Chapter 3 – HUMAN FACTORS ISSUES OF TACTILE DISPLAYS FOR MILITARY ENVIRONMENTS

by

B.P. Self, J.B.F. van Erp, L. Eriksson and L.R. Elliott

The overall goal of this chapter is to give the reader insights into the human factors issues related to the use of tactile displays. Torso-mounted displays, which are particularly suited for direction and orientation cues, are emphasized. First, perceptual issues relevant to tactile stimulation are discussed. These include issues regarding spatial acuity and absolute localization of tactile cues on the torso, such as internal reference points, anchor points, and spatial accuracy. In addition, tactile illusions, burst durations, and temporal effects are discussed in relation to tactile torso display design. A second section focuses on issues related to coding principles; that is, how best to develop tactile patterns to be intuitively understood within a specific operational context. Cognitive issues are then addressed, such as how tactile stimulation can either alleviate or exacerbate attention tunneling, and the extent to which multiple tactile patterns can be used effectively. Cognitive processes related to tactile cueing are described, followed by issues related to multisensory integration and multifunction displays. Finally, issues related to user acceptance are discussed.

3.1 PERCEPTUAL ISSUES

Chapter 2 discussed the sense of touch and related perceptual issues at a general level. Since it is expected that tactile displays in military environments will often use vibrotactile stimuli applied to the torso (see Figure 3.1 for an example; see also Chapters 4 and 6), we will present more detailed perceptual data below. The relevant perceptual issues include the spatial acuity of the torso for vibrotactile stimuli, the ability to localize stimuli on the torso and the perception of external directions based on a localized vibration on the torso.

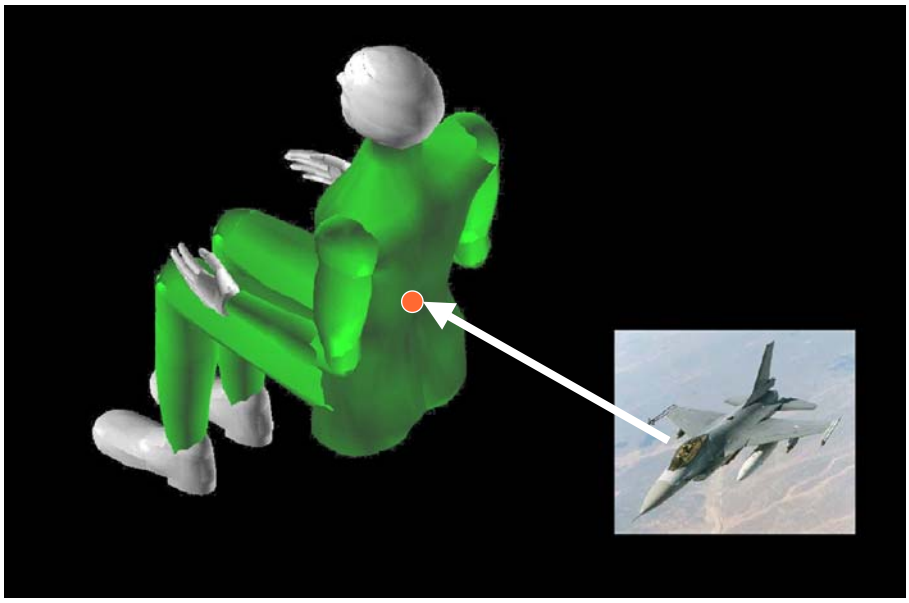

Figure 3.1: Example of the Use of a Tactile Display in a Military Environment. The localized vibration on the pilot's torso presents the direction of an aircraft.

In experiments investigating the spatial acuity of the torso, Van Erp [1] found an evenly distributed resolution of 3 – 4 cm, except for the horizontal direction near the body midline where the resolution was 1 – 2 cm. A possible explanation for this phenomenon (which was called the midline effect) is that the way vibrotactile stimuli on the torso midline are processed makes the midline a so-called anchorpoint. Stimuli on the body midline are processed in both the ipsilateral and the contralateral hemisphere (cref. Chapter 2). Previous studies have shown that anatomical anchorpoints improve performance in vibrotactile localisation tasks [2].

