks were also recorded and included in a multitask performance metric (see "Multitask Performance Metric" section below) to measure overall task performance. All dependent measures are described in Table 4-5.

Table 4-5: Definitions of Performance Measures.

Tasks	*Performance Measures*	*Definition*
Patient Monitoring	Event Detection Rate (%)	Measures the percentage of critical PVC events that are correctly detected. Events are considered "detected" by participants when they have pressed the appropriate button on the charting display. A value of 0% was given if the participant fails to respond or presses the button once a later event occurs or if the participant misinterprets an event (presses the wrong button on the charting display)
	Event Response Time (seconds)	Measures time elapsed from the first instance that a critical PVC event could be recognized (visually or with use of the vibrotactile display) until the correct button was pressed
MATB-II	Accuracy (%)	Measures the number of SYSMON warning lights and scale faults the participant correctly responded to using the computer keyboard or mouse
	Response Time (seconds)	Measures the time from the onset of the SYSMON warning light and scale faults until the participant responded
	RESMAN Score	Summary measure of the area between the acceptable volume range and measured volume levels, whenever the range was exceeded, over the entire scenario
Surveillance	Accuracy (%)	Measures the number of times a participant correctly detected the "rogue patient" on screen. Events are considered "detected" by participants when they have given verbal response
	Response Time (seconds)	Measures time elapsed from the first instance that the "rogue patient" could be recognized on screen until the correct verbal response was given

Patient Monitoring Performance

Event Detection Rate for Vibrotactile-Cued PVC Events

An analysis of EDR*s* for vibrotactile-cued PVCs – with workload level (*high, low*) and display condition (*S, N, M*) as independent variables – showed that neither workload level (mean EDR: *high* = .94, *low* = .97) nor display condition (mean EDR: *S* = .96, *N* = .95, *M* = .96) had a significant effect on the percentage of correctly identified PVC events (workload level: $p = .108$, $\eta_p{}^2 = .187$; display condition: $p = .887$, $\eta_p{}^2 = .009$). Additionally, no interaction was found between the main effects of workload level and display condition ($p = .340$, $\eta_p{}^2 = .080$). Mean EDR*s* are reported in Table 4-6. Again, event detection rate for conditions involving the *M* display were numerically lowest under high workload conditions, but highest under low workload conditions.

Table 4-6: Mean Event Detection Rates for Correctly Identified PVC Events Monitored with Aid of the Vibrotactile Display Across High and Low Workload Levels.

Workload Level	*Display Condition*	*Mean EDR* (*SD*)
High	*S*	.94 (.084)
	N	.95 (.072)
	M	.93 (.093)
Low	*S*	.97 (.052)
	N	.94 (.095)
	M	.98 (.040)

Event Response Time for Vibrotactile-Cued PVC Events

A similar analysis showed that mean ERTs to correctly identified PVC events were significantly faster in low workload conditions than in high workload conditions ($F(1,13) = 16.847$, $p = .001$, $\eta_p{}^2 = .564$; mean ERTs: 4.32s and 5.18s, respectively). Display condition was not found to have a significant effect on ERT ($p = .320$, $\eta_p{}^2 = .084$; mean ERTs: $S = 4.92$s, $N = 4.78$s, $M = 4.55$s), however a significant interaction effect was found between workload level and display condition ($F(2,26) = 5.065$, $p = .014$, $\eta_p{}^2 = .280$).

Posthoc analyses comparing workload level within each display condition indicated that response times were faster for the nonspatial (*N*) display when used in low workload conditions (mean ERT = 4.00s) than when used in high workload conditions (mean ERT = 5.563s, $p < .001$). A similar numerical trend was found for the spatial (*S*) display, however significance was not reached ($p = .055$; mean ERTs: *Low workload level* = 4.552s, *High workload level* = 5.29s). Lastly, no significant difference was found between high and workload levels when the multicode (*M*) display was used ($p = .433$), but response times were numerically faster during periods of low workload levels (mean ERT = 4.40s) than response times during periods of high workload levels (mean *ERT* = 4.69s).

Analyzing the interaction effect within workload level revealed that response times to PVC events monitored with aid of the *M* vibrotactile display were significant faster than events that were monitored with aid of the *N* vibrotactile display when higher levels of workload were imposed (mean ERTs: 4.69s and 5.56s, respectively; $p = .036$).

No significant differences were found between any other comparisons within high or low workload levels ($p \geq .102$). All mean ERTs to correctly identified PVC events are reported in Table 4-7.

Table 4-7: Mean Event Response Times (Second) to Correctly Identified PVC Events Monitored with Aid of the Vibrotactile Display Across High and Low Workload Levels.

Workload Level	*Display Condition*	*Mean ERT* (*SD*)
High	*S*	5.28 (.382)
	N	5.56 (.368)
	M	4.69 (.293)
Low	*S*	4.55 (.370)
	N	3.99 (.279)
	M	4.40 (.258)

Comparison of Vibrotactile- and Visual/Auditory- cued PVC Events

As mentioned in the Experimental Design section of this chapter, analyses were also performed to compare monitoring performance of PVC events correctly identified with aid of the vibrotactile display and PVC events correctly identified using redundant visual and auditory displays alone.

Event Detection Rate for Vibrotactile-Cued and Visual/auditory-cued PVC Events

A two-way analysis of variance with workload (*high* and *low*) and cued condition (*vibrotactile-cued* and *visual/auditory-cued*) as variables was performed to compare

EDRs of PVC events monitored with aid of the vibrotactile display and PVC events that were monitored using redundant visual and auditory displays alone.

