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The Role of Tactile Cueing in Multimodal Displays: Application in Complex Task Environments for Space Exploration

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Acronyms and Definitions

2D	two-dimensional
3D	three-dimensional
AC	alternating current
cm	centimeter
CNS	central nervous system
DC	direct current
DL	difference threshold
DoF	degree of freedom
ERM	eccentric rotating mass
EVA	extravehicular activity
g	gravity
g-load	gravity-load
HCI	Human-Computer Interaction
HDD	head-down display
HRP	Human. Research Program
HUD	head-up display
Hz	Hertz
IOR	inhibition of return
ISS	International Space Station
JNDs	just noticeable differences
LRA	Linear Resonant Actuator
mA	milliAmpiere
MRI	Magnetic Resonance Imaging
ms	millisecond
NASA	National Aviation and Space Administration
PSE	points of subjective equality
RT	reaction time
s	second
SA	situational awareness
SDKs	Software Developer Kits
SOA	stimulus onset asynchrony
TBW	temporal binding window
TLS	Tactor Locator System
TOAST	Tactile Orientation Awareness Support Tool
TOJ	temporal order judgement
TSAS	Tactile Situational Awareness System
VA	visual-auditory
VRI	visual reorientation illusion
VT	visuotactile
µs	microseconds

The Role of Tactile Cueing in Multimodal Displays: Application in Complex Task Environments for Space Exploration

Elizabeth M. Wenzel[1] and Martine Godfroy-Cooper[2]

This document is based on a 2016 Final Report commissioned by the Human Research Program, Space Human Factors and Habitability Element, Risk of Inadequate Human-Computer Interaction (HCI).

1. Introduction

The work reviewed here addresses the *Human Research Program (HRP) Risk of Inadequate Human-Computer Interaction (HCI):* Given that human-computer interaction and information architecture designs must support crew tasks, and given the greater dependence on HCI in the context of long-duration spaceflight operations, there is a risk that critical information systems will not support crew tasks effectively, resulting in flight and ground crew errors and inefficiencies, failed mission and program objectives, and an increase in crew injuries, and *HRP Gap: HCI-03:* We need HCI guidelines (e.g., display configuration, screen-navigation) to mitigate the performance decrements and operational conditions of long duration spaceflight.

This paper reviews the potential role of tactile cueing in multimodal displays that will need to be developed to enable Extravehicular Activity (EVA) and telerobotic exploration for both Moon and Mars missions. Specific missions to be accomplished during EVA surface and space operations will include construction and assembly, surface and geologic exploration, and excavation for protective shelter from radiation and significant solar particle events. EVA crews have limited time, resources, mobility, visibility and dexterity, and activities take place in a perceptually impoverished environment. Limitations include a loss of spatial reference frame leading to spatial disorientation, a loss of information normally provided by the auditory and somato-sensory systems, and a restricted field of view. In addition, in non-surface operations crew must be able to navigate and operate in a fully six degree of freedom (DoF) environment. Fatigue resulting from suited EVA tasks will also critically affect performance and safety. In order to mitigate these factors, it is important that crews be well trained prior to executing actual missions. There is a critical need to design multimodal interfaces to optimize performance under these conditions for both training and actual operations. Because of the high level of complexity of the EVA environment on the one hand, and the "sensory restrictions" on the other, it makes sense to envisage enhancements to the astronauts' visual environment. Such an enriched environment may include virtual auditory as well as tactile inputs.

In perhaps the earliest example of a tactile display, the sense of touch was used to convey visual information to the blind in a device called the Visagraph (Naumberg, 1931) that converted a raised replica of the printed word to embossed aluminum foil. Initially, other early examples of tactile displays were also focused on this role of sensory substitution for aiding the blind. Later, Geldard

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(1957, 1960) proposed tactile information as a more general means for communication and developed a (now defunct) tactile language called *Vibratese*. He described several important perceptual properties of touch: the ability of the skin to make temporal and spatial discriminations comparable to vision and hearing, the effectiveness of cutaneous sensations for capturing attention, the large area available for potential stimulation of the skin, and the underutilization of this sensory channel for presenting information. Jones and Sarter (2008) note that the sense of touch is also unique in that, unlike vision and hearing, touch is a bi-directional, proximal sense that senses objects in contact with the body and simultaneously supports both perception of and action on the environment. It also has natural directional capabilities analogous to the omnidirectional property of spatial hearing. Its proximal nature also enables "private" displays where information can remain confidential to the user and does not add clutter to a noisy environment.

2. The Somatosensory System and Tactile Sensation

The somatosensory system receives both external and internal information about the state of the body. It includes the sense of touch (including the perception of pain and temperature), proprioception and the visceral senses. Proprioception includes the vestibular system that conveys the sense of balance and the kinesthetic senses which convey information about the relative positions and movements of body parts from receptors in muscles, tendons, and joints. The visceral system conveys information about the internal state of the body and organs (e.g., fatigue, hunger, stomachache). The cutaneous sense (touch) consists of taction, a sense of pressure or vibration, arising from mechanical stimulation of the skin, thermoception (sensation of temperature), and nocioception (sensation of pain).

Touch receptors are embedded in the epidermis (outer layer) and dermis layers (under the epidermis) and contain the nerve endings of the skin and all over the body (mouth, muscles, tendons and joints). Multiple types of touch receptors form the basis for multiple "channels", i.e., specialized information processing subsystems, that contribute to the overall sense of touch: temperature, shape, smoothness, tactile receptors, kinesthetic receptors, thermoreceptors, nocioceptors. Each touch receptor can be characterized by three attributes:

- The type of stimulation the receptor responds to: e.g., pressure, vibration, and temperature change.
- The size of the receptive field: i.e., the extent of the body area to which the receptor will respond.
- The rate of adaptation:
  - Fast-Adapting phasic receptor that responds within 0.1 second with bursts of Action Potentials when its preferred stimulus is applied and when it is removed, but not during the steady state between stimulus onset and offset.
  - Slow-Adapting tonic receptor (10 to more than 100 seconds) that remains active throughout the period during which the stimulus is in contact with its receptive field.

3. Vibrotactile Perception

Vibrotactile stimulation activates a number of mechanoreceptors (receptors that respond to mechanical stimulation or pressure, Table 1) in the skin whose responses depend on the frequency, amplitude, and duration of vibration and the location of the contactor stimulating the skin. Three primary mechanoreceptors have been identified in hairy skin and are relevant to most tactile displays that are often mounted on either the torso or the arms. A fourth type (Meissner's corpuscles) is found primarily in the glabrous or hairless skin of the fingertips and eyelids and to a lesser extent in the palm. Two types (Merkel's disks, Ruffini endings) are slowly adapting (e.g., pressure detection) and two (Meissner's corpuscles, Pacinian corpuscles) are rapidly adapting (e.g., variable or change detection, vibration). Each receptor type is most responsive to a different range of stimulus frequencies, intensities and durations and an understanding of their overall functional characteristics is important for developing effective tactile displays (Jones & Sarter, 2008; van Erp & Self, 2008; Myles & Binsteel, 2015).

Table 1. Basic Characteristics of Mechanoreceptors

Mechanoreceptor Type	*Adaptation Rate*	*Frequency Response*	*Receptive Field*	*Perception*
Merkel	Tonic	.3–3Hz	Small	Slow pushing (pressure detection), fine details
Ruffini	Tonic	15–400Hz	Large	Stretching
Meissner	Phasic	3–40Hz	Small	Flutter, hand grip control
Pacini	Phasic	10–500Hz	Large	Rapid vibration, texture by moving fingers

3.1. Frequency

A number of studies have measured detection thresholds for vibrotactile stimuli as a function of their frequency for different regions of the body (e.g., Bolanowski, Gescheider, & Verrillo, 1994; Gescheider, Bolanowski, Pope, & Verrillo, 2002; Cholewiak, Brill, & Schwab, 2004). The minimum detectable displacement measured for frequencies ranging from 0.4 to 1000 Hz showed optimal sensitivity in the range of 150 to 300 Hz for all body sites, although the overall sensitivity varied with body region. The lowest thresholds were observed in the fingertips and the highest thresholds were in the abdominal and gluteal regions. Sensitivity around the torso remained constant making it a potentially useful site for a vibrotactile display.