Spatial acuity is concerned with the relative localisation of two stimuli. However, for a tactile display that maps an external event (e.g., the direction of an aircraft) on a specific location on the torso, absolute localisation is also relevant. Van Erp found that observers are able to localise a vibratory stimulus close to its veridical location. The pattern of responses indicates that stimulus locations on the torso may be coded in polar co-ordinates with the body midaxis as the origin. When the true, or veridical, and observed stimulus location do not coalesce, the difference is in distance but not in angle (shifts up to several centimetres occur, which actually means that observers could have localised the stimulus below or above the skin surface). Interestingly, a shift along the radius has no effect on the perceived direction of the stimulus. The results indicate that angles are the perceptual invariant for torso stimuli.

The critical perceptual issue for tactile displays now becomes whether observers are able to externalize a localized vibration on the torso to a direction in the external world, and what the accuracy (and bias) is in this direction perception. Van Erp [3] investigated direction perception with a horizontal belt with 15 tactors around the waist. Inspection of the response patterns revealed that observers did not use the body mid-axis as the origin for the observed direction, but used two spatially separated internal reference points, one for each body half. The results show that the accuracy is dependent on the location on the torso: variability is lower on and near the midsagittal plane (4° for the direction straight ahead) than on the sides of the torso (10 – 14°), probably due to the fact that the midline locations act as anchorpoints. There was also a bias in the perceived direction. This bias is toward the midsagittal plane, that is, perceived directions are toward straight forward for tactors on the frontal side, and toward straight backward for tactors on the dorsal side when compared to their veridical directions. The bias is close to 0° for the four cardinal directions and increases up to 10° for the directions in between. Although this may be acceptable for many applications (for example, the 12 hours of the clock used in military environments to indicate directions have a 30° resolution), some applications may require greater resolution. Such situations may require individual calibration of the mapping of perceived directions on skin locations, that is, constructing a torso-related transfer function (TRTF). The TRTF would map each perceived direction to a unique location on the torso. Although individually derived TRTFs will optimally reduce the difference between perceived and actual direction, a general TRTF may be sufficient. This general TRTF will at least compensate for the bias toward the midsagittal plane.

The results imply that optimal performance may be expected for tasks that require the perception of directions straight ahead or straight behind. This is the case in a situation in which a visually handicapped individual wants to walk to the next waypoint in a preprogrammed route, or a fighter pilot wants to fly toward a target. This also implies that tactile direction perception can be complementary to 3D sound, due to the fact that 3D sound is optimal in presenting lateral directions but has a relatively high occurrence of front – back reversals [4].

The available research has not addressed two important issues. First, it might be expected that tactile performance is different when the observer is allowed to move around; this is analogous to how slightly moving the head can improve auditory direction perception. In addition, investigations about direction estimations in a 2D transverse plane leave the question open if observers are also able to indicate accurate elevation based on a tactile stimulus on the torso.

3.1.1 Burst Duration and Timing Parameters

As discussed in Chapter 2, it is well known that localization is dependent on timing parameters [5 – 9], and the usefulness of spatiotemporal patterns thus depends on (location dependent) spatial acuity and on temporal parameters. To gain more insight into the processing of simple spatiotemporal patterns on the torso, a second experiment in Van Erp [1] concerned localization performance as a function of two timing parameters:

a) Burst duration (BD); and

b) Stimulus onset asynchrony (SOA).

The results showed that localization performance increased when the BD increased and/or when the SOA increased. This means that tactile display applications that require high localization accuracy can benefit from longer BDs and SOAs. On the other hand, tactile display applications that require fast presentation of (consecutive) stimuli, as in vehicle control applications, may require a larger distance between the tactors.

Apparent motion, temporal masking, and adaptation were also discussed in Chapter 2. The occurrence of apparent motion seems to enhance performance. The fact that the skin automatically integrates specific spatiotemporal patterns is likely to be important in designing such patterns. The effect may have both positive and negative effects, including spatial and temporal masking. Temporal masking can be prohibited by using different loci or frequencies (one below 80 Hz and one above 100 Hz), while adaptation effects can be prevented by switching between a frequency below 80 Hz and one above 100 Hz [10].

3.1.2 Tactile Illusions

There are tactile illusions that may be useful in tactile displays [11]. These tactile illusions use psychophysical properties of the somatosensory system to change the perceived intensity, location, or motion of the tactile stimulus. When two tactile stimuli of equal intensity are presented simultaneously to adjacent locations on the skin, the resulting sensation is not two separate tactile sensations. Instead, the stimuli combine to form a sensation midway between the two tactors. This illusion is called the "Phantom sensation" [12 – 15], and could be used to generate "virtual tactors" located between physical tactors, thereby reducing the number of tactors required in an operational tactile instrument. The phantom sensation is dependent upon the physical separation of the stimuli, the amplitude, and the timing of the stimuli. A second relevant illusion is that of apparent motion. Depending on the temporal parameters, the sequential activation of spatially separated tactors can elicit the sensation of smooth, continuous motion from the first activated tactor to the last activated tactor (see Chapter 2 for details on apparent motion).