The analysis showed that the high and low workload levels did not significantly differ in response accuracy (p = .087, $\eta_p{}^2$ = .208; mean EDRs: .91 and .94, respectively). However, the percentage of PVC events correctly identified with aid of the vibrotactile display (mean EDR = .95) was significantly higher than the percentage of PVC events identified with use of redundant visual and auditory displays alone (mean EDR = .90) (F(1,13) = 12.840, p = .003, $\eta_p{}^2$ = .497). Follow up comparisons revealed that the percentage of correctly identified *Vibrotactile-Cued* events was significantly higher than *Visual/auditory-Cued* events identified in both high (p = .017) and low (p = .007) workload conditions. No significant interaction effect was found (p = .629, $\eta_p{}^2$ = .018). All mean EDRs are reported in Table 4-8.

Table 4-8: Mean Event Detection Rates for Correctly Identified PVC Events.

Workload Level	*Cued Condition*	*Mean EDR* (*SD*)
High	*Vibrotactile Cued*	.97 (.037)
	Visual/auditory Cued	.91 (.055)
Low	*Vibrotactile Cued*	.94 (.052)
	Visual/auditory Cued	.88 (.066)

Event Response Time for Vibrotactile-Cued and Visual/auditory-cued PVC Events

A second two-way analysis of variance with workload (*high* and *low*) and cued condition (*vibrotactile-cued* and *visual/auditory-cued*) as variables was performed to compare ERTs of PVC events monitored with aid of the vibrotactile display and PVC events that were monitored using redundant visual and auditory displays alone across both levels of workload.

The analysis showed that responses times when low workload levels were imposed were significantly faster than responses times when high workload levels were imposed ($F(1,13) = 29.052$, $p < .001$, $\eta_p{}^2 = .691$; mean ERTs: 4.73s and 5.62s, respectively). Additionally, the response time to PVC events correctly identified with aid of the vibrotactile display (mean ERT = 4.75s) was significantly faster than the response to PVC events identified with use of redundant visual and auditory displays alone (mean ERT = 5.60s) ($F(1,13) = 20.407$, $p = .001$, $\eta_p{}^2 = .611$). Posthoc analysis again revealed that monitoring performance with aid of the vibrotactile display was significantly better than performance using the redundant visual and auditory displays within both high ($p = .006$) and low ($p = .002$) workload levels. Moreover, comparisons within cued condition indicated a significant difference in event response times between high and low workload levels for both the *Vibrotactile-Cued* ($p = .001$) and *Visual/auditory-Cued* ($p = .002$) conditions (see Table 4-9). However, no significant interaction between workload level and cued type was found ($p = .858$, $\eta_p{}^2 = .003$). All mean EDRs are reported in Table 4-9.

Table 4-9: Mean Event Response Times (seconds) to Correctly Identified PVC Events.

Workload Level	*Cued Condition*	*Mean ERT* (*SD*)
High	*Vibrotactile Cued*	5.18 (1.10)
	Visual/auditory Cued	6.05 (.802)
Low	*Vibrotactile Cued*	4.32 (.924)
	Visual/auditory Cued	5.13 (.694)

Multitask Performance Metric

A multitask performance metric was created to quantify participants' overall performance combining measures for all tasks (*P*, see Equation 4-1). The metric normalizes each participant's performance according to his or her average performance across all conditions and assigns weightings to each dependent measure based on instructions (e.g., each equally important task represents ½ of the metric). *Z*-scores were calculated for each dependent measure prior to calculating the metric, thus a negative *P* value indicates worse relative performance to the participant's average across all conditions, and a value of 0 is equivalent to average performance across all conditions. Metrics were calculated for each participant and compared in a two-way repeated-measures ANOVA with workload level (*high*, *low*) and display condition (*S, N, M*) as independent variables. Note, only vibrotactile-cued data from the patient monitoring task is included in this analysis.

$$\mathrm{P} = \left[{}^{1}\!/_{3}\left[{}^{1}\!/_{3}\,(SYSMON\_RT) + {}^{1}\!/_{3}\,(SYSMON\_RA) + {}^{1}\!/_{3}\,(RESMAN\ SCORE)\right] + {}^{1}\!/_{3}\left[{}^{1}\!/_{2}\,(\mathrm{PVC\_EDR}) + {}^{1}\!/_{2}\,(\mathrm{PVC\_ERT})\right] + {}^{1}\!/_{3}\left[{}^{1}\!/_{2}\,(\mathrm{SURV\_RT}) + {}^{1}\!/_{2}\,(\mathrm{SURV\_RA})\right]\right]$$

Equation 4-1: Multitask performance metric (P), where SYSMON_RT/RA and RESMAN score are the performance measures for MATB-II tasks, PVC_EDR/ERT are the performance measures for the patient monitoring task, and SUR_RT/RA are the performance measures for the surveillance task, as described in Table 4-5.

Analysis of the *P* metrics showed a significant effect for workload level ($F(1,13) = 33.252$; $p < .001$, $\eta_p{}^2 = .719$), in which performance was worse for conditions with a high workload level (mean $P = -.220$) than those with a low workload level (mean $P = 0.220$). No interaction effect was found ($p = .912$, $\eta_p{}^2 = .007$) neither was display condition found to significantly affect multitask performance ($p = .790$, $\eta_p{}^2 = .018$; mean *P* for $S = -.015$; $N = -.027$; $M = .042$). It is interesting to note that the *M* display condition was the only condition that resulted in multitasking performance above the overall average (a positive numerical value). Mean *P* scores are provided in Table 4-10.