In order to use vibrotactile frequency to reliably encode information, e.g., representing increased urgency with increased frequency, it is important to know how sensitive people are to changes in vibration frequency. Relatively few studies on vibrotactile frequency discrimination have been conducted, probably because there is an interaction between frequency and amplitude. For a given frequency, as the amplitude of vibration increases, the perceived frequency of the signal (i.e., pitch) also increases. The rate at which perceived frequency changes as a function of stimulus frequency varies considerably across individuals (Békésy, 1959; Morley & Rowe, 1990) and over different regions of the body. In regions with high mechanoreceptor density like the fingertips, perceived frequency increases more rapidly with increases in frequency than it does in areas with lower densities, like the arm (Békésy, 1962). Studies measuring difference thresholds are sometimes contradictory and may differ in whether or not the interaction between frequency and amplitude was controlled (Goff, 1967; Mahns, Perkins, Sahai, Robinson, & Rowe, 2006; Mowbray and Gebhard, 1957; Rothenberg, Verrillo, Zahorian, Brachman, & Bolanowski, 1977). In general, they show that the Weber fraction (differential threshold divided by reference frequency expressed as a percentage) tends to increase with increasing frequency, may vary as a function of body site, and indicate that the skin is far less sensitive than the ear to changes in frequency (i.e., Weber fractions on the order of 30% vs. 0.3%).

Based on these findings, it is difficult to specify the change in vibrotactile frequency that could be reliably distinguished by users of a tactile display. Rothenberg et al. (1977) suggested that there might be seven distinguishable steps in vibrotactile frequency on the forearm. For the finger, Sherrick (1985) proposed that only three to five rates might be distinguished over the range of 2 to 300 Hz (or 5 to 8 steps if intensity is added as a redundant cue). Thus, it is unclear that vibration frequency would be a useful parameter to vary in a tactile display, given the limited bandwidth of the tactile system and the complex interactions between frequency and amplitude in vibrotactile frequency discrimination. Geldard (1960) cautioned that frequency “would have to be handled gingerly in a [tactile] communication system, especially if intensity were simultaneously manipulated as a variable” (p. 1586).

3.2. Intensity

Changes in vibration intensity or amplitude could also be used to convey information such as proximity or range of a vehicle to an obstacle. The just-noticeable difference threshold for intensity depends on the reference amplitude of the vibration but does not follow Weber’s law. At moderate to high intensities of vibration the threshold is smallest with estimates ranging from 5% to 30% with an average around 16% (Craig, 1972). Again, the interaction between intensity and frequency means that changes in intensity for a given vibrotactile frequency will affect both perceived amplitude (tactile “loudness”) as well as frequency (tactile “pitch”), suggesting that only one of these parameters should be varied at a time when encoding information. If information is encoded by vibrotactile frequency alone in a tactile display, equal-sensation magnitude curves derived from judgments of equal subjective magnitude for combinations of frequency and intensity can be used to determine the intensity of vibration at one frequency that is required to equal the subjective intensity of vibration at another frequency (Verrillo, Fraioli, & Smith, 1969).

Both absolute and differential thresholds for vibrotactile intensity are needed to determine how much stimulus intensity should be varied in order for an observer to detect a change in a tactile display. Analogous to the inverse-square law for auditory intensity, psychophysical functions for suprathreshold stimuli relate the amplitude of a vibrotactile stimulus to its perceived intensity and indicate the perceptual effect of doubling or halving stimulus intensity (Stevens, 1968; Verrillo & Chamberlain, 1972; Verrillo et al., 1969). Such studies using single tactors also show that the perceived intensity of vibration increases as a power function of the physical intensity of the vibration with an exponent ranging from 0.45 to 0.95, depending on the frequency of vibration (Stevens, 1968) and the skin site tested (Verrillo & Chamberlain, 1972). The exponent (slope) of this psychophysical function is inversely related to the density of neural innervation at the skin site tested meaning that the perceived magnitude of vibration increases more rapidly for the forearm than for the hand or finger. Thus, in a tactile display, changes in vibrotactile intensity are perceived to be greater when presented to the torso or arm, rather than to the fingers.

The perceived intensity of vibrotactile stimulation can also be manipulated by varying the number of tactors used to present the stimulus. Cholewiak (1979) used a tactile display on the thigh and found that when the number of active tactors increased from 1 to 64, there was a linear increase in the perceived intensity of the vibrotactile stimulation for frequencies above 40 Hz. This suggests that the subjective intensity in a tactile display can be varied by changing the number of concurrently active tactors, although Geldard (1960) has suggested that the resolution would be quite crude, with only three widely spaced intensity values that would probably be usable in a display.

3.3. Temporal Variation

Temporal variation in a tactile stimulus (burst duration, pulse repetition rate, inter-pulse interval, and number of pulses) is another variable that may be used to encode information in a tactile display. In most tactile displays the duration of the stimulus ranges from 80 to 500 ms, typically repeated in a sequence of on/off pulses. As the duration of a tactile stimulus increases from 80 to 320 ms, the ability to identify a tactile pattern improves (Summers, Cooper, Wright, Gratton, Milnes & Brown, 1997). Users prefer that the duration of the tactile pulses be shorter (50 to 200 ms) when being used as an alert; longer duration stimuli are perceived as annoying (Kaaresoja & Linjama, 2005).

3.4. Waveform

Rhythms can also be created to encode information by grouping vibrotactile pulses of varying durations (e.g., signaling urgency of message, proximity of vehicle). Brown, Brewster, and Purchase (2005) showed that participants could identify three different rhythms with an accuracy of 93%. They independently varied both the tactile rhythm and complexity of the waveform to create tactile patterns called tactons, analogous to visual icons or auditory earcons. Perception of vibrotactile frequency appears to largely depend on temporal cues rather than spectral properties. Unlike timbral perception in the auditory system, the tactile system seems to be relatively insensitive to variations in waveform (Cholewiak et al., 2004; Summers et al., 1997). However, differences in waveform can be perceived if waveform complexity is varied by using amplitude-modulated sinusoids, e.g., a base signal (250 Hz) modulated by a second sinusoid (30 Hz). Perceived “roughness” of the resulting waveform increases as the modulating frequency decreases and could be used as an additional parameter for a tacton that encodes information such as traffic flow (Brown et al., 2005).

3.5. Body Locus

Spatial coordinates of tactile stimuli are topographically represented in the sensory cortex according to the location and density of innervation of the various body parts (the so-called somatosensory homunculus, Penfield & Rasmussen, 1950). Thus, it has been proposed that spatial information about the external world can be intuitively communicated by the tactile channel for displays cueing events in 3D space (e.g., van Erp, 2001, 2005) or directing attention to spatially congruent targets in a visual display (Tan, Gray, Young, & Traylor, 2003).

In general, the ability to localize a point of vibrotactile stimulation on the body is best when it is presented near anatomical points of reference such as the wrist, elbow, spine, or navel. For example, Cholewiak et al. (2004) used a tactile display that mapped space around the torso to the 12 hours of the clock. They determined the number of sites that participants could accurately localize vibrotactile stimuli using a belt with 12, 8, or 6 equidistant tactors around the waist. Localization accuracy averaged 74% correct with 12 tactors, 92% with 8 tactors, and 97% when 6 tactors were used. Performance was also better (by 2%–5%) when anchor points, such as the spine or navel, were used as stimulation sites. Similar to spatial resolution in the auditory system, van Erp (2005) found that localization accuracy was highest for stimuli presented in the mid-sagittal plane of the body and that errors were higher for stimuli presented on the side of the torso. He proposed that such a vibrotactile torso display could be utilized for navigation displays or vehicle control.

When two-dimensional tactile arrays are used, localization accuracy appears to be highly dependent on inter-tactor spacing and body location. Lindeman and Yanagida (2003) used a 3 x 3 tactor array on the back and observed an 84% correct identification rate for a single vibrotactile stimulus on the back with a 60 mm spacing between tactors. However, Oakley, Kim, Lee, & Ryu, (2006) observed only 53% correct for a 3 x 3 array placed on the dorsal forearm with only a 25 mm spacing due to the limited skin surface available. These results clearly demonstrate that inter-tactor spacing, array configuration, and the specific location on which the display is mounted all influence localization accuracy and must be considered carefully in the design of a tactile display used to communicate spatial information.

In addition to providing cues about the location of events in the environment, spatial cues can also be represented in the pattern of vibrotactile stimulation. For example, Jones, Lockyer, & Piateski (2006) developed a tactile display that sequentially activated a series of tactors with the pattern of activation representing a specific command, e.g., "move to the left." Such a tactile display requires that the spacing of the tactors on the body be greater than the two-point threshold for vibrotactile stimulation (i.e., the minimum distance at which two points of stimulation are reported). On the back, the two-point threshold for discriminating vibratory stimuli is approximately 10 to 11 mm and is the same for both simultaneous and successive stimuli (Eskildsen, Morris, Collins & Bach-y-Rita, 1969). These thresholds are considerably smaller than the static two-point thresholds of 20 to 40 mm measured on the back (Weinstein, 1968), indicating that dynamic stimuli enhance the spatial acuity of the torso.