3.2 CODING PRINCIPLES

Stimulus characteristics can also be utilized to present specific types of information to the user. Coding principles are used to create easily discernable tactile messages and multi-information displays. Often, two or more coding principles can be used to create an intuitive tactile signal. As tactile displays become more widely used, coding standards must be considered for particular uses. For example, different approaches can be taken to counter spatial orientation regarding altitude, roll, pitch, and yaw of aircraft (see Chapter 6 for applications). Tactile characteristics include size, shape, orientation, position, moving patterns, frequency, amplitude, rhythm, and waveform. These characteristics are listed below and summarized in Table 3.1.

Table 3.1: A Summary of the Properties of Nine Tactile Characteristics

Characteristic	Properties
Size	– Limited number of distinctive levels – Large difference between sizes preferable – A clear boundary is needed – Simultaneously displayed sizes is feasible
Shape	– Fair number of distinctive levels – Similar tactile shapes should be avoided – A clear boundary is needed – Simultaneously displayed shapes is feasible
Orientation	– Limited number of distinctive levels – The shape should not be rotational symmetric – A clear boundary is needed – Simultaneously displayed shapes is feasible
Position	– Many distinctive levels possible – Large distance between displays preferable – Simultaneously displayed positions is highly feasible
Moving patterns	– Any distinctive levels possible – The moving patterns should be quickly recognizable after their start – Simultaneously displayed moving patterns is moderately feasible
Frequency	– Limited number of distinctive levels – Low feasibility for simultaneously displayed frequencies
Amplitude	– Limited number of distinctive levels – Low feasibility for simultaneously displayed amplitudes
Rhythm	– Many distinctive levels possible – The rhythms should be quickly recognizable after their start – Low feasibility for simultaneously displayed rhythms
Waveform	– Includes square, triangular, saw tooth, and sine waves – Requires sophisticated hardware

3.2.1 Tactile Characteristics

3.2.1.1 Size

Size refers to the overall surface area that the tactile display uses to depict the information. A small square of tactors might be activated to depict a low-priority threat, while a larger square centered at the same location could represent the location of a high-priority threat. Size can be used to create a limited number of distinctive perceptual levels that are more easily distinguished when the boundaries of the depicted patterns are better defined. This requires small tactors in a high density configuration, which may not always be possible.

3.2.1.2 Shape

The shape of a tactile symbol depends on having a clearly defined boundary. The number of distinctive shapes that can be created is dependent on the number of tactors in the display. It is possible to display an enemy aircraft as an “x” and a friendly as an “o”, but little data exist on how easy it is to distinguish different symbols created with tactors.

3.2.1.3 Orientation

Orientation of a tactile symbol can also be varied to provide information to the wearer. An enemy threat might be depicted as a vertical line of three tactors, while a friendly aircraft could be depicted as a horizontal line of three tactors. It is unclear if these types of displays are easily discernible in an operational setting.

3.2.1.4 Position

Position is probably the most used and most intuitive characteristic to utilize during tactile coding, especially if the coded information concerns spatial information. The advantage of position is that it can be used to create many distinctive perceptual levels as long as the distance between two neighboring positions is large enough and the positions do not overlap. It is feasible to present multiple targets at different positions on a tactile display, and it is even possible to utilize different locations on the body to attach two or more position-based tactile displays. For example, navigation information may be displayed on the frontal part of the torso, while threat information is displayed on the dorsal side. A similar principle can be used to display horizontal directions to, for instance, dismounted soldiers by using two tactile belts. The lower belt may present navigation information while the upper one presents critical communications. This may, however, cause cognitive overload or attention tunneling that will be discussed later in this chapter.

3.2.1.5 Moving Pattern

Another characteristic that can be used to create many distinctive perceptual levels is moving patterns. A moving pattern is a time-varying shape that can create sensations of movement. The moving pattern should be designed such that it can be distinguished from other moving patterns quickly. One example of using moving patterns is for communication. One row of tactors is rapidly activated in succession to create a sensation of moving around the wearer. This circumferential pattern has been used to communicate to soldiers to “rally to the left” or “rally to the right” [16, 17]. Another suggested use is to create a flow field that might mimic how the wind feels when moving forward or in a specific direction (e.g., Van Erp et al., [18] used flow patterns to display helicopter direction and speed in a low-hover task).