Table 4-10: Mean Multitask Performance Metrics (*P*).

Workload Level	*Display Condition*	*Mean P* (*SD*)
High	*S*	-.263 (.365)
	N	-.230 (.369)
	M	-.167 (.461)
Low	*S*	.233 (.451)
	N	.176 (.257)
	M	.251 (.211)

Subjective Ratings

Between experimental sessions, participants rated their perceived level of helpfulness for the immediately completed display condition on a ten-point scale ranging from 1 (*not helpful*) to10 (*very helpful*). Analysis revealed a significant difference in ratings of helpfulness between the display conditions ($F(2,26) = 5.886$; $p = .008$, $\eta_p{}^2 = .312$). Further analysis indicated that participants felt the spatial display (*S*) was significantly more helpful in performing tasks than the nonspatial display (*N*) ($p = .046$). Similarly, participants felt the multicode display (*M*) was also significantly more helpful in performing tasks than the *N* display ($p = .011$). Although the mean rating for multicode display was numerically higher than that of the spatial display, it did not reach statistical significance. A summary of the subjective ratings is provided in Table 4-11.

Table 4-11: Summary of Subjective Ratings of Helpfulness in Performance of Monitoring Task.

Display Condition	*Mean rating (SD)*
S	7.21 (2.04)
N	5.86 (2.63)
M	8.07 (1.98)

In addition to the aforementioned rating scale, participants also ranked the vibrotactile displays in order of 1 to 3 by how well they perceived the display helped their overall multitasking performance. A summary of the rankings is presented in Table

4-12. It is interesting to note that the *M* display received the highest ranking overall for useful in multitask performance.

Table 4-12: Summary of Subjective Rankings of Usefulness in Overall Multitask Performance.

Rankings	*S*	*N*	*M*
Ranked as 1st	28.57%	28.57%	50.00%
Ranked as 2nd	28.57%	21.43%	42.86%
Ranked as 3rd	42.86%	50.00%	7.14%

Redundant Visual- and Auditory-cued PVC Events

Lastly, to verify anecdotal reports of differences in salience between the vibrotactile displays, i.e., one display may have been more attention-grabbing than another, an additional analysis was completed to test whether monitoring performance with use of the visual and auditory displays alone was affected by vibrotactile display type.

Event Detection Rate for Visual/auditory-cued PVC Events

Analysis of the event detection rate (EDR) with workload level (*high, low*) and display condition (*S, N, M*) as independent variables showed that percentage of critical PVC events that were correctly detected in high workload conditions (mean EDR = 0.88) was numerically worse than the percentage in low workload conditions (mean EDR = 0.92). However, significance was not reached ($p = .161$, $\eta_p{}^2 = .145$).

Additionally, display condition did not significantly affect response rate (mean EDR for *S* = 0.91; *N* = 0.90; *M* = 0.893, *p* = .836, $\eta_p{}^2 = .014$) and no significant interaction was found (*p* = .956, $\eta_p{}^2 = .003$). Mean EDRs of critical PVC events for workload conditions involving each type of display condition (S: spatial; N: nonspatial; M: multicode) are reported in Table 4-13. It is interesting to note that event detection rate for conditions involving the *M* display were numerically lowest under both high and low workload conditions.

Table 4-13: Mean Event Detection Rate of Critical PVC Events for Workload Level Involving Each Type of Display Condition (S: spatial; N: nonspatial; M: multicode).

Workload Level	*Display Condition*	*Mean EDR (SD)*
High	*S*	0.90 (.092)
	N	0.88 (.081)
	M	0.87 (.144)
Low	*S*	0.92 (.081)
	N	0.92 (.126)
	M	0.91 (.100)

Event Response Time for Visual/auditory-cued PVC Events

A similar analysis of event response time (*ERT*) revealed a significant difference among workload conditions (*F*(1,13) = 14.809; *p* = .002, $\eta_p{}^2 = .533$). As expected, participants responded significantly faster in low workload conditions (mean *ERT*: 5.14s) than in high workload conditions (mean *ERT*: 6.05s). However, display configuration did not significantly affect *ERT* (mean *ERT*s: *S* = 5.641s, *N* = 5.729s, *M* = 5.414s; *p* = .550, $\eta_p{}^2$ = .045). Posthoc comparisons within workload level showed that conditions involving the *M* display resulted in significantly faster response times than conditions involving the *N* display (*p* = .023) when workload was relatively low; however, no differences were found when higher workload levels were employed. Comparisons within display type revealed a significant difference in performance with the *S* display and the *M* display in which performance was significantly worse in high workload conditions versus low workload conditions (*S* display: *p* = .036, *M* display: *p* = .011). No interaction was found between workload level and display condition (*p* = .455, $\eta_p{}^2$ = .059). Mean event response times to correctly identified PVC events for workload conditions involving each type of display condition are reported in Table 4-14.

Table 4-14: Event Response Time (Seconds) to Correctly Identified PVC Events for Workload Levels Involving Each Type of Display Condition (S: spatial; N: nonspatial; M: multicode).

