Identifying Errors in Tactile Displays and Best Practice Usage Guidelines

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Abstract. Wearable tactile cueing provides a significant opportunity for performance and safety improvement during human-in-the-loop tasks. However, wearable technology and the human factors associated with tactile cueing presents specific challenges and many pathways for potential errors. This paper reviews tactile cueing displays, usage characteristics and identifies potential error pathways. We use a model for tactile salience to describe adaptive cueing and case-specific examples of potential errors. We propose that tactile designers work towards intelligent systems that recognize user responses, adapt the tactile signal characteristics and close the loop between the display and the task.

Keywords: Tactile displays · Error pathways · Systems engineering · Cueing

1 Introduction

The sense of touch offers a relatively untapped and intuitive channel for communication and orientation. Tactile displays comprise of a number of small, wearable vibrotactile actuators, or tactors, that are distributed over the body. Tactile arrays have been integrated into clothing (e.g., vests, body suits, gloves and head attire) or implemented as wearable components that are often worn over clothing (for example torso-worn belts). Tactile arrays have the potential to provide effective cueing even under situations where the conventional communication channels such as visual, audio and even vestibular become disorientated [1, 2]. Meta-analytic investigations have shown that tactile cueing can enhance performance when added to visual cues, particularly under conditions of high workload [3]. Research has demonstrated that properly implemented tactile cueing yield significantly faster and more accurate performance than comparable spatial auditory cues [4].

Torso-mounted tactile displays have proven effective for navigation and communication in military field evaluations and were very highly regarded by experienced Soldier-evaluators [5–7]. These displays, when integrated with GPS, enabled Soldiers to navigate at night, hands-free (allowing the Soldier to hold his/her weapon) and eyes-free (allowing focused attention to surroundings as opposed to a display). In those studies, torso-mounted displays were proven effective for Soldier covert communications.

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Any human interface display technology can be susceptible to errors. Tactile cueing displays can be intuitive, but human factors and systems designers have usually had less experience with this modality. We argue that they are susceptible to system design errors (implementation and design defects), and more often, insufficient consideration of environmental context, task demands, and user characteristics. A system may be built to specifications, and yet still be unsuited for purpose, when specifications are not matched to context of use. Therefore, designers need to be cognizant of these potential error pathways and in addition, develop operator training that minimizes and/or compensates for any errors. We discuss potential error pathways and suggest approaches for the identification and mitigation of errors.

2 Outlining a Systems-View of Tactile Cueing

2.1 Human Response to Vibrotactile Stimuli

Mechanoreceptors in the skin are responsible for detecting contact, deformation and motion across the skin surface. The type, location and density of mechanoreceptors varies with skin type and body location. Human response to vibrotactile stimuli can be defined in terms of our vibration detection threshold, the stimulus, and our spatial and temporal resolution. Spatial resolution can be measured in terms of two-point discrimination and single point localization, and as may be expected, there are large variations in perceptual performance across different body sites. There are many interactions between variables, especially time and space during perception [8]. Interactions can be in terms of perceptual changes, sensory illusions or masking. Another factor that must be recognized is sensory adaptation, where the response to a stimulus may vary with time. Adaption is mechanoreceptor and stimulus specific.

Most cueing constructs have utilized stimuli that fall into the vibration window between 200–300 Hz where the body is most sensitive to vibrations [9]. Although lower frequency stimuli can be distinct, the sensitivity for detection on the torso at 100 Hz is about 20 dB (Re 1 μm) lower than at 250 Hz [10]. Thus, to be perceptible, lower frequency 100 Hz vibration amplitudes must be ten times greater than vibrations at 250 Hz.

It has been estimated that the information capacity of the fingertip is 100 bits/s and this represents a practical limit for an experienced, undistracted subject [11]. When factors such noise, distractions, workload and postural movement is included, our tactile information capacity decreases [12]. There is also a difference between feeling a stimulus, and being able to assign meaning to that sensation. Therefore, the extension of tactile orientation cues to tactile command or language symbology is not straightforward.

The issue of tactile commands requires careful attention to the various factors that influence the production and perception of stimuli. It is also well known that the human channel capacity for information cannot be ignored when designing a human in the loop system [13]. Channel capacity varies with a number of stimulus and situation variables, including individual differences among users, like gender, age, and experience. Human perceivers are affected by their environment, task, workload, multisensory interactions, their experience, training, and expectations when presented with stimuli. These factors can all affect the accuracy and reliability of user interactions with the tactile display [14]. We have modeled the interaction between the environment, task, user and the tactile technology using tactile salience.