3.2.1.6 Frequency

The frequency at which particular tactors are activated can also be used to convey information. In the hairy skin, there are three different types of mechanoreceptors that can be activated at specific frequencies (see Chapter 2). However, at suprathreshold stimulation more than one channel will be activated at the same time [10, 15, 19 – 22] . Within each tactile channel, only a few discernable levels of frequency can be created. This may limit using different frequency levels as a way to convey different types of information.

3.2.1.7 Amplitude

The amplitude of the stimulation can also be varied. This results in a stronger sensation, because more mechanoreceptors are activated [23]. The disadvantage of this dimension is that only a few discernable levels can be recognized. The number is further reduced, because stimulation amplitudes just above the detection threshold are normally not used.

3.2.1.8 Rhythms

Users can discern many distinctive levels in rhythms, and humans can replicate rhythms presented in the tactile modality better than presented in the visual modality [24, 25]. Different patterns in rhythms are often called tactons [26]. Tactons can be defined as specific tactile patterns or a series of tactor actuations

that refer to a specific image, object, or action. In effect, one can relate tactons to a type of Morse Code that is presented by tactile means rather that auditory or visual means. To create rhythms, a tactor vibrating at a constant frequency is switched on and off rhythmically. If amplitude and frequency of the signal are also varied, tactile melodies can be created, differing in intrusiveness and tempo [27]. The rhythms should be quickly recognizable, but discrimination between simultaneously presented rhythms can be difficult. Using different tactons to convey different types of information is very valuable in coding tactile information.

3.2.1.9 Waveform

Different patterns of the activation amplitude can also be presented to convey different information. Examples of this include using square, triangular, saw tooth, and sine waves. The sensation created by each waveform is dependent on the frequency and amplitude of the signal, and the tactor must be very precise to create the specific waveforms listed. While each type of waveform is perceived quite differently, the need for sophisticated hardware to create each waveform probably precludes using it as a primary means to provide different types of information.

3.2.2 Multiple Information Displays

As increasing amounts of information are being conveyed to the user in a growing multitude of land, air, and sea environments, it is often desired to convey more than one piece or type of information. The characteristics discussed above can be used to provide different types of information to the user. Although it is technically feasible to display multiple pieces of information simultaneously within a single tactile display, the design must be carefully considered. A study conducted by McKinley et al. [28] used three different tactile patterns or tactons to present the type of target aircraft (enemy, unknown, and friendly) to the pilot. The location of the tacton on the tactile vest indicated the position (azimuth and altitude) of the target aircraft relative to the participant's own aircraft. Because targets rarely appear alone, three targets were displayed simultaneously. The experimental results combined with subjective feedback from the participants indicated that it was difficult to differentiate between the tacton indicating an unknown type aircraft and the tacton indicating an enemy type aircraft. This was largely due to the fact the first half of the tactile pattern used for the unknown aircraft was the same as that used for the enemy aircraft pattern. This was also observed during the development of tactons to represent Army hand and arm signals – patterns that started with the same tactor and began with a similar pattern were more often confused and/or took longer for accurate identification [17]. Hence, when designing a tactile display that will provide multiple pieces of information simultaneously, it is important to ensure each tacton used is clearly identifiable and categorically different than the other tactons (see Section 3.1 on perceptual issues).

Additional issues that should be considered in multiple information tactile displays include the notion of overlap and tactile resolution. For example, it is currently not possible to clearly present two different tactons simultaneously at the same location of the body. This indicates that the design should carefully consider what information needs to be displayed as well as how the information should be prioritized. For example, in the case of presenting aircraft target information to the pilot, it might be possible for two different types of aircraft to reside in close proximity. Hence, the two patterns would overlap on the same part of the body. Van Erp et al. [27] introduced the term tactile clutter for this effect (please note that visual and auditory displays face the same challenge). A possible remedy is to only present the tacton for the aircraft that poses the greatest threat. In addition, it should be noted that the number of items that can be presented on a single display largely depends on the number of tactors available. The other tactile display characteristics in Table 3.1 may also be used to convey multiple targets or types of information, but characteristics such as size, shape, and orientation are also highly dependent on the number of tactors. Consequently, tactile displays utilizing few tactors will not have the capacity to provide multiple pieces of information simultaneously.