Dynamic stimuli may also result in various illusory phenomena that could be used to enhance information presentation in a tactile display. One example that has been studied at several different locations on the body is sensory saltation (Geldard, 1975), a tactile illusion of displacement also known as the "cutaneous rabbit." The illusion can be created by placing three stimulators at three equally spaced locations on the skin, e.g., on the forearm (Cholewiak & Collins, 2000) or on the back (Tan, et al., 2003). Three brief pulses are delivered at the first stimulator, followed by three pulses at the middle stimulator, and finally three pulses at the farthest stimulator. Rather than feeling three successive taps at three distinct locations, most people perceive that the mechanical pulses are evenly distributed across the skin surface, as if the stimuli were a small rabbit hopping from one location to the next. The temporal separation between the bursts of vibration appears to determine the perceived spatial layout in sensory saltation. When the inter-stimulus intervals are between 20 to 300 ms (optimally ~50 ms), the stimuli are perceived as being spatially distributed across the skin surface. On the back, the tactors need to be placed no more than 100 mm apart with the optimal number of pulses delivered to each tactor between three and six (Geldard, 1975; Geldard & Sherrick, 1972). Such an illusion suggests that it should be possible to simulate a higher spatial density of tactors than is actually present in a display by manipulating the tactor spacing and inter-stimulus intervals. When Cholewiak and Collins (2000) directly compared saltatory presentations with veridical presentations of vibrotactile stimuli on the back, they observed that the sensations in the two cases were indeed indistinguishable most of the time.

3.6. Summary of Vibrotactile Perception

Of the four possible parameters available for a vibrotactile display discussed here, duration (temporal variation) and body locus hold the most promise for encoding information in a tactile display. Frequency and intensity are problematic due to the poor frequency resolution of the skin, the complex interactions between frequency and amplitude in vibrotactile frequency discrimination, and the fact that stimuli of the same intensity applied to different loci on the body are perceptually different. Rothenberg et al., (1977) proposed that there are at least 7 distinguishable steps in vibrotactile frequency and 15 different intensities that can be discriminated on hairy skin. Similarly, the European Telecommunications Standards Institute (2002) recommended that nine different levels of vibrotactile frequency be used. However, it seems likely that reliable identification accuracy of such stimuli would require substantial training and this situation would only be exacerbated by the complex multi-tasking applications for which tactile displays have been proposed.

More in-depth discussions of tactile perception can be found in the reviews by Jones & Sarter (2008), van Erp & Self (2008), Spirkovska (2005), Giang, et al., 2010, and Myles & Binsteel (2015).

4. Tactile Display Devices

Most tactile displays depend upon taction (the act of touching) derived from mechanical receptors in the skin that may result in either constant tactile simulation, a sense of constant pressure, or variable (vibrotactile) stimulation resulting in the sensation of skin vibration. Tactile and kinesthetic displays are sometimes used synonymously in the form of a haptic display. A well-known example of a haptic display is a force feedback device such as the stick shaker in an airplane cockpit that signals an impending engine stall. Other haptic displays that have been developed impart a sense of surface texture or roughness as the user controls a force-reflecting interface device (Adelstein, Ho, & Kazerooni, 1996; Adelstein, Gayme, Kazerooni, & Ho, 1998). Here, we will focus on vibrotactile stimulation that forms the basis of most current tactile display systems that are commercially available.

Tactile display devices can be categorized into three types of devices based on the mechanism with which they stimulate the skin: vibrotactile, electrotactile, and static actuators. The intended use often determines the choice of device. Wearable displays must be lightweight and small, with low power consumption if the user is also mobile. Other considerations include durability, reliability, wearability, and cost. Vibrotactile devices have been most commonly used in such displays. Touch displays, such as handheld devices, often use some form of static display.

4.1. Vibrotactile Devices

Vibrotactile (electro-mechanical) displays stimulate the skin using an actuator that converts electrical energy into a mechanical displacement of either the whole tactor or a contactor pad at frequencies ranging from 10 to 500 Hz. The main types of vibrotactile actuators are rotary inertial, linear actuators, and pneumatic tactors.

The rotary motion tactor consists of a housing incorporating a direct current (DC) motor with an eccentric rotating mass (ERM). The rotation of the motor stimulates the skin by causing the housing to vibrate, creating omni-directional waves that propagate throughout the device, enabling whole device haptics. A well-known example of an ERM tactor is the pager motor found inside cell phones. The size, cost, robustness, and low power characteristics of the “pager-motor” tactor make it a popular choice for many applications. For example, such devices have been used for torso-based displays (Jones, et al., 2006; Lindeman, Yanagida, Noma, & Hosaka, 2006; van Erp, van Veen, Jansen, & Dobbins, 2005). They are simple to control and produce readily perceptible vibrations on the skin. However, they have limited power-to-mass ratios, and the frequency and amplitude of the vibration is difficult to control independently, unlike some of the electromagnetic linear actuators. The small DC motors are activated at a fixed frequency (typically between 80 and 250 Hz) and amplitude, with the number and location of the motors that are simultaneously active used to convey information.

Linear Resonant Actuators (LRAs) are electromagnetic actuators comprised of a simple magnet attached to a spring that modulates up and down creating its vibrations. The moving "contactor" is lightly preloaded against the skin. When an AC electrical signal is applied, the "contactor" oscillates perpendicularly to the skin, while the surrounding skin area is "shielded" with a passive housing. This provides a strong, point-like sensation that is easily felt and localized. Linear, coil-based actuators have good frequency and amplitude control in the range around their resonance frequency (~200-300 Hz). Thus, the LRA can offer a richer user experience in a lower power solution compared to ERMs. A commercial example of the LRA is the C2 tactor developed by Engineering Acoustics, Inc (http://www.atactech.com/). Their C2 and related tactors form the basis of one of the most complete commercial tactile displays, the Tactile Situational Awareness System (TSAS), developed for fixed and rotary wing aircraft and other military platforms (see Rupert, 1996; 2000). A recent version is composed of three types of tactile arrays (seat cushion, shoulder harness, and waist belt arrays), integrated with hardware controllers, and a TSAS test bed, integrated with a flight simulation tool and software developer kits (SDKs) for software development and testing of tactile display concepts. A number of other labs have developed similar integrated systems, but these generally appear to be prototypes specific to individual research projects and are not commercially available.

Pneumatic tactors are a form of alternating current (AC) linear actuator that consist of a hard shell/reservoir with a soft membrane covering the opening of the shell and an air supply tube attached to the plastic shell. Oscillatory compressed air is driven into the plastic shell that forces the soft membrane or bladder to vibrate, generally at a lower frequency range than electromagnetic tactors (0–100 Hz, optimal 50 Hz). Similar to the pneumatic tactor, the hydraulic tactor uses fluid as the working medium. Problems associated with pneumatic devices include air/fluid leakage, a limited frequency range, and they may be bulkier and harder to control.

A new technology similar to the pneumatic tactor is the Tactus Intelligent Surface (www.tactustechnology.com/), primarily marketed as a keyboard overlay for tablets or cell phones with physical buttons that dynamically appear and disappear into a flat touch screen. It uses microfluidics, small fluid channels routed throughout the Tactile Layer that enable fluid to expand the top polymer layer to create the physical buttons. A small Tactile Controller is connected to the Tactile Layer, which controls the state of the buttons. The controller interfaces via USB, SPI or I2C to a processor. A basic API is provided to allow for integrated software/application-based control.

Piezoelectric tactors are another type of linear actuator that use piezoelectric materials to produce vibratory stimuli. High cost, low force and displacement, and high voltage requirements have limited their use. However, the non-magnetic properties of the piezoelectric tactor make it a possible solution when magnetic materials must be avoided, as in magnetic resonance imaging (MRI) applications. The commercially available Thunder™ actuator (http://www.thunderandlightningpiezos.com), based on a piezoelectric composite technology originally patented by NASA, is one example of this type of device.