Workload Level	*Display Condition*	*Mean ERT (SD)*
High	*S*	6.24 (1.47)
	N	6.00 (1.24)
	M	5.10 (1.05)
Low	*S*	5.04 (1.23)
	N	5.46 (.98)
	M	5.92 (1.01)

Discussion

Detecting critical health events in environments such as an overview monitoring station requires continuous monitoring of cardiac rhythms along with a number of other visual and auditory displays and alarms. This often creates a very high demand for visual and auditory resources. If these displays are attended too infrequently or frequently (at the expense of others), there is an increased likelihood that events may be missed meaning lower response rates and/or declined performance in concurrent tasks.

Previous research has demonstrated that the introduction of tactile displays can be effective in supporting the detection, identification of, and response to patient health events in visually- and auditorily-demanding medical environments and thus provide a promising means of supporting non-visual overview monitoring and management of patient physiology (Ferris & Sarter, 2009; Ford et al., 2008; Ng, Man, Fels, Dumont, & Ansermino, 2005). Furthermore, tactile displays – more specifically multicode displays – have shown promise as a way to minimize processing interference that can occur when concurrent tasks, even those that employ different sensory modalities, compete for the same cognitive resources (Ardoin & Ferris, 2016; also see Chapter II). However, it was concluded that additional investigation was needed to gain an understanding of performance using a multicode display in a more real-world, multitask environment as they often impose higher baseline levels of cognitive workload than those evaluated in previous studies. Thus, before multicode displays can be introduced into more complex domains, it was important to investigate the cost they impose under various workload conditions. The aim of this study was to investigate the performance effects of multicode redundancy within a continuously-informing display under two different levels of workload demand (high and low), as well as how these effects compare to that of unicode displays.

Overall, when evaluating performance in the patient monitoring task, a trend could be seen such that performance with aid of the multicode (*M*) display produced highest numerical event detection rates when workload was relatively low, but the lowest numerical event detection rates when workload was high. Similar to previous findings in Chapter II, this suggests both performance costs and gains: gains when operator workload is low and costs when operator workload is relatively higher. Additionally, performance with the *M* display most often produced the fastest response times in comparison to the unicode displays regardless of workload level, a clear performance gain; however, this gain may have come at the expense of accuracy at higher workload levels.

In evaluating performance of the *M* display among vibrotactile-cued events, results illustrated that aid with the *M* display produced faster response time to correctly identified PVC events in the high workload conditions; however, event detection accuracy tended to decline pointing to a speed-accuracy tradeoff. It can be inferred that this tradeoff is attributable to the *M* display's effectiveness at capturing the attention of participants leading to faster response times, but the increased complexity of the redundant signal may have imposed a higher processing load, especially during times of high workload, leading to decline in accuracy. This inference was reflected in anecdotal reports that participants often felt the *M* was one of the “most helpful in capturing attention” due to the redundant, multi-processing code display of the signal.

Generally, when evaluating performance of the *M* display among vibrotactile-cued events, it is interesting to note that monitoring performance with aid of the *M* display more closely align with performance of the *S* display than the *N* display. This observation aligns with ratings of perceived level of helpfulness where both the *M* and *S* displays were rated by participants as significantly more helpful than the *N* display. This suggests that participants tended to pay more attention to the spatial nature of the signal rather than the nonspatial component similar to findings of the study described in Chapter II of this dissertation. However, performance was better with aid of the *M* display under low workload conditions – yielding faster responses and a greater number of correctly identified events – than the *S* display, but event detection declined when a higher level of workload was employed. It can be inferred that the multi-processing code display of information provided an advantage over the spatial in low workload conditions in that it better captured participants’ attention, directing them to the phycological display; however, since participants tended to attend more to the spatial component of the signal, the additional cognitive load required to suppress the nonspatial component likely resulted in the performance decrement when higher levels of workload were imposed.

Performance with respect to PVC events correctly identified with aid of the vibrotactile display and events monitored using redundant visual and auditory displays alone was also compared. As expected, monitoring performance was worse when participants relied solely on redundant visual and auditory displays regardless of workload level. This finding aligns with previous research demonstrating the performance benefits of tactile displays in visually- and auditorily-demanding environments (Ferris & Sarter, 2009; Ford et al., 2008; Ng, Man, Fels, Dumont, & Ansermino, 2005). It is important to note that events detected with aid of the vibrotactile display were always presented in the same visual field of the monitor. However, the location of displayed PVC events detected using redundant visual and auditory displays alone varied in the visual field. For example, the events were sometimes displayed at the top, middle, or bottom of the monitor.

Generally, performance measures illustrated a pattern demonstrating how the multicode (redundant spatial+nonspatial) display offers a *redundancy gain* in low workload conditions and a *redundancy cost* in high workload conditions. These findings suggest humans do show a least a limited ability to switch their attention between aspects of the redundant signal, thus providing performance *benefits* due to additional ways to process information. This was supported by anecdotal reports that the redundant spatial+nonspatial display of information was most helpful in the patient monitoring task with statements such as “it reminds me of what’s important, but when I forget location, the frequency [of the vibrations] reminds me. They reinforce each other.” Another participant reported feeling the additional display of information was “backup.” Furthermore, when participants ranked the vibrotactile displays by how well they perceived their usefulness in overall multitasking performance, fifty percent ranked the multicode displayed as number one. Although multicode displays have demonstrated a number of performance benefits (redundancy gains) in multitask environments, it remains a possibility that redundancy costs resulting from higher processing loads in interpreting a more complex signal could offset the benefits.