2.2 Tactile Displays

Tactile displays can be classified into; feedback, sensory substitution, sensory augmentation, communication and alerts systems [9]. The tactile display cueing components are usually comprised of combinations of relatively short tone-burst vibratory patterns. These patterns will have a natural or learned user association with a situational variable. Thus, the tactile display will comprise of distributed (wearable) actuator hardware as well as a means for the delivery of sensory stimuli (e.g., patterns/tactons/tactions).

One design approach to optimize tactor and taction effectiveness has been to configure tactors to have a "contactor" that oscillate perpendicularly to the skin, surrounded by a housing and radial gap [12]. The moving "contactor" is lightly preloaded against the body. When an electrical signal is applied, the "contactor" oscillates perpendicular to the skin, while the surrounding skin area is "shielded" with a passive housing. Using these criteria, all EAI's tactors are designed to minimize the effects of loading by the skin or garments [15].

An effective tactile display configuration for an intuitive communication of direction information is a torso worn belt [16]. It should be noted that the waist circumference varies between 22″ (5th percentile) to 28″ (95th percentile) for females and, 30″ to 40″ males [17]. Therefore, care must be taken in designing belts with different sizes and/or materials that can accommodate different waist sizes. The tactile cueing belt approach can be extended by using two rows of different types of advanced tactors to provide a wider design variability in the potential tactile stimulus. The dual belt approach (shown in Fig. 1) has been used to communicate both navigation information and incoming alerts [7]. In these experiments, the EAI EMR tactor was used primarily for navigation signals and the C-3 tactors were used to provide incoming alerts from a simulated robot asset. The C-3 produces a highly salient, "sharp" sensation as it operates at 250 Hz while the EMR provided a lower frequency, comfortable but less salient signal [14].

Fig. 1. Dual Belt (Engineering Acoustics, Inc.) tactile display comprising of a row (1–8) of eight EMR motor based tactors and a row (9–16) of eight C-3 tactors. The Dual Belt is constructed using stretchable material, with each tactor in a pod. The belt closure in the front using an overlap to accommodate the belly tactor (1 and 9) and electronic connection through an egress connector.

2.3 Model for Human Performance – Tactile Salience

We have previously developed a model based on tactile salience to describe the perception pathway [18]. Tactile salience can be simply defined as the probability that the tactile cue will be detected. In controlled laboratory settings, salience can often be modeled as a function of tactor engineering and the vibratory stimuli characteristics—i.e. physical characteristics of the signal itself, when context, or "noise", is very low. However, as context becomes more complex, additional factors become significant. Tactile salience as mediated by three core factors; characteristics pertaining to the user, the technology, and the environment and their interactions. A simplified model for tactile performance is shown in Fig. 2.

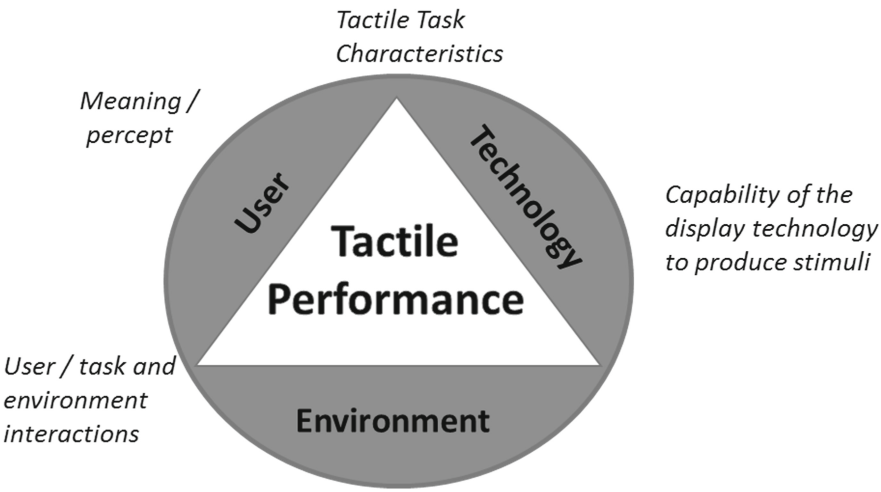

Fig. 2. Simplified model for viewing the interactions between the user, the tactile display (user-interface) technology and the environment.

Controlled comparisons showed some tactile patterns to be more salient than others [14]. It's been shown that tempo of sequential activations create "melody" type of sensations that are easily recognized and distinguished based on their rhythmic features [19]. Simply changing the frequency of activation from slower to faster can change perceptions of urgency [9]. Patterns may be communicated across multiple body locations, such that an additional cue in a particular location can increase salience and indicate urgency.