Recently, a new piezoelectric tactor has been developed by Midé Engineering Solutions (http://www.mide.com/collections/piezoelectric-haptic-feedback). SHIVR™ high performance, low-profile piezoelectric haptic actuators enable low power, thin, lightweight, and non-magnetic touch communication making them ideal for specialized bio-medical, military and industrial communication applications. SHIVR actuators are able to create a richer haptic experience, as they allow single cycles, fast start-up, static deflection, and independent frequency, amplitude, and phase control capabilities—allowing the user to control the feel and intensity of the sensation. The high performance and broad array of haptic feedback of the SHIVR actuators are made robust and reliable by utilizing Midé's patented manufacturing process that encapsulates high-performance brittle piezo ceramics between copper-clad insulating materials creating a robust, hermetically sealed, electrically insulated transducer with easy connection ready to integrate into your system or application. The Army has recently contracted with Midé to incorporate arrays of these tactors into a snug, flexible t-shirt with tactors and connecting wires embedded/woven into the fabric (Angus Rupert, personal communication, 2016). Such a technology has great potential as a display device during NASA EVA missions since it would likely be lightweight, comfortable, and potentially more reliable than currently available tactor arrays.

A new type of vibrotactile device that works via electrostatic rather than electromechanical vibration, TeslaTouch, exploits the principle of electrovibration that allows the creation of a broad range of tactile sensations, including surface texture, by controlling electrostatic friction between an instrumented touch surface and the user's fingers (Bau, Poupyrev, Israr & Harrison, 2010; https://www.disneyresearch.com/project/teslatouch/). Advantages are that it is fast, low-powered and dynamic, with broad bandwidth and uniformity of response across a wide range of frequencies and amplitudes. It is also highly scalable and can be used efficiently on touch surfaces of any size, shape and configuration. Because it does not have any moving parts, it can be easily added to existing devices with minimal physical modification.

4.2. Electrotactile Devices

Electrical tactile systems provide the sensation of touch through electrotactile excitation. Also known as electrocutaneous stimulation, this technology uses tiny electrodes to produce stimulus-controlled, localized touch sensations by passing a small electric current through the skin with brief (50–100 μs), constant current pulses (0.1–10 mA). The electric field generated excites the neighboring afferent nerve fibers responsible for normal mechanical touch, resulting in sensations variously described as a tingle, pressure, vibration, or pain, depending on the electrode and waveform properties (van Erp & Self, 2008).

Electrotactile displays have been developed for use as sensory aids for those with hearing and visual disabilities (Summers, Dixon, Cooper, Gratton, Brown & Stevens, 1994; Kaczmarek & Haase, 2003; Saunders, 1973). Benefits include reduced weight and size and increased reliability compared to mechanical tactors due to the lack of moving parts. Also, the sensation is very localizable allowing for high-density tactile arrays over a relatively small surface area. However, a general limitation of electrotactile displays is the small dynamic range available to present tactile cues that are painless (Jones & Sarter, 2008). Both the absolute threshold and subjective magnitude of electrotactile stimulation increase rapidly with changes in constant-current amplitude (Rollman, 1973) so the stimulus must be controlled carefully to avoid painful sensations. Further, if there is poor contact between the skin and an electrode, the decrease in effective area results in a higher current density and a much stronger sensation of a sudden, sharp pain (Kaczmarek, Webster, Bach-y-Rita & Tompkins, 1991). The dynamic range from threshold to the maximum painfree level depends on the individual, stimulation site, type of electrodes and stimulus waveform used; it varies from 1.6-20 dB compared to 40 dB for vibrotactile devices.

4.3. Static Displays

Unlike the more dynamic properties of vibrotactile and electrotactile tactors, there are also static devices that either statically indent or apply shear forces to the skin surface (Jones & Sarter, 2008). They are typically used in displays fabricated for presenting tactile cues to the fingers, such as in displays embedded in handheld devices (e.g., Poupyrev, Maruyama, & Rekimoto, 2002) and in virtual Braille displays (Lévesque, Pasquero, Hayward, & Legault, 2005).

A more in-depth discussion of tactile devices and their implementations can be found in the reviews by Jones & Sarter (2008), van Erp & Self (2008), Spirkovska (2005), and Myles & Binsteel (2015). It should be noted that tactile display systems appear to come and go: several devices, such as the Tactaid and Optacon disability aids and the Steadfast Technologies P2 pneumatic tactor, mentioned in these reviews no longer exist.

5. Tactile Display Roles and Applications

To date, the primary applications of tactile information presentation can be grouped into two main categories: sensory substitution and spatial guidance.

5.1. Sensory Substitution

Tactile cues have been used to substitute/offload other modalities to aid those with visual or hearing impairments (Kaczmarek & Bach-y-Rita, 1995), help with overcoming difficulties related to data overload, presenting non-visual communication (Hale and Stanney, 2004), and providing information that is confidential (Jones & Sarter, 2008).

Many tactile displays were initially developed to support sensory substitution in a number of aids for the visually or hearing impaired and later, to provide cues about the properties of objects in computer-generated virtual environments. In these applications, the sense of touch is used to compensate for deficiencies in other senses or to provide information that is best represented using the tactile modality (e.g., surface texture). The role of tactile displays for sensory substitution will also be important for space exploration activities. EVA crewmembers have limited time, resources, mobility, visibility and dexterity, and activities take place in a perceptually impoverished environment. Limitations include a loss of spatial reference frame leading to spatial disorientation, a loss of information normally provided by the auditory and somato-sensory systems, and a restricted field of view.

Sensory substitution systems developed in the 1970s used a camera and computer to capture the visual information that was then presented via a tactile array to the hand or torso as a pictorial representation. Aids for reading (the Optacon, Bliss, Katcher, Rogers & Shepard, 1970) and object recognition (Videotact, Kaczmarek & Bach-y-Rita, 1995; Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969; Segond, Weiss, & Sampaio, 2005) were also developed, although their performance was limited in speed and could be degraded by any visual clutter present within the camera viewpoint. Tactile aids for the hearing impaired have also been developed to support speech perception. The Teletactor system relied on tactile representation of a simplified cochlear model with positional encoding of frequency information in the speech signal (Teletactor: Saunders, Hill, and Franklin (1981). Another system, the Tactaid, used vibrotactile inputs to encode properties of the speech signal such as the spectral location and amplitude of the first two formant regions of speech (Reed & Delhorne, 1995). A more recent innovation is the use of tactile displays as sensory substitution in balance prostheses for people with vestibular dysfunction, presenting tactile cues for body tilt/sway to the torso (Wall & Weinberg, 2003) or feet (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003). Tactile signals delivered to the forearm have also been shown to be useful for sound localization (Békésy, 1955), with a similar average localization error for the skin and ears of 10.3° and 8°, respectively (Gescheider, 1965).

5.2. Spatial Guidance

With respect to spatial guidance, tactile cues have been used to support interaction with objects (McLean, 2008), to help with orienting/guiding 2D localization (McLean, 2008), and to aid in navigating unfamiliar terrain (Jones et al., 2006).

5.2.1. Orientation and Localization

A variety of tactile displays have been developed to aid spatial orientation and navigation in situations in which the human operator can become disoriented. Circumstances leading to disorientation may include an absence of stable reference frames, such as when flying through clouds or flying under high G-load conditions (Rupert, 2000; van Veen & van Erp, 2003), working in microgravity environments in space (Rochlis & Newman, 2000; Traylor & Tan, 2002; van Erp & van Veen, 2003; 2006; van Erp, van Veen, & Ruijsendaal, 2008), or navigation in unfamiliar terrain (Gilson, Redden, & Elliott, 2007; Jones et al., 2006; Lindeman, Sibert, Lathan, & Vice, 2004). In such displays, vibrotactile actuators are used to present information about the intended direction of an operator or vehicle, the pitch and roll of an aircraft, and/or the location of way points in the environment.

The TSAS was developed for fixed and rotary wing aircraft and other military platforms (see Rupert, 1996; 2000). A recent version is composed of three types of tactile arrays (seat cushion, shoulder harness, and waist belt arrays), integrated with hardware controllers, and a software test bed. An earlier prototype was used in experiments testing a tactile display to aid hover control in a UH-60 helicopter. Velocity direction was represented by tactor location and velocity vector magnitude was represented by the tactor pulse pattern to help maintain motionless flight over a reference point. A computer connected to the altitude and velocity sensors on the helicopter translated its position and movement into tactile signals. Results from test flights involving 4 pilots showed that the aircraft could be controlled primarily using tactile cues with minimal visual cues. Also, there was improved control of the aircraft during these complex flight maneuvers, and subjective measures indicated that TSAS enhanced situational awareness (SA) and reduced workload (McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; Rupert, 2000). The TSAS and other tactile displays have also been tested for tasks such as maintaining control of altitude, heading, and airspeed, and to counteract aircraft drift and pilot disorientation (see van Erp & Self, 2008).