One limitation of this study was sample size. The small sample size used may have affected the study's ability to detect certain effects that may have been present or detected with a larger sample. Another possible limitation involved task-switching effects, specifically the possibility that participants engaged the same processing code of the previous task condition when beginning *multicode* conditions. However, to reduce task-switching costs (Monsell, 2003), participants were given mini tests between each scenario that required a change in vibrotactile display type in order to refamiliarize them with the display (*S*, *N*, or *M*) that would be utilized in the upcoming scenario.

CHAPTER V

CONCLUSION

The task set of operators in many complex, data-rich domains, is characterized by high mental workload and the need for effective attention management. As more and more sources of task-relevant information are made available in these environments, it is important to consider how to best display that information to allow for efficient attention allocation and thus an improved ability to multitask effectively. A great deal of previous research has focused on redundancy in multisensory information presentation, i.e., the presentation of identical information via two or more sensory channels, as a means to better support attention management between multiple tasks and sources of task-relevant data. However, studies have found this requires more than consideration of the sensory modality (e.g., vision, audition, or touch), but also consideration of the working memory functions (processing codes) that must be engaged to interpret the encoded message (Ferris & Sarter, 2010; Wickens, 2002). This dissertation research expounds upon the concept of multi-processing code redundancy and investigated how use of multicode vibrotactile displays – which allow decoding a message by engaging either spatial or nonspatial/verbal processing resources – affect multitasking performance in a series of experimental and observational studies.

The first experiment (described in Chapter II) investigated how discrete vibrotactile displays that use spatial, nonspatial, and redundant encoding methods affect performance in dual-task scenarios where both tasks require the same processing resources. Findings of the study illustrated that multicode redundancy shows promise for combating the processing code interference, as dual-task conditions with the multicode display produced better performance than both conditions that required direct competition for the same processing code. However, the added complexity of a multicode display may lead to performance costs when cognitive loads of concurrent tasks are higher than those used in the experiment. Therefore, future work is needed to investigate the mental cost they impose under various workload conditions more representative of real-world environments. To address this need, an observational study of four separate, but related overview patient monitoring systems was performed to gather input about the human and technological components of the systems and how they interact as well as any challenges related to technological components that may affect patient safety and console technician efficiency. Findings from the task analysis and observations highlighted two potential challenges contributing to monitoring task workload – sensory overload and processing interreference – and also served to inform the design of the test environment and vibrotactile displays utilized in the final study. They also served to ensure that the study adequately addresses some of the real-world challenges faced by operators in the task of remote patient monitoring. The final study in this dissertation applied findings from the first two studies to test whether multicode redundancy applied to a continuously-informing display would aid performance in a monitoring task under different workload levels. Generally, performance measures illustrated a pattern demonstrating how the multicode (redundant spatial+nonspatial) display offers a *redundancy gain* in low workload conditions (which may be attributed to the flexibility the multicode signal allows in processing messages) and a *redundancy cost* in high workload conditions (which may be due to an additional processing load imposed when an operator is experiencing an already heavy workload demand). These results were consistent with findings of previous work discussed in Chapter II, which similarly demonstrated performance gains and costs using a discrete set of tacon displays.

Overall findings of this research suggest that humans do show a least a limited ability to switch their attention between aspects of the redundant, multicode signal. It can be inferred that *multicode* redundancy shows promise for combating the processing code interference described by the Multiple Resource Theory of human information processing (by allowing either processing code to be engaged in message interpretation) and may prove beneficial in data-rich complex domains that involve concurrent tasks with competing working memory resources. The research efforts of this dissertation contribute to a better understanding of human information resources by providing insight into a fundamental question of human information processing regarding whether humans can effectively select which processing code/working memory functions they engage when interpreting a redundantly-encoded message. This research is also important for the design of both multimodal and vibrotactile displays intended to support multitasking in complex domains.

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APPENDIX

TASK ANALYSIS: UNDERSTANDING CONSOLE TECHNICIAN TASKS AND CORRESPONDING SYSTEM CHARACTERISTICS

SYSTEM 1

Most patients (up to 32 monitored)

Requires remote runner, also a 2nd runner during weekdays

More interventional patients (ablations or stents)

Highest workload

SYSTEM 2

Second-least number of patients (up to 15 monitored)

Could also include LVAD patients (Left Ventricular Assist Device) – nurses where those patients are have less CV knowledge, have to watch a bit more closely

More surgical patients

Co-located runner

Second-lowest workload

SYSTEM 3

Also includes System 1-7th floor "suite" patients (up to 25 plus patients in System 1-7 monitored)

Alarm settings are set by unit not console monitors

Second-most patients and second-highest workload

North wing – long-term transplant patients, more familiarity with them

SYSTEM 4

Very few patients, but growing

No runner, interact only with nurses

(Currently) lowest workload

Alarm settings are set up by unit not console monitors

SYSTEM 5

Up to 140 patients

2 monitoring technicians during weekdays

No runner

Depending on day, can be heaviest workload

Interact with (unfamiliar) nurses via phone

Must first click on patient box

Look at room number

Find room number on log sheet

Then look at very next column to find the number associated with the nurse's phone

INPUT/CONTROL MECHANISMS

KVM switch

Select two active screens for mouse scrolling

Roller ball (only one technician prefers mouse)

Mouse over patient in monitoring screen

Patient window button: patient window (bottom right monitor) shows patient detail

All ECG leads, ordered by most relevant

Allows access to arrhythmia alarms management for that patient

Record button: prints most relevant 2 waveforms on strip printer

Wait for printer to complete

Tear off strip

Touchscreen (AV screen)