Our research has investigated how Soldiers interact with tactile displays and we have developed some experience of user interface design and usability engineering (UE). Generally, these effects are measured in terms of a specific task performance measure. However, errors can, and do occur in tactile displays. It is beneficial to design systems and studies with an understanding of the potential error pathways.

3 Potential Errors

The tactile salience model can be a useful initial framework for investigating and identifying potential error pathways. Tactile devices and hardware are often developed and tested in laboratory or controlled environments while the intended usage may be significantly different (for example, indoors vs. outdoors). Therefore, our framework for discussing tactile display errors must include the user, environment and technology. While we separate by these categories, it will become evident that many errors arise from a systems perspective that considers the interrelationships among these three core sources. For example, technology characteristics pertaining to a particular system may be effective for one set of users, but not another. In the same way, the same technology may be effective in one environment or set of task demands but not another. Thus, we first list sources of error due to the technology, then we discuss sources due to mismatch of technology with environment, task demand, and user characteristics.

3.1 Sources of Error Related to the Technology

By technology, we refer to the characteristics of the tactile array and supporting components. If the tactor does not vibrate, or the vibratory stimulus is not detectable (i.e. not salient) to the user, an error of omission occurs. There are several component systems that may be involved in tactor display activation. Sensors are often responsible for activating tactile cues (i.e., tactions). Examples include use of tactions that indicate altitude from ground to helicopter pilots, dependent on altitude sensors, GPS cues that drive tactions cuing navigation direction, or software that identifies high priority information for taction alerts. Sensor systems often determine a figure of merit, or estimate of their reliability (and this may also change during a mission). Clearly, tactile display information must be based on accurate sensor data.

Tactor actuators are generally mechanically robust and relatively reliable. However, there are many pathways for technology failure including electrical and wireless connectivity, breakages and failures. Such problems may also prevent or distort tactile pattern generation or tactile activation. Errors may also arise due to power supply. If batteries are used, they must be adequate for the anticipated duration of use. Best practice guidelines include including mechanisms for robust communication transmission, error checking and system status monitoring for all tactile display system components.

Diagnosis of problems due to technology is a well within the realm of standard engineering design and use. Many other problems can arise when the system leaves the laboratory setting and is used in applications by users. These problems can be anticipated through consideration of the environment context, including task demands, and user characteristics. We discuss environment and task demands separately; however, it should be noted they can interrelate greatly. The following section addresses sources of error arising from a mismatch of technology that work, but is not suited to the environment, the task demands, and/or the user.

3.2 Sources of Error Related to User, Task and Environment

Mismatch with Environment. Tactors are versatile and have been used in many different environments including underwater [21], high vibration (noisy) rotorcraft [22] and even in space [23]. However, tactile technology characteristics may differ among these environments; a system that is effective for an indoor low-noise environment will likely not be effective in conditions of high noise. Similarly, systems must be designed to be compatible with underwater or in high altitude aircraft. Environmental factors that must be considered include regular exposure to water, vibration, wind, sand, humidity, and heat. Tactor system sensors also have potential limitations that are due to the environment (for example, operation in GPS-denied settings such as caves and tunnels). Each setting and use case may require hardware, stimuli and suitable mounting configurations to be effective. Mitigation involves appropriate design and iterative testing in conditions that replicate the environmental context, and is regularly performed within the realm of engineering design.

Mismatch with Task Demands. Task demands can have a large impact on the effectiveness of tactile display systems. Technology that is effective for stationary tasks may not be adequate when the user is highly active (e.g. crouching, crawling, running). Tactor characteristics associated with strength of signal and resistance to loading effects [15] greatly affect the ability of a user to perceive signals when activity levels are high [26]. Our understanding of tactile perception has also been typically based on a laboratory or a controlled environment. Simply changing the posture (sitting to standing or lying) can potentially change the perception.

Tasks that require high levels of attention, memory (e.g., short term memory), and/or cognition (e.g., information processing and decision making) contribute to overall cognitive workload [27]. As the user's cognitive workload increases, cognitive bottlenecks or demands from other sensory channels can rapidly decrease the effectiveness of complex tactile displays that involve recognition and discrimination of multiple tactile array signals. In these situations, tactile cuing should strive to alleviate the workload, through attention management, information prioritization (e.g., high priority alerts), and alleviation of higher workload tasks (e.g., tactile cues as augmenting or replacing visual cues) [25]. An example of this is the use of tactile direction cues for ground waypoint navigation, such that the user need not consult or interpret visual map-based displays; instead, they get a torso belt single direction cue that indicates "go this way". Tactile direction cues have been shown to be very rapidly understood, with little or no training, and thus are a good example of an intuitive design.