5.2.2. Spatial Orientation: Microgravity Environments

A few studies have investigated the use of tactile displays in microgravity environments, primarily as a means of counteracting spatial disorientation. Rochliss and Newman (2000) developed the Tactor Locator System (TLS) to increase an astronaut's SA during EVA when weightlessness can lead to conflicting visual and vestibular cues, resulting in disorientation and decreased SA. The TLS was designed as a non-intrusive, intuitive display capable of conveying position and velocity information via six vibrotactile tactors mounted at the participant's neck and torso, providing somatosensory cues to complement the visual system. An EVA task was simulated on a computer graphics workstation with a display of the International Space Station (ISS) and a target astronaut at an unknown location. Participants were required to move about the ISS and acquire the target astronaut using either an auditory cue (verbal cue re the ISS module nearest the target) at the outset, or the TLS. Participants used a six degree of freedom input device to command translational and rotational motion. The TLS was configured to act as a position aid, providing target direction information to the subject through a localized stimulus. Results showed that, compared to the auditory cue, the TLS significantly decreased reaction time (time to make initial movement toward target) and movement time (total time to acquire target) for simulated astronaut motion around the

ISS. The authors concluded that the TLS was a useful aid in increasing an astronaut's SA, and warranted further testing to explore other uses, tasks and configurations.

Traylor & Tan (2002) developed a wearable vibrotactile display to impart directional information on a user's back for SA. Two studies were conducted aboard the NASA KC-135A reduced gravity aircraft to investigate the perception of tactile information in altered-gravity environments produced by parabolic flight conditions. The first study used a 3 x 3 tactor array attached to the back of a vest that conveyed directional information based on sensory saltation, a perceptual illusion that creates a compelling sense of direction of motion. Using this display, untrained observers were able to correctly identify one of eight directions (east, west, north, south, northeast, northwest, southeast, and southwest) with an accuracy of 79 to 91% (Tan, Lim, & Traylor, 2000). In the altered gravity study, participants were trained with four directional signals (east, west, north, and south) and achieved close to perfect identification performance prior to the flights. During the zero-g portions of the flights, participants were presented with one of the four directional signals on their back, and asked to indicate the perceived direction relative to the torso. The results from two subjects showed that the overall identification accuracy was 44% in zero-g, as compared to close to 100% in 1-g from the same subjects. They also reported that the vibratory signals felt considerably weaker in zero-g than in 1-g.

To further investigate the differential effect of gravity, a second study was conducted to compare the perceived "loudness" of vibrotactile stimulation, as well as tactor mechanical performance, under different gravity conditions. Four participants compared seven fixed-frequency varying-amplitude vibrations in 1.8-g to a reference vibration delivered in zero-g using the method of constant stimuli. The results showed that the points of subjective equality (PSE) measured in 1.8-g were essentially the same as the intensity of the reference signal delivered in zero-g. The difference between the PSE and the reference were less than the difference threshold (DL) measured in 1.8-g. The study also confirmed that the tactors themselves behaved similarly under altered gravity; displacements (measured with an accelerometer) produced by the tactors in one-g and zero-g conditions were the same using identical driving waveforms. The data suggest that the perceived loudness of vibrotactile stimuli remains the same in altered-gravity environments. Rather, user reports indicated that the ability to interpret vibrotactile signals in zero-g may be hampered by the increased attentional and cognitive load required to continuously monitor the position and movement of one's body, particularly for relatively inexperienced participants during parabolic flight.

Van Erp, van Veen, and colleagues (2003; 2006; 2007) have also developed a vibrotactile vest to support orientation awareness for astronauts to compensate for the sensory deprivation of the proprioceptive system during weightlessness. To our knowledge, this is the only research project that has tested such a prototype in an actual space environment on the ISS. The Tactile Orientation Awareness Support Tool (TOAST) contained 56 vibrators in a matrix covering the torso and used ERM (cell phone type) tactors. It employed an artificial gravity vector analogy with the location of vibration on the torso indicating the direction of a vector representing the standard ISS down orientation. A second mode, to be used during rest, activated additional vibrating elements attached to the ankles, knees, elbows and wrists of the astronaut. Using specific, pre-programmed spatiotemporal patterns, whole body stimulation was used to support the astronaut in sensing and locating his extremities in space.

In one study, van Erp and van Veen (2006) used several rotation tasks performed by Dutch astronaut André Kuipers in the ISS to determine whether the brain can integrate artificial orientation information that has no real life equivalent. The astronaut's task involved being rotated by a crewmember a variable number of times, and then asked to report which way was ISS "down."

Performance (orientation accuracy and reaction time) was compared with visual only (not blindfolded), touch only, or both cues. The results showed that, compared to performance with visual cues alone, artificial touch information in the form of a localized vibration on the torso signaling the nominal down direction of the ISS made orienting in microgravity faster, better, and easier. The importance of the artificial touch information also increased over the initial 7 days of staying in microgravity while the weight of visual information decreased over the same period. The results support the capacity of the brain to adapt to unusual environments and to use and integrate artificial cues.

Van Erp, van Veen, and Ruijsendaal (2007) also investigated operational issues of the TOAST display system. In an experiment with a single male astronaut, they tested whether he could detect the vibrations in microgravity as fast as on Earth. Several questionnaires were also used to assess issues such as comfort and usability. The authors compared reaction time (RT) to tactors worn on the torso by the astronaut in 1-g and zero-g environments. Despite the overall performance gain in microgravity (i.e., faster RTs), the RTs for tactors located in the upper and lower rings on the torso were negatively affected by weightlessness: the RTs were higher than in 1-g. This indicated that although the garment that held the tactors was custom made for the astronaut, the fit at the lower and upper rings should be improved. The optimized fit for 1-g may be less optimal in microgravity due to a different posture and shifts in body fluids. The questionnaires showed that the tool supported the astronaut in orientation tasks and has potential in challenging situations, but was not needed during daily operations, particularly since the somewhat bulky equipment of the prototype reduced its wearability. The authors concluded that the demonstration was successful but that more microgravity data are needed. They also planned to use it in other applications for pilots, divers, individuals with a visual or vestibular dysfunction, emergency services, and the automotive and sports industries.

5.2.3. Navigation

A number of studies have demonstrated that tactile displays can be used as navigation aids when traversing unfamiliar environments (Gilson et al., 2007; Jones et al., 2006; van Erp et al., 2005). The studies also investigated the optimal configuration of the tactors in the display (e.g., a belt, vest, or arm bands) and the most effective representation of direction and distance information. Gilson et al. (2007) tested tactile belt displays for individual soldiers intended to aid in navigation, obstacle, and threat avoidance, and targeting under battle conditions. Van Erp et al. (2005) tested a navigation aid using a belt containing eight tactors that represented the direction and distance of waypoints using tactor location and vibration rate, respectively. Performance was measured in the context of either a pedestrian, a helicopter pilot, or the pilot of a rigid inflatable boat following the waypoints along a route. Participants were 100% successful in navigating waypoints using tactor location in all contexts. However, in the walking task, distance feedback in the form of various temporal patterns of vibration rate did not facilitate the time to complete the route. The results were also consistent with Rupert's (2000) observations that participants can readily interpret vibrotactile cues in a vibrating environment, even with high-g loads up to 6-g in a centrifuge (van Veen & van Erp, 2000). Jones et al. (2006) also observed nearly 100% performance in an outdoor navigation task in which required direction of movement was represented by different vibrotactile patterns presented on a four by four tactor array on the back. Such studies indicate that torso-mounted tactile navigation aids can be readily used with minimal training in a variety of operational environments.

5.3. Virtual Environments

Tactile display devices have also been used to enhance virtual environments. For example, some displays present collision information when interacting with virtual objects via a position-tracked, instrumented glove (CyberTouch glove, Immersion Corp.), or the vibration and rumble in the chairs (Lindeman & Yanagida, 2003) and platforms of driving simulators. The CyberTouch glove used six individually programmable vibrotactile actuators, mounted on the back of each finger and one on the palm, with hand configuration recorded from 22 sensors located over the finger joints and the wrist. Measurements from these sensors determined the position and configuration of a virtual hand presented to the user on a visual display with the vibrotactile actuators activated whenever the virtual hand touched or collided with a virtual object. Recent Immersion Corp. developments have shifted to haptic feedback in handheld devices such as mobile phones, tablets, and gaming controllers (www.immersion.com).