Mouse still works there, used by some for preference

Room videos

Touch room to activate

Red button to deactivate – when done conversing

Critical Alert button – to initiate a code

Headset

Select room on AV screen and talk

one audio can go through at a time (monitor and those in the room must wait to talk)

delay in audio signal affects conversation initiation

Phone

One button: page call nurse

Call other departments as necessary

TASKS

Monitor and manage patients

Manage alarms

   Activate/deactivate alarms for specific patients

      Do this when

         new patients are entered

         nurses call for various reasons, e.g., pacemaker testing

      Click patient in monitoring screen – goes to patient window

      “Arrhythmia alarms” button

      Edit values for red alarms

      Asystole: > [value] s

Default [value] = 3.0

VFib/Tach

VTach > [value] b/min >= [value2] PVCs

Default [value] = 100

Default [value2] = 5

Extreme Tachy > [value] b/min

Not editable, [value] = 140

Extreme Brady > [value] b/min

Not editable, [value] = 40

Check/uncheck various yellow alarms

Non-Sustain VT

Vent Rhythm > [value] PVCs

Default [value] = 10

In observed case, 14 PVCs

Info, didn't need to know as closely

Documented on paper ectopy

Verbally state to next technician (next sitter or next shift)

Run PVCs > [value] PVCs

Not editable, [value] = 2

Only clinical could adjust this

Pair PVCs

2 consecutive PVCs, don't even notify nurses about this one

R-On-T PVC

Vent Bigeminy

Vent Trigeminy

PVC Rate > [value] PVCs/min

Default [value] = 10

Multiform PVC

Alarm can be activated with single PVC

PVCs showing more than one type of wave pattern, no regularity

PVCs “just look different, irregular”

Pacer not capture

Only relevant if patient is wearing a pacemaker

Pacer not pace

Only relevant if patient is wearing a pacemaker

Missed Beat

Pause > [value] s

Default [value] = 2.00

SVT > [value] b/min >= [value2] SVBs

Default [value] = 180

Default [value2] = 5

AFIB

If patient has atrial fibrillation, usually uncheck this alarm

Irregular HR

Cannot Analyze ECG (sound)

Means sound can be turned on/off but notification will still show

Observe alarms

Visual

Blue – notification

Leads fell off

Cannot analyze QT segment

- If this happens for a long period of time, technician should go to patient and check
- Could be because of a new ectopy
- Visually see if it looks alarming
    - May have to change gain
- May have to move from V3 to V4 or other
- Try the “relearn” buttons
    - 15 seconds of good waveforms to relearn
- Frequently an issue with unusual beats
    - PVCs
        - Paced beat
        - Bundle branch block
        - A sinus beat could mess this up because trying to learn common pattern
        - Patients go in and out of AFIB

Battery low

SpO2 sensor off

Monitoring suspended

Telemetry suspended

Yellow – warning, requires attention

Atrial fibrillation

SpO2 low (< 90) or can't be read

Run of 3 ventricular beats

> If many more than 3 – have to manually count if more because system loses count
>
> In printout or on screen
>
> Nurses may specify that they don't want to know every run of 3, only if it's as bad as [whatever]

Document this instruction on ectopy sheet

[See list above]

Red – emergency

Ventricular fibrillation

Run of 5 ventricular beats

Extreme conditions, depends on criteria

> Call charge nurse
>
> Initiate Code

[See list above]

Auditory

Blue – low volume, soft tone

Yellow – medium volume, soft tone

Red – high volume, urgent and repeating tone

Continues until alarm is silenced

Content

Read written content

Read patient name

Read patient room

Silence/process alarm

Patient highlighted in blue when alarms are active

Mouse over patient strip, 2 buttons appear

Patient Window (sends to that screen)

Silence and Review (saves for later)

Go to Patient Window

"Close" = save into alarm review

"Delete" = clears alarm

"Record" = prints off paper strip

"Print" = goes to large printer

Multiple alarms for a patient

Observe drop-down arrow in alarm box

Mouse-over to display list of alarms, sorted by recency

Length of list is an urgency/severity indicator

Interpret (evaluate) alarms

Use color coding/auditory signal to prioritize attention to those with more urgency/severity

Red: should address immediately

Yellow: attend to, determine severity and address when appropriate and able

Blue: usually ignore/silence

Determine severity

False alarms:

Identify as false: 80% (agreement on this estimate among 4 technicians)

When patient takes shower:

higher frequency false alarms

have to disconnect and reconnect with waterproof

nurse calls to announce this

silence alarms temporarily

Ignore or delete/clear alarms

Nuisance alarms

Due to standardized thresholds not fitting every patient

Blood pressure

HR

Pre-existing condition (not changing)

AFib

Lots of PVCs

Elevated STs

Usually silence these alarms in alarm panel

True alarms

Determine validity and severity

Clinically relevant

Change in status/pattern

Significant event

Expected event, e.g., pacemaker testing

Act on patient events

Document

Get additional info as necessary

Deeper analysis of waveforms

Print on small "strip" printers

- Select strip of interest
- Click to print it
- Analyze print off
- Patient condition changing/worsening?