There is a balance between intuitive tactor display constructs, message length and task demands. Tactile stimuli patterns and stimuli must also be designed in terms of the intended usage, task and informational flow. Single stimuli can be missed while continuous stimuli may be ignored or masked. Changes may not be noticed. Therefore, stimuli must be robust and recognizable and what constitutes effectiveness may change based on the task, user-workload and environment.

Mismatch with User. The user is part of a human in-the-loop-system. There are many user preferences regarding what constitutes an intuitive, understandable tactile display output. There are also many individual differences [24] and these can be related to age, training (expectations) and prior experience. Care should be taken to evaluate displays on sufficient numbers of representative user populations (rather than samples).

Form and fit of the tactile system to the user's body is often a critical factor; wearable designs should preferably use design techniques that position the tactors with a pre-load against the user and recognize the potentially wide variation in the user's anatomical features. The tactor itself can potentially detect the body of the user by sensing the mechanical impedance load or physiological measures [20]. As described in Sect. 2, the threshold for detection of vibrotactile stimuli depends on the stimuli, the body location and many interacting factors that generally act to increase the threshold. We recommend that a best practice tactor display stimulus should also have a dynamic range that is at least 30 dB (Re 1 μm) above the threshold of vibration sensitivity to account for practical increases in the required threshold.

Users can potentially assemble the wearable tactor display incorrectly. Even if the array is sized correctly, wearable arrays can be mis-localized (for example, the front tactor not corresponding to the belly), or installed incorrectly (for example, upside down or even inside-out). Training is vital for novice users and in controlled studies should be scripted and user proficiency should be confirmed.

Users can also perceive stimuli in unintended manners. This is particularly important when designing tactile messages. If the tactor pattern occurs during activities when the user is focused on other tasks, the cueing can be unwanted or parts of the tactile pattern could be neglected (missing data). Multiple tactors that are simultaneously ON can be masked, while patterns that are too long too short may be missed. User's may also be subject to change blindness [27] where changes in the display are unnoticed. Delays in cueing information can lead to instability. Best practice guidelines would therefore include an identifying (attention focusing) feature at the start of a tactile message pattern to prevent missing the start of a pattern (can't recognize the middle or end) and utilizing tactile salience and multimodal sensory modalities to increase message priority.

4 Discussion

Table 1 provides an overview of the potential error pathways we have outlined for tactile display systems, and some example errors.

System and technology errors must be identified early and the user notified. This is standard practice for the technology components in the system. It is somewhat more difficult to recognize user and display use errors. The user may use the display technology incorrectly or the task and environment may change and potentially render the display less effective. User errors may be mitigated with effective user training and competency, but if they are unrecognized they can result in unsafe and ineffective tactile display use. The addition of smart technology that can adapt displays to situational and individual factors should be driven by theory and research-based guidelines [28].

Table 1. Potential error pathways in tactile displays.

Category	Description of the potential error	Impact
Technology	Hardware faults, sensor & communication errors.	Display error
User	Array usage errors, incorrect tactile pattern recognition, insufficient tactile salience & incorrect display data. Mode recognition & effectiveness of training	Display use error
Environmental	Specifications for tactile system sensors and displays operating environment exceeded	Display error
Task	Tactile display not effective during high-workload. Tactile display not adaptive to user requirements, information not recognized	User errors

There are several mechanisms that can be introduced to increase trust in the system. Primary to user trust is development of a system that is reliable and effective in the context of use. While tactile systems are generally passive, in terms of user interaction, care must be taken to ensure ease of use—in terms of preparing the system before use (e.g., creating or choosing signals and meanings), as well as during use. Signals should be easily felt, distinguished, and interpreted. If the tactile system is used to communicate verbal concepts (e.g., multiple alerting signals), training must ensure immediate and easy recognition. When tactile communications are added to visual and audio display, the resulting multimodal display has been associated with higher levels of trust, and allow users to not only identify potential errors but also use redundant information to synthesize and combine data more effectively than individual data streams.

Ultimately, systems should be designed to adapt to dynamic context – to recognize that as the environment, task demands, and/or user-workload change – the display must be adaptive and change the salience of the information. Adaptive systems can also be included intelligent systems where the response or reactions of the users is used to determine whether the user has processed the display information. Tactile display systems to date have not usually been bidirectional in nature, to allow the user to acknowledge or query a message construct. This is an option for intelligent systems where gestures and other user-interfaces can be used to provide a naturalistic user response.

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