More recent work on tactile displays for exploring virtual environments has also focused on developing instrumented surfaces or touch pad displays. For example, Mengoni and colleagues have developed a system that combines electrotactile and mechanical vibration technology to simulate softness, texture coarseness and roughness properties (Mengoni, Colaiocco, Peruzzini & Germani, 2011; Germani, Mengoni, & Peruzzini, 2013). Similarly, TeslaTouch uses an electrovibration technology that allows the creation of a broad range of tactile sensations, including surface texture, by controlling electrostatic friction between an instrumented touch surface and the user’s fingers (Bau, et al., 2010).

5.4. Tactons: Communication of Complex Concepts

A promising line of research in tactile displays has focused on the development of tactons, or tactile icons (Brewster & Brown, 2004; MacLean & Enriquez, 2003; Rinker, Craig, & Bernstein, 1998; Roberts & Franklin, 2005). Analogous to visual icons or auditory earcons, tactons are structured abstract tactile “messages” that are designed to convey complex concepts and ideas beyond simple parameters like location and distance. Pasquero (2006) proposed that in order to be useful, tactile icons must: (a) be easy to learn and memorize; (b) carry meaning or emotional content; and (c) be universal and intuitive, while also supporting increasing levels of abstraction for expert users. Like earcons, a critical aspect of creating tactons is identifying which of several possible, simultaneous stimulus parameters can map most effectively onto which concept or type of information to be conveyed. For example, as noted above in the discussion of vibrotactile perception, simple parameters such as vibration frequency and amplitude may interact producing combined perceptual effects that are different from manipulating each parameter alone. For a given frequency, as the amplitude of vibration increases, the perceived frequency of the signal (i.e., pitch) also increases. Psychophysical studies of vibrotactile perception provide an initial framework for determining which stimulus dimensions and what range of values are most likely to be perceived and how some of these dimensions may interact.

Stimuli that vary along a number of dimensions hold the most promise for the development of tactons that convey abstract concepts. A number of methodologies have been used to try to map this multidimensional stimulus space. MacLean and Enriquez (2003) used multidimensional scaling techniques to determine how haptic icons can be created from signal parameters such as waveform, frequency, and force, with the exact number and value of levels for each parameter based on pre-determined perceptual thresholds. They found that for the ranges of parameters that they implemented in a handheld force-feedback knob, frequency played the dominant role in distinguishing between the multidimensional stimuli with waveform and force being less salient.

Several studies have exploited the relatively high perceptual salience of temporal cues and rhythms in constructing tactons. Brown et al. (2005) found that tactons distinguished by different rhythms were easily identified and that by changing the modulation frequency of a base signal, the perceived roughness of the waveforms could be varied. Summers (2000) also found that rhythmic patterns, along with frequency and amplitude variations, were particularly effective for encoding speech information in an aid for the hearing impaired. Brewster and King (2005) developed a desktop interface that included a vibrotactile progress bar, e.g. to represent software download time. The time remaining was represented by variations in the time between vibrotactile pulses with the rate increasing as the download neared completion time. Participants, who evaluated the design, preferred the tactile progress bar to the traditional visual one and performed better when tracking download progress while performing a competing visual task.

A number of researchers have proposed frameworks for organizing tactons into a more coherent "language." Brewster and Brown (2004) proposed three different types of tactons: compound tactons, hierarchical tactons, and transformational tactons. Compound tactons consist of a combination of two or more simple tactons (such as a high vs. a low-frequency pulse). Hierarchical tactons represent nodes at various levels of a so-called tacton tree, in which tactons at lower levels inherit properties from tactons at higher levels. Transformational tactons encode several properties or pieces of information using different parameters. For example, in an aid for the blind when using a computer, a transformational tacton can be used to represent a computer file. The file type could then be encoded by rhythm, the file size by frequency, and the creation date by body location. Enriquez, MacLean, and Chita (2006) described another approach to developing haptic/tactile icons that involved identifying basic elements, called haptic phonemes, and using these to create different icons. They created a set of nine haptic icons that varied in waveform and frequency and trained participants to associate each haptic icon with an arbitrary concept, such as the name of a fruit. Participants were able to learn these associations after about 25 min of training, although identification rates were higher for stimuli with frequency (81% correct) vs. waveform variations (73% correct).

Tactons have also been developed as a means of supporting attention, fault management and supervisory control in complex, event-driven task domains. For example, Woods (1995) discusses using tactile alarms to encode several properties of an interrupting task or event to support users' decision making in whether to reorient their attentional focus during dynamic fault management situations involving time pressure, multiple interacting goals, high consequences of failure, and multiple interleaved tasks. Examples include flight deck operations in commercial and military aviation, control of space systems, and anesthetic management under surgery. Hameed, Ferris, Jayaraman, and Sarter (2006) developed an interface in a large-scale supervisory control environment to support water control engineers in task scheduling and prioritization. They mapped the nature, urgency, and duration of a pending task to the location, characteristic frequency, and duration of a tactile signal resulting in correct interpretation rates of 94%, 90%, and 83%, respectively. Based on this partial information, participants were able to make more informed and appropriate decisions about attention switching compared to more traditional and less informative interruption cues, without incurring performance costs on their main visual task.

However, other research has shown that while complex tactile signals are, in principle, feasible and useful, their success is highly context dependent. Chan, MacLean, and McGrenere (2005) developed seven haptic icons that could easily be learned in the absence of workload and with minimal training. Increased workload, however, resulted in detection times that were significantly longer, although acceptable, in most task contexts. The specific characteristics of the different icons, such as their degree of intrusiveness, differentially influenced their susceptibility to workload effects as well.

5.5. Summary of Tactile Display Roles and Applications

Vibrotactile displays have been successfully demonstrated as sensory substitution systems, as navigation aids in unfamiliar and hazardous environments, and as a means of interacting with virtual environments. As tactile technology improves, their application will no doubt be facilitated as they become lighter and less cumbersome with lower power requirements. The optimal characteristics of a tactile display, such as the number, spacing and location of tactors, clearly depend on the nature of the task and the complexity of the information to be conveyed. A moderate configuration of seven to eight tactors has been shown to be effective in aiding speech comprehension for the hearing impaired (Reed & Delhorne, 2003) or providing directional cues during navigation (van Erp et al., 2005).

Many systems that have been evaluated have primarily used the location and number of tactors to encode information, without varying the frequency and amplitude of the vibrotactile signal. The work on developing tactons and tactile vocabularies suggests that it should be possible to convey more complex information using a number of carefully optimized signal parameters. However, tactile signals are subject to masking effects and forms of change blindness in the spatial dimension (Gallace, Tan & Spence, 2006) and also in non-spatial dimensions such as intensity (Ferris, Stringfiled, & Sarter, 2010), that can inhibit the signals from being reliably perceived. The limited perceptual resolution and processing bandwidth of the tactile channel may require that display signals remain relatively simple, compared to auditory and visual displays.

A more complete summary of the properties and applications of tactile displays can be found in Jones & Sarter (2008), van Erp & Self (2008), Spirkovska (2005), Giang, et al. (2010), and Myles & Binsteel (2015).

6. The Role of Tactile Cues in Multimodal Displays

6.1. Structural and Functional Differences Between Vision, Audition, and Touch

Over the last decades, multisensory research has demonstrated that although important differences are present between information processing in the different sensory modalities, certain stages of information processing (such as those contributing to maintaining and updating the representation of space, or those believed to direct attention toward particular aspects of external stimuli) may actually be shared between modalities (Downar, Crawley, Mikulis & Davis, 2000; Spence & Gallace, 2007).

The inherent structural and functional differences between vision, audition and touch have important implications for multisensory integration. As reported earlier, the somatosensory system carries information as diverse as tactile, proprioceptive and interoceptive. Like vision and audition, the tactile sense provides information from stimuli external to the body, such as “what” and “where.” In the “what” domain, the tactile sense carries both static and dynamic information. Static stimuli characteristics accessible to the tactile sensory system, such as shape, size and texture can also be made available to the visual system. Dynamic information, such as frequency, intensity and temporal variation can find equivalents both in the visual and in the auditory systems. The registration of the spatial properties of a stimulus (“where”) between modalities is more challenging for the central nervous system (CNS) and yet, a necessary step towards multisensory integration. Auditory, visual and somatosensory signals are represented in different neural encoding formats at the level of the cochlea, the retina, and the body, respectively. Whereas vision is tuned to spatial processing supported by a 2D retinotopic (eye-centered) spatial organization, audition is primarily tuned to frequency analysis resulting in a tonotopic map, i.e. an orderly map of frequencies along the length of the cochlea (Culler et al., 1943). As a consequence, the auditory system must derive the location of a sound on the basis of acoustic cues that arise from the geometry of the head and the ears (binaural and monaural cues, Yost, 2000). Tactile stimuli undergo a distributed coding of attributes such as pressure, vibration and temperature. Information about stimuli location is first represented relative to the skin surface in the primary sensory cortex's homunculus (Penfield & Boldrey, 1937). However, because the body is flexible, the location of touch in space crucially depends on the body's posture at the time of touch. Therefore, the external touch location must be derived by integration of skin location and postural information, i.e. proprioceptive inputs (Heed & Azañón, 2014), a process referred to as tactile remapping (Driver & Spence, 1998).