3.2.3 Coding Standardisation

Often, two or more coding principles can be used to translate the information into a tactile 'picture'. For instance, two self-motion coding principles have been applied to help counter spatial disorientation in pilots [29]. These principles resemble the inside-out and outside-in concepts, also recognized in the design of the artificial horizon display. Inside-out coding of yaw rotation (i.e., rotation around the vertical axis) can be realized by a tactile signal pointing to a fixed direction in the outside world. This means that the tactile signal rotates clockwise when the pilot rotates counter clockwise, and vice versa. In the outside-in coding alternative, the signal rotates on the display in the same direction and with equal velocity as the pilot rotates in the outside world; it is the same speed but opposite direction of the inside-out display. An important advantage of the inside-out coding is that the position of the tactile signal on the display is Earth-fixed and thus also congruent with out-the-window visual information. This may have beneficial effects on the situation awareness of the pilot, while the outside-in coding may have benefits in control tasks. As with visual displays [30], the preferred coding on the tactile display is most likely task dependent.

It should be noted that the lack of guidelines on the design of tactile cockpit displays has already resulted in the use of different coding principles in the design of a helicopter hover display. Van Erp et al. [31] coded the direction of drift in a helicopter hover display using a 'follow the needle' principle. The pilot had to follow this "command" tactile signal as if it indicated the next waypoint. Raj et al. [32] coded the direction of drift using a "status" algorithm, which means that the pilot had to steer away from the stimulus as if the pilot bounced against a virtual wall. In the first coding algorithm, the vibration unambiguously indicates the optimal direction of motion. The virtual wall analogy indicates the direction to avoid, which leaves the pilot with the choice to determine the optimal steering action; many motion inputs will free the pilot from the wall.

Dobbins and Samway [33] mention this same issue in coding a virtual corridor on a tactile display to support course control in operating high-speed powerboats. Although there are no data available that directly compare performance with both codings, one may expect that performance may degrade if the pilot has to switch between codings. This latter issue was also found with pilots who transferred from an outside-in to an inside-out coding of the artificial horizon [34].

3.3 COGNITIVE ISSUES

Determining the appropriate coding principles to use for an application does not guarantee that the user will be able to fully comprehend the information that is provided in a tactile display. Two issues that are present in both visual and auditory displays must also be considered in the tactile modality: attention tunneling and cognitive overload.

3.3.1 Attention Tunneling

Attention tunneling refers to a narrowing and general lessening of attention such that perception is reduced to a narrower band of information relative to available cues. Wickens [35] provides the definition of attention tunneling as "the allocation of attention to a particular channel of information, diagnostic hypothesis or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks." Note that the definition must include both the forces that "lock the tunnel" to its current channel, as well as a definition of a channel of neglect. The US Air Force identified attention tunneling as being a major cause of F16 mishaps, and a great many aviation accidents in general can be associated with attention tunneling away from important altitude information [35]. Wickens identified four different factors affecting attention tunneling in pilots: head up display location, the compellingness of 3D displays, fault management (e.g., "fixating" on a single problem), and automation (e.g., complacency).

Attention tunneling can be brought about in situations of sustained attention and fatigue. A common experience is that of long-distance driving, where the driver focuses attention on the road immediately ahead, and is less attentive to peripheral cues. The same phenomenon can be generalized across many long-duration operational situations, particularly when attentional demands are low. In this case there may be too much automaticity and arousal/stimulation or higher attentional requirements could be more effective [36]. Automaticity is closely and reciprocally related to the difficulty, mental effort, and attention resource demands of a given task [37].

In situations of long duration and high monotony, tactile cues may be most effective in arousing attention without the "override" associated with audio cues. Such cues may help to "break" the attentional fixation, especially if the modality has been "silent" during the majority of the task. Compared to visual warning signals, auditory and tactile signals have been found to be more effective at drawing cross-modal attention to particular positions [38]. Dynamic tactile information (e.g., five tactors placed on the forearm vibrating sequentially) was used to accurately reorient visual attention [39]. Tactile cues, or any attention-directing cues, should be designed to be recognized in parallel to ongoing tasks, to provide information on the significance of the interruption, and to allow for evaluation that does not require foveal attention [40]. In a study of U.S. Army command and control decision making, soldiers preferred the tactile cues to that of visual or audio alerts, stating that the tactile cue gained their attention better and faster than the visual icon, while not being as disruptive as the audio cues [41]. Further research is needed to investigate the effectiveness of using tactors for attention directing cues, particularly in long-duration situations of low workload and infrequent but critical information cues.