Compare with previously-stored data

Use knowledge of past experience with patient

Talk with nurse

Consult Paired Technician

- With electronic display
- With printed strip

Check room on video

Zoom or move as necessary

- Touch/gesture on video display

Observe patient activity

- Benign

Sitting up

Coughing

Walking

In commode

- Problem

Fall

Not present in room

Call room

talk to nurse

- activate room video
- put on headset
- talk
- can’t talk over each other
- slight delay in audio feed is problematic

talk to patient

- activate room video
- put on headset
- talk
- can’t talk over each other
- slight delay in audio feed is problematic

Identify artifact

Select patient on monitor screen

Attention on patient window

Verify alarm-inducing data on patient window

Bring up relevant data to compare with alarm-inducing data

- Additional ECG leads
- 6 leads: V1/V3 default locations, check others
- Plethysmography

Judgment call on whether it looks regular (then data is good) or irregular (likely artifact)

- SpO2
- Patient remote location/movement

Inferred by where the signal “pings” – as they walk by other rooms it will look like coming from there

Act on patient events

Decide to act immediately or delay

Severity/urgency

High: act immediately

Low: workload driven, attend when possible or leave for partner/next shift

Act

Address need

Runner or nurse?

  Nurse if remote (ED, Masimo) or if the nurse wants to perform a simple task (such as reattaching leads)

  Runner otherwise

Consider personal relationships when determining who/how to complete task

  with patient

  with nurses

Male/female only?

  Identify if this is the case

  Identify available runners

  Send appropriate sex

Call runner/nurse

  In monitoring room: speak/yell

Depending on location/privacy, may need to be vague so as to not openly communicate patient info

  System 1 station: call runner over video/audio – activate via AV screen

One way visual. Runner only has audio.

If runner is away from desk, console operator can page charge nurse or wait for runner to return (may be able to page runner???)

For System 5: contact nurse via phone

Click on patient box via touch screen

Look at room number

Locate room number on “log sheet”

Move to next column to get one digit # associated with the nurse’s phone

Click RMH/SMH button on phone along with the one digit number

Issue instructions for activity

Sensors/electrodes/leads/etc

Check them for good contact

Replace as necessary

Sensor module

Restart as necessary

Replace battery as necessary

If patients in isolation

If admitted, automatically isolated until evaluated for MRSA

If its leads or evaluations, our techs should do this, but sometimes asking nurse to do something simple like reattach lead

Skin irritation

If you don’t go to patient’s room, couldn’t tell if their skin is breaking out, could be getting infections

Heart transplant patients on for so long, so many medicines, skin is very fragile

Chemotherapy skin very fragile

Have to manage this and let nurse know

Call charge nurse

Criteria:

    BPM 39 or less

    Pause of 3.0 seconds, less than 5.0 seconds

Alarm will go off for greater than 3, but judgment call on whether or not it's 5 or more

    10 or more ventricular beats

Infer from alarm and additional data whether to call nurse or initiate code

Call nurse, converse about the situation

Initiate Code

Criteria:

    Pause greater than 5.0 seconds

Could look like this when leads are off – false alarm

    Full screen of ventricular beats

    Ventricular fibrillation

Identified by extremely chaotic waveforms

Is patient DNR/DNI?

    DNR indicator on AV screen

    Patient room colored yellowish on AV screen

    If yes, do not activate code

Click room to see patient

"Critical Alert" button

"Yes" to verify code

Delete/clear alarm

Click patient in monitoring screen – goes to patient window

'SpO2 sensor off' alarms

> If a patient is on telemetry

> Judge if this is important or just noise/nuisance

Nurse will tell if continuous SpO2 monitoring is wanted

> There is a way to turn it off, but have to re-turn it off repeatedly because it resets

Because this is how Phillips designed it

Considered an active alarm – as soon as it comes into contact with the patient, it automatically turns on

This is useful because usually it saves a step

> Click "Suspend" alarms

> Click "Unsuspend" alarms

Blood pressure

> Similar to SpO2 notes

Other alarms off

> "Arrhythmia alarms" button

If AFIB or other common, recurrent, and relatively benign conditions

> Check/uncheck various alarms

> If DNR – still watch for degrading conditions but remember to not go to full code

> Trying to stop alarms because the system will dump in more and more data that don't have to evaluate

Observe and Evaluate rhythms

> *Select patient from monitor screen to show with more detail in patient window*

If strange rhythm is recognized

Otherwise, default to most problematic patients

Recognize problems not necessarily indicated by alarms

If amplitude of signal is not high enough, the system can't learn it

Have to increase gain

Increasing gain could make it look like ST elevation

When HR changes, that can significant affect the accuracy of the alarm system

Can see changing STs before system

System is "backup" – use visual inspection and knowledge to identify these

Atrial fibrillation (A-Fib)

New instance, or recurrent?

If new, more significant

If recurrent, be sure it is noted in ectopy form

"runs": consecutive ventricular beats

Have to count them

Manual assessment of rhythms

Notice unusual rhythm

Print it off

Use manual calipers to measure waveform segments

Document patient issues

Select patient

Mouse over

Select "Patient Window"

Select relevant data

Representative sample of waveform

Wave review

Select it

Save there, it populates over into Alarm Review

Could have a start and stop timeline within the Event Mode

Alarm

  From Alarm Review

Print

Annotate

  Select from drop-down list or enter text to describe issue

  Sign with initials

Enter which leads/data stream

  New or worsening ectopy

Wave review

Select

Save to Alarm Review

Go to Alarm Review

Select

  Call code if necessary

If new or noteworthy change in ectopy

Print off via large printer

Select representative EEG strip electronically

  Re-select as necessary

Click to send to printer

Go to printer

Orange sticker to denote printoff needs initials of receiving nurse

Determine which nurse to report to

- From personal experience
- By lookup on written documents
- Consult charge nurse

In person

Via phone

Alert charge nurse

- If can't find patient's immediate nurse
- If ectopy is severe enough

Deliver and communicate with nurses

Runner delivers to nurses

- Give to nurse
- If don't know who the nurse is, place outside patient's room
- Give to charge nurse

Orange sticker: to be added to patient chart

Special tasks

Per monitoring hour

Record on paper ectopy form

Top and bottom half of each hour

- Note each patient that showed Afib
- Update with most severe ectopy of the past hour

Look up ectopy episodes

Determine the most severe

Highest HR

Afib

Highest run of PVCs

Write in form

Review/update pertinent information: ISO, etc.