To solve the problem of the differences in reference frames[3] between modalities, the CNS must proceed to the transformation of the information in a common, absolute spatial representation of the world, and later, read the information back out into the motor coordinates needed for each effector system ("how"). This process, encompassing the integrated neural representation of a "body schema" and of the space around the body (peripersonal space), is a prerequisite for the effective "piloting" of the body to avoid or manipulate objects in pursuit of behavioral goals (Popper & Eccles, 1977).

6.2. Rules for Multisensory Integration

Two principles, the temporal and the spatial rules, determine the likelihood and the strength of multisensory integration.

6.2.1. Temporal Synchrony

The "temporal rule" states that multisensory interactions are dependent on the coincidence of the neural responses to different stimuli (albeit within a certain window). Stimuli with overlapping neural responses yield interactions, whereas those yielding asynchronous responses do not. The concept of a temporal binding window (TBW) was introduced that determines the maximum temporal separation between two sensory events to be perceived as referring to the same object. For visual and auditory stimuli such as simple flashes and beeps, the temporal window extended from 25 to 50ms and was found to be asymmetrical, i.e. the tolerance to stimulus onset asynchrony (SOA) is greater when the visual stimulus precedes the auditory stimulus, than in the opposite configuration (Keetels & Vroomen, 2005; Zampini, Guest, et al., 2005a). For audio-tactile pairs, Zampini, Brown, et al. (2005b) obtained just noticeable differences (JNDs) of about 80ms, and for visual–tactile pairs, JNDs have been found on the order of 35–65ms (Keetels & Vroomen, 2008b; Spence et al., 2001). The size of the audiovisual TBW is up to 5 times larger (200ms) with audio-visual speech stimuli (van Wassenhove, Grant, & Poeppel, 2007). In other words, when the stimulus complexity increases, the sensitivity for temporal order deteriorates (Vatakis & Spence, 2006). Paired comparisons between visual, auditory and tactile stimuli with a discrimination threshold method revealed that the temporal resolution for synchrony perception was similar for visual-auditory (VA) and visuotactile (VT), while audiotactile (AT) showed superiority in terms of temporal resolution (Fujisaki & Nishida, 2009).

For VA stimuli that are repetitively presented in streams, the perception of synchrony breaks down if the temporal frequency is above ~4 Hz (Benjamin, van der Smagt, & Verstraten, 2008; Fujisaki & Nishida, 2005). Above this rate, observers are no longer able to discriminate whether

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[3] The term "reference frame" is used to refer to the center of a coordinate system for representing objects, including the body itself, and relations between objects (Cohen & Andersen, 2002).

the auditory and visual stimuli are synchronous and the two modality streams are perceived as being segregated with no order between them (VT and AT temporal resolutions were ~4 Hz and ~10 Hz, respectively).

To summarize, temporal lags below 20ms are usually unnoticed, probably because of hard-wired limitations on the resolution power of the individual senses. Above this limit, delays do become noticeable, in particular if stimuli: (1) have fast transient rise times; (2) are spatially separated; (3) have predictable onsets;and (4) are presented rhythmically at rates < 4Hz.

Bresciani, Dammeier & Ernst (2008) investigated the interactions between visual, tactile and auditory sensory signals for the perception of sequences of events. Sequences of flashes, taps and beeps were presented simultaneously. For each experimental session, the participants were instructed to count the number of events presented in one modality (Target) and ignore the stimuli presented in the other modalities (Background). The results showed that for the perception of sequences of events: (1) vision, touch and audition are automatically integrated;(2) the respective contribution of the three modalities to the integrated percept differs; (3) the relative contribution of each modality depends on its relative reliability (1/variability); and (4) task-irrelevant stimuli (potential distractors) have more weight when presented in two rather than one modality.

Thorough VT, AT and VAT synchronization may be an issue when time delays are introduced in the context of teleoperations. Time delays present in the control loop of human teleoperation in space can be considered another aspect of increased task workload and can have a critical impact on human performance and mission effectiveness (Sheridan, 1993; Fong, 2010; Podnar, et al., 2010; Schmidt, et al., 2012). Relatively low latencies on the order of 400ms will be present during lunar telerobotic control from Lagrange points or from Mars orbit during future surface exploration and control missions (Lester & Thronson, 2011; Valinia, et al., 2012. Lester and Thronson (2011) have described the limits of a "cognitive horizon" for teleoperation in space, i.e. a latency limit of ~500ms beyond which performance degrades. However, the sensory modality and the type of task determine the size of specific latency thresholds: 100ms for haptic surface perception, 200ms for visual feedback applications (Lester & Thronson, 2011). For visual just-noticeable differences, Ellis et al., (1999a, b) reported thresholds of 15–20ms, while for points of subject equality, the threshold was 50ms. Thresholds for the perception of visual image instability, on the other hand, have been reported as 180–320msec depending on head velocity (Allison, et al., 2001; see also Adelstein, et al., 2003). Relatively little research exists for audition: in one study, Wenzel (2001) showed no performance disruption in an auditory localization task (head motion enabled) until latency increased to 250–500ms (for 3s-duration stimuli) while disruption was minimal for longer duration stimuli (8sec duration stimuli, 500ms latency). In a 2015 study comparing the single and combined effects of a visual auditory docking task, Wenzel & Godfroy-Cooper reported that the auditory system is less sensitive to latency compared to the visual system. A similar effect was found for docking response time in the auditory condition. However, there was no facilitatory effect in the bimodal condition.

6.2.2. Spatial Alignment

The "spatial rule" states that multisensory interactions are dependent on the spatial alignment and/or overlap of receptive fields responsive to stimuli. That is, facilitative multisensory interactions can be observed even when stimuli are spatially misaligned in their external coordinates, provided that the responsive neurons contain overlapping representations. If these representations do not overlap, no interaction is seen, and in many cases, even response depression is observed (i.e., inhibitory interactions). However, a perfect spatial and temporal alignment is not required for multisensory integration to occur as long as the sound and light are presented within close spatial (Stein & Meredith, 1993) and temporal proximity (Colonius & Diederich, 2012; Vroomen & Keetels, 2010). Some authors have suggested that stimuli must be presented within a ~30-40° of each other (though not necessarily within the same hemispace) for effects to occur either in the case of facilitating stimulus detection (for visual-auditory interactions: Hughes et al., 1994; Harrington & Peck, 1998; for visual-tactile interactions: Foster et al., 2002) or in the case of influencing localization judgments (for auditory-tactile interactions: Calclin et al., 2002), with wider separations failing to generate facilitating interaction effects (Stein et al., 1989). Others have found interaction effects across wider spatial disparities for tasks requiring visual intensity judgments, sometimes independent of the locus of sounds (Stein et al., 1996; Hairston et al., 2003). Others emphasize the spatial ambiguity of a stimulus over its absolute position, such as in the cases of the ventriloquism effect and shifts in attention (Bertelson, 1998; Spence & Driver, 2000; Hairston et al., 2003). Such a crossmodal shift of exogenous (or automatic/reflexive) spatial attention can occur between pairs of auditory, visual, and tactile stimuli (Spence & McDonald, 2004). The effects of a shift of crossmodal exogenous spatial attention are generally most pronounced when there is some time between the onset of the sound and the light (~100–300ms, see Berger, Henrik & Rafal, 2005) and when they originate from approximately the same spatial location (Spence & McDonald, 2004). Crossmodal exogenous spatial attention shifts result in faster RTs and higher detection sensitivity for information appearing at attended as compared to unattended locations (Santangelo & Spence, 2009). When there is more time between the onset of the sound and the light (>300ms) an inhibitory after-effect can be observed (inhibition of return [IOR]) that has been demonstrated between all possible pairings of audition, vision, and touch (Klein, 2000).

The variability of these findings raises the possibility that task requirements may influence spatial limitations on multisensory interactions (Spence, 2013). Another possibility is that some varieties of multisensory interactions occur with neurons and/or brain regions with large spatially insensitive receptive fields.