While situational awareness can decrease under low workload conditions due to boredom and complacency, it can also suffer under high workload situations [42]. Operators may fixate on solving a single problem during high workload, and tunnel their attention only to a single specific visual display. Tactile displays or alerting cues may help mitigate this problem. Tactile cues have been found to be effective in high-workload multi-task situations [43] and in dynamic, event-driven domains [44]. Of course, there is some danger that the operator could also become fixated on the tactile display. Some studies suggest that tactile perception may override perception through other sensory channels [4]. The use of a torso-mounted tactile land navigation device by soldiers should ideally free their "eyes, hands, and mind" to better attend to perception of terrain obstacles and potential threat. However, in long-duration night operation missions, will they instead simply fixate on the tactile cues? If this is the case, how can it be ameliorated? Many attention issues in tactile displays must still be investigated, from theory-based issues of attention management to more operational aspects that enhance performance in the field.

3.3.2 Cognitive Overload

Cognitive overload refers to an over demand of the (momentarily available) cognitive capacities of the user. Taking car driving as an example, evaluation of visual based information systems has shown that such systems may negatively influence the drivers' scanning behaviour and attention allocation (i.e., they distract the driver [45]). Visual displays have a specific disadvantage when presenting three dimensional (3D) navigation information. Because the displays are flat or 2D, one (or more) dimensions must be compressed. This results in loss of information and usually requires cognitive effort to reconstruct the 3D picture from the 2D display. In the same way, meta-analytic investigations have found that listening and speaking during driving (e.g., using cell phones) are detrimental to performance, regardless of whether the cell phones were hands-free [46]. Although the driver may be able to *sense* all of the different input received, they may not be capable of *cognitively processing* all of the information into a coherent model of the surroundings.

There are many models on workload and navigation, including Sheridan's model for supervisory (vehicle) control [47], Wickens' information processing model [48 – 50], Veltman and Jansen's workload

framework [51], and Rasmussen's framework on skill-based, rule-based and knowledge-based [52, 53] behavior. One of the most commonly accepted models is Wickens' Multiple Resource Theory, or MRT [48 – 50, 54], which can explain why tactile displays seem to be successful at providing information to the wearer.

The MRT predicts no performance degradation under normal workload when independent resources or information channels are used to present information. The MRT predicts, to some extent, concurrent processing of tasks. The concept of resource decomposition is of specific interest here. The resource decomposition concept states that task interference (i.e., performance decline) will only manifest itself to the extent that the two or more tasks share resources under conditions of high overall workload. Several researchers found that decrements in performance in multi-task-situations were not additive, as a single-resource theory predicts; instead, their studies suggested that the decrement depended on the degree to which the competing tasks also competed for the same information channel [48][55]. Time-sharing between two tasks was more efficient if the two used different information processing structures than when they used the same. This suggests separate information channels have, to some extent, independent resources that are still limited, but could function in parallel. This means that task interference will be reduced when the tasks' demands are maximally separated across resources. This separation can be along different resource dimensions such as sensory modality (including touch [56]) and verbal versus spatial processing codes. Since critical information in many applications is predominantly visual (e.g. for driving, see [57]), the MRT model would predict less interference of a second task when information is presented to another sensory modality – hence the introduction of tactile displays. Simply put, MRT proposes that:

a) People have several independent capacities with resource properties;

b) Some resources can be used simultaneously, some cannot;

c) Tasks using different modules can often be performed together; and

d) Competition for the same modality can produce interference.

Based on the principles of the MRT, tactile displays may reduce the threat of both sensory and cognitive overload. Because the sense of touch is a relatively underused modality in human-computer interaction, the threat of sensory overload through tactile displays is small. Thus, tactile displays may help reduce the chance of cognitive overload by utilizing a separate resource that is typically underutilized. Transferring information from visual displays, which are heavily used in high stress environments such as flying, to tactile displays may reduce the chance for sensory overload in the other senses. If the tactors are programmed effectively, the intuitive nature of tactile displays can be utilized. Interestingly, many of our reflexes are based on the sense of touch. An example is the rooting reflex in babies, that is, turning the head in the direction of a tactile stimulus to the cheek. A similar effect is found on the torso, which has been called the "tap-on-the-shoulder" principle [58]. A tap left draws and directs your spatial attention to the left. Additional advantages of the torso are its natural 3D form and its ego-centricity.