Clear clinically-irrelevant alarms

Common: SpO2 alarms, low batteries, leads off

Alarm review

With 5 – 20 minutes left in hour at console

Select function in patient window

Delete/clear any irrelevant alarms

Usually many of these, those they didn't get to yet

SpO2 Sensor off

Low battery

Leads off

Or leave them for the next seated technician

Good working relationship motivates not doing this

Time may not be available to clear them all, have to verbally describe to next seated technician

Double-check for any missed alarms that are clinically relevant

Document as necessary

Various times, each 8-hour shift

Save example strip of each patient

Especially important with nursing changeover

2nd hour of each shift: coincides with nursing changeover

All consoles do this

Find characteristic rhythms for each patient

Bring patient into patient window

Select representative rhythms

Save rhythm

Repeat as necessary

Charge nurse review

System 2: review in person

System 1: review more often via phone

Timing depends on shift

Day shift 6 AM – 2 PM

6:30 AM night shift charge nurse

7:30 AM day shift charge nurse

Evening shift 2 PM – 10 PM

Weekend:

2:30 PM day shift charge nurse

6:30 day shift charge nurse?

7:30 night shift charge nurse

Weekday:

2:30 day shift charge nurse

3:30 evening shift charge nurse

Night shift 10 PM – 6 AM

Weekend:

No charge nurse review?

Weekday:

10:30 evening shift charge nurse?

11:30 night shift charge nurse?

Verify/update each patient on console/wing

Note patients on continuous monitoring

Note ISO

Contact isolation (gown and gloves)

Droplet isolation (gown, gloves, mask)

Airborne isolation (gown, gloves, mask, suit)

DNR/DNI

Note pacemaker settings

Type of pacemaker setting:

DDDR (dual)

VBIR (ventricular)

AAIR (atrial)

Upper and lower limits

Update info in Screen notes

Update info in pacemaker patient "rolodex"

Grab rolodex

Find patient card

Edit with pen – cross out/white out and rewrite

Verify that pager works – send a page to charge nurse

Communications

"Give an SBAR": formalized procedure for handoff, no matter who (other technician, nurse, physician, etc.)

Handoffs

Swap with runner each hour

Communicate notable problems with patients

Change of monitor shift

Communicate notable problems with patients

Call from room

From nurse or patient

Long-term patients (e.g., transplant patients) more likely to call

Ding-dong, green lit room on AV monitor

Put on headset

Press room to activate video and audio communication

Converse to receive info:

Need to suspend monitoring or telemetry

Determine which

Suspend telemetry: monitors still on, important for local monitoring

Suspend monitors: turn them off, saves batteries

Patient on continuous monitoring?

if yes, remind nurse of need to attend patient

nurses may correct if continuous requirement has been lifted, update in monitoring system

manage transition to portable system

Determine and note reasoning:

    Going to a test

    Taking a shower

    Going for a walk

    Going to library/other hospital center

    Etc.

Document suspension

Activate patient in patient window

Select "standby"

Select reason (e.g., Angio, Cardiovert, Cathlab, Generic test, etc)

Return from suspended monitoring (nurse or runner)

Reattach electrodes in relevant positions

Reattach leads

    Nurse call to update monitors with new patient info

    Patients put on/taken off continuous monitoring

    Changes in DNR/DNI (do not resuscitate/intubate)

    Changes in pacemaker settings or limits

    Miscellaneous patient characteristics

    Language, speak English?

Male-only; female-only?

    New patient admit

More of these during day shift

Click blank room

Click "Admit"

Get new admit sheet (delivered by nurses)

Enter patient info from admit sheet

- Name
- DOB
- Patient category
- Medical record number
- Screen notes

Where are leads? Usually V1/V3

- Initials of the technician who hooked up leads

Assess new patient

- Visually assess waveform, note any noteworthy conditions

A-Fib, Bi-geminy, Tri-geminy, elevated ST

- Go into “Arrhythmia Alarms” in patient window and de-select any pre-existing conditions
- ST baseline for ST monitoring setup

cannot if have pacemaker, A-fib, A-flutter, left bundle, in these cases use SpO2 or QT rhythms

select representative strip in waveform data

enter notes: “ADMIT [monitoring tech initials] [leads] ST SETUP”

Click “E-Caliper”

Select PR segment and click “PR”

Select QRS segment and click “QRS”

Save: auto-calculates ST

- Patient discharge

More of these during day shift

Put alarms on standby

Take out card from rolodex, match it up with data on Patient window to verify

Mark on card: DC out, time, date, console

Paper ectopy form: Cross out patient in red, note "DC"

Specific times, certain shifts

Alarm reset activities at midnight