3.4 MULTISENSORY INTEGRATION

In most applications, tactile displays will be integrated with visual and/or auditory displays, making it necessary to understand how this multisensory information might be processed. In everyday life we see, hear, feel, smell and taste the world around us, and apparently without much effort we are able to integrate this continuous multimodal stream of information into coherent percepts. Even if the signals from the different senses are incongruent, our brain still tries to integrate the conflicting information in a sensible way, sometimes resulting in perceptual illusions. Crossmodal perceptual illusions vary from subtle changes in the interpretation of ambiguous stimuli to very robust qualitative changes in perception. In the 'bounce illusion' [59], two moving disks seem to bounce instead of crossing each other under the influence of a brief sound at the moment of collision. The 'visual motion illusion' is a change in

interpretation of the motion direction of an ambiguously moving grating induced by changing the auditory pitch level [60]. Besides these crossmodal effects on the interpretation of stimuli, even crossmodal alterations of perception of non-ambiguous stimuli are observed. Well-known examples are the McGurk effect, in which the perceived sound is modulated by an incongruently articulating mouth [61], the ventriloquist effect where sound is mislocalized towards the apparent visual source, and visual capture in which incongruent visual stimuli influence the localization of vibrotactile stimuli [62]. Shams [63, 64] discovered a 'visual illusion that is induced by sound: when a single flash of light is accompanied by multiple auditory beeps, the single flash is perceived as multiple flashes'.

Andersen et al. [65] discuss the relative dominance of modalities in light of four hypotheses; the *stimulus discontinuity hypothesis* [63], the *modality appropriateness hypothesis* [66], the *information reliability hypothesis* [67], and the *directed attention hypothesis* [66] . The stimulus discontinuity hypothesis states that a modality that has discontinuous stimulation will tend to dominate those with continuous stimulation. This hypothesis was offered to explain why a single brief flash of light was perceived as two flashes when accompanied by two audio beeps. According to the modality appropriateness hypothesis, the modality that is most suitable for a certain task dominates the other modality. Of course, it can be difficult to determine which modality is more appropriate for a particular task without resorting to circular arguments. Andersen argued that the modality appropriateness hypothesis should be considered as one of several factors defining the range within which a modality can dominate perception. The information reliability hypothesis asserts that the modality providing the most reliable information is dominant. The directed attention hypothesis states that attending to a modality influences perception. Andersen et al. propose that discontinuity, modality appropriateness, information reliability, and directed attention are all factors which contribute to the relative influence of each modality.

Recently Andersen et al. [68] proposed a Maximum Likelihood Integration (MLI) model for multisensory integration. They assume that multisensory integration occurs in an early stage of sensory processing, before stimulus categorization; therefore this model is referred to as early MLI. The model accounts for three of the above mentioned hypotheses that contribute to the relative dominance of each sensory modality. Both directed attention and modality appropriateness are interpreted in terms of information reliability. Directed attention to one modality increases the reliability of that modality and the sensory modality that is more appropriate for a certain discrimination task provides more reliable information. In the MLI model, the weights assigned to information in each modality are based on this reliability, hence the more reliable the information of a modality, the larger the relative influence of that modality in the integrated percept. Bresciani, Dammeier and Ernst [69] follow a similar approach, but use a Bayesian probabilistic model for multimodal integration that accounts for the coupling between the sensory estimates. These results indicate that even when one signal is explicitly task irrelevant, sensory information tends to be automatically integrated across modalities. They also suggest that the relative weight of each sensory channel in the integration process depends on its relative reliability.

It is anticipated that in the majority of applications the tactile display will support a primary visual display, and in some cases an audio display. In this situation the tactile display may reinforce the visual display by providing a warning signal, or may de-clutter a 'busy' visual display by displaying some of the information via a tactile display. Studies have shown that combining modalities can improve human performance in a variety of environments [4, 32, 37, 43]. Though much information concerning a discrete event (e.g., a warning) can be presented by a single modality, it is clear that the brain achieves a sum that is greater than the parts by integrating a multimodal warning across sensory modalities [70]. The central nervous system (CNS) sorts sensory signals to combine those likely to originate from the same source, thus strongly determining the final perceptual experience. The selection and combination of multisensory signals in the CNS can be considered an optimization process taking advantage of cue redundancy. This has been shown to reduce the variance of perceptual estimates and to enhance stimuli detection [71]. Thus, combining modalities offers an opportunity to take advantage of multimodal presentation of intuitive and redundant cues. These intuitive and redundant cues can (in many cases) deliver information

that allows an operator to better manage important information. There are many examples of how perception can be enhanced or biased by the integration of multisensory signals; the following is provided by Moorhead et al. [72]:

> "Low contrast or noisy visual and sound stimuli can be combined to improve spatial localization. On the other hand a salient visual stimulus can readily 'capture' the perceived origin of a sound, as occurs when we view a ventriloquist [73]. Being able to see ones arm improves the spatial resolution of tactile discrimination when two (unseen) pinpoint stimuli are applied near one another on the skin [74]."

In conclusion, multimodal interfaces can be important in assisting perceptual decisions, and may represent the spatial dimension in a more direct, natural, and intuitive manner [4].

3.5 USER ACCEPTANCE

It is reasonable to expect that user acceptance and trust will depend on equipment accuracy and reliability. Automation reliability is an important determinant of human use of automated systems because of its influence on human trust [75 – 77]. When information is uncertain, the level of uncertainty should also be communicated to the operator, otherwise trust will be affected. Certainly, practice and familiarity with a reliable and accurate system will affect trust. When tactile in-car displays were utilized in an automobile driving task, drivers had to learn to trust the tactile device [78]. In another example, Army soldiers moved much more quickly once they learned they could rely on the tactile land navigation device to guide them to their waypoint, and that the tactile device can "keep up" regardless of their speed [79].

In addition to accuracy, reliability, and familiarity, another determinant of user acceptance is ease of use. The ease of use is highly dependent on making tactile messages self-explanatory [24]. Another aspect determining ease of use is how intuitive it is to interpret the display information. The display of information should match with the sense that is the most intuitive. For example, in response to numerous aviation accidents caused by spatial disorientation, engineers added more visual displays for pilots. However, this did not reduce the occurrence of accidents, partially because the visual channel was overloaded (so the new information was not being processed). In contrast, the tactile cues were more naturally interpreted as orientation cues compared to visual cues [80]. In addition, given a particular sensory channel, displays can be designed that are more or less intuitive with regard to task demands. For example, torso-mounted tactile cues have been found to be very effective as direction cues for navigation and direction cues (i.e., target detection) when the soldier is in the natural environment (e.g., moving or looking in the same direction as the cue [79]). However, they were less effective when used for target detection in a computer simulation task as compared to a visual icon that was particularly suited to specific task demands [81]. In another investigation, tactile cues were compared to 3D audio in a visual search task, and were not found to be as effective. However, this investigation utilized three tactors (indicating left, middle, and right) which were placed side-by-side on the forearm. This was a much less intuitive display for direction information than a belt or torso display. When used for land navigation, soldiers reported higher levels of satisfaction ("satisfied" to "extremely satisfied") with the ease of use and preference for the tactile system, relative to existing Army navigation systems. Most frequently cited reasons for preferring the system was that it was hands-free (thus allowing the soldier to keep their weapon ready), intuitive (e.g., easy to follow signals, "idiot-proof") and accurate (e.g., leading directly to the waypoint).

Ease of use can be indicated by short training times and high levels of automaticity in performance. Soldiers effectively used the tactile land navigation system after a five minute hands-on demonstration [79]. In an investigation of torso-mounted tactors for communication, soldiers readily learned and distinguished five tactor-based patterns for communicating common arm-and-hand signals (halt, rally, move forward, attention, NBC alert) after five minutes of practice. This was likely due to careful

development of the tactile patterns to match the arm-and-hand signal patterns. In fact, participants (Army cadets) who were simply given the tactile signals and the five choices of hand signal, but were not told which tactile pattern represented which hand signal, guessed the correct representation 51% of the time. After 5 minutes training, another group performed with 71% accuracy [82].

3.6 SUMMARY

Human factors issues will play a major role in the design and implementation of any tactile display. Designers must consider the psychophysics of touch, described in Chapter 2, as well as a myriad of perceptual factors. Both sensory and cognitive overload must be avoided, and theories such as Wickens' Multiple Resource Theory should be consulted when developing multisensory and multi-function displays. Finally, coding principles to convey tactile information were discussed. It should be clear to the reader that there are numerous human factors issues when designing tactile displays, and while there are many emerging principles to guide display design, there are also many avenues that need further investigation. Chapter 4 identifies and describes the hardware to actually implement and investigate these principles.

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