6.2.3. Inverse Effectiveness

A third principle, called the "principle of inverse effectiveness" was formulated based on the observation that the relative increase in spike rate in multisensory neurons after multisensory stimulation was larger when the unimodal stimuli (sound or light alone) evoked only a weak response as compared to those unimodal stimuli that evoked a strong response in the neuron (Meredith & Stein, 1983; Holmes, 2009). This multisensory facilitation can be reinforced by a semantic congruence between the sensory inputs, and is susceptible to being modulated by attentional factors, instructions, or inter-individual differences. Overall, these neurophysiological principles have been useful in predicting the circumstances in which multisensory integration occurs in human behavior (see Stein & Stanford, 2008 for a review).

7. Applied Studies of Tactile Cues in the Context of Multimodal Displays

Although direct behavioral inferences from neuronal data can be problematic, general insights into multisensory integration provided by neurophysiological studies, such as the spatial and temporal rules, have generally been confirmed in applied behavioral studies. However, it is also clear that behavioral integration is complex and depends on factors such as the type and reliability of each unisensory stimulus involved, the nature of the task being performed, and the level of operator workload (Gray, Spence, Ho & Tan, 2013). Such factors may determine whether the combined performance effects of multisensory integration are additive, superadditive, or no better than unisensory performance. If stimuli are chosen that violate human perceptual and attentional systems (e.g., intersensory conflict due to incongruent spatial locations, temporal asynchrony, or even semantic incongruency; Laurienti, Kraft, Maldjian, Burdette, & Wallace, 2004), performance may actually be subadditive (worse than unisensory performance) by setting up conditions that confuse or overload the user and result in multisensory suppression.

Although many multimodal display studies have been conducted in recent years, they have often been developed in a somewhat trial and error manner without consideration of the basic mechanisms of human multisensory integration and cross-modal attention (Sarter, 2006). Further, performance measures are not always directly compared among the possible unimodal, bimodal, and/or trimodal displays in a given study, making clear inferences about relative multisensory benefits problematic. Here we present representative studies of multisensory integration performance in bimodal and trimodal displays, particularly for attentional orienting and warnings, that have been investigated for applications in automobiles, military combat vehicles, aviation, and medical equipment.

7.1. Automobile Displays

Multimodal automobile interfaces warning drivers of events such as the source and spatial location of potential collisions have been under development for a number of years. Research in this area has demonstrated inconsistent results regarding whether multimodal displays produce better performance compared to unimodal displays. For example, in a driving simulator, Lee, McGehee, Brown and Marshall (2006) investigated the effectiveness of an interface designed to reengage attention during adaptive cruise control when a driver may need to assume control in a potential emergency braking situation. They compared performance for four unimodal displays: a visual icon depicting a collision, an auditory warning tone presented via a dashboard speaker, two different tactile signals (seat vibration or brake pulse), and a trimodal combination of the unimodal displays. Their results showed no significant differences in braking RTs between the multimodal and unimodal signals. Spence and Ho (2008) later noted that there was a large spatial separation between the different signals with visual and auditory signals at approximately eye level and the tactile displays at seat and foot levels in the Lee et al. (2006) study. Ho, Reed and Spence (2007) compared audio, tactile and bimodal audio-tactile signals in a collision avoidance display with frontal locations that were more spatially congruent, i.e., a car horn presented via a speaker on the dashboard and a tactile signal presented in the middle of the driver's stomach. The results showed that braking RTs were significantly shorter for the bimodal signals compared to the best unimodal signal. Similar multimodal benefits have been demonstrated in other driver warning systems when auditory and visual stimuli are spatially congruent (Spence & Ho, 2008; van Erp & van Veen, 2004). Such data support the idea that multimodal effects may vary considerably depending upon factors like the presence or absence of spatial congruency.

7.2. Military and Aviation Applications

Multimodal interfaces have also been developed for military ground combat vehicles and aircraft for applications such as threat alerting. Oskarsson, Eriksson and Carlander (2012) compared the effectiveness of unimodal, bimodal, and trimodal threat warning displays in a simulated combat vehicle where the task was to turn toward a threat as fast and accurately as possible. The display components consisted of virtual 3D sounds presented via headphones, directional tactile signals delivered via one of 12 tactors located on the operator's belt, and either a visual head-down display (HDD) or head-up display (HUD). The allocentric HDD visual display used moving lines to indicate the direction of threat and was placed at waist height approximately 30º left of the center. The exocentric HUD used a pulsing arrow that indicated both threat direction and angular distance and was superimposed at eye level on the out-the-window screen mounted in front of the operator. Performance was assessed in terms of accuracy in localizing the threat and mean RT to orient to it.

Experiment 1, which utilized the visual HDD, showed that the trimodal display produced better performance compared to the best of the unimodal and bimodal displays. Interestingly, multisensory facilitation occurred with this interface even though there was some physical spatial incongruence between the signals, i.e., the auditory and tactile signals were presented from around the body while the visual signal was always presented in front of the operator. It may be that subadditive integration did not occur because the different signals were associated with different types of attentional orienting. The tactile and auditory cues were exogenous (an automatic/reflexive capture of attention by peripheral cues) while visual cues were endogenous (voluntary shifting of spatial attention). In experiment 2, Oskarsson et al. (2012) utilized the HUD so that all three cues were spatially congruent. Three displays for cueing threat direction were compared: the HUD with 3D audio, tactile with 3D audio, and HUD, 3D audio, and tactile belt combined into a trimodal display. Performance was significantly better for the trimodal HUD display compared to the bimodal displays. The trimodal HUD was also better than the trimodal display with the HDD. Similar benefits for multimodal directional alerting systems have also been observed in the context of military aviation under conditions such as high acceleration in simulated aerial combat (van Erp, Eriksson, Levin, Carlander, Veltman, & Vos, 2007) and in the presence of helicopter noise (Brill, J. C., Lawson, B. D., & Rupert, 2015).

In another aviation context, Ngo, Pierce & Spence (2012) compared unimodal and multimodal performance in a simulated air traffic control scenario in which participants had to monitor and control aircraft. The task goals were to ensure that the aircraft landed or exited at the correct altitude, speed, and direction and maintained a safe separation from all other aircraft and boundaries. The performance measures recorded included enroute time, handoff delay, and conflict resolution delay. The standard baseline visual condition (the aircraft in conflict was highlighted in red) was compared to experimental conditions in which the visual cue was accompanied by a temporally sychronous auditory cue (500 Hz tone), a vibrotactile cue (tactors at each side of the waist), or a combined audiotactile cue. The results showed that performance was significantly better when auditory or audiotactile warning signals were presented. However, performance with the unimodal tactile warning signal did not improve performance compared to the unimodal visual alert.

7.3. Medical Applications

A relatively new area for multimodal display research is in medical applications. Ferris and Sarter (2011) recently investigated multimodal interfaces for attentional orienting and task management in the context of a surgical procedure to enhance patient monitoring by anesthesiologists. They compared performance with the commonly used auditory and visual warning systems to conditions in which tactile displays were added. In a surgery simulation, visual (popup messages on a patient screen in front of the anesthesiologist) and auditory signals (alarm sounds and an auditory sonification, i.e., a periodic signal that conveyed heart rate and blood oxygenation information) were combined with three types of vibrotactile signals delivered via a vibrotactile vest. In addition to a tactile alarm, two tactile displays were presented that provided continuous information concerning the patient's status. Several performance measures were collected for two tasks, physiological monitoring and anesthesia induction, and combined in a multitask performance score. Unlike the simple alerting function of many of the previously described multimodal interfaces, this system was designed to both inform the operator about the nature of a critical event as well as orient attention to a particular spatial location. For example, lung volume information was presented via signals to the anesthesiologist's back while blood pressure information was presented via the arm. For all tactile displays, the combined trimodal interface produced superior performance compared to the typical auditory-visual interface alone. However, it is not clear that this enhancement was due to multisensory facilitation since performance was not measured for the tactile system alone.

7.4. Effects of Workload and Experience Level

A number of studies have indicated that although multisensory cues may not be more effective than unimodal cues under conditions of low perceptual workload (Lavie, 2005), they may still retain their capacity to capture an operator's spatial attention under high workload when unimodal cues are no longer effective (Spence, 2010). Similarly, the multimodal interfaces described here may or may not function as well in real operating environments where workload can be substantially higher than can be produced in a laboratory or simulator. Few multimodal interface studies involving tactile cues have systematically varied operator workload. In one such study, Mohebbi, Gray & Tan (2009) reported that the effectiveness of unimodal auditory and tactile collision warnings varied substantially with workload in a driving simulator. Auditory warnings that were highly effective under low workload (just driving) were totally ineffective under moderate workload conditions (simple mobile phone conversation while driving). Tactile signals, on the other hand, were effective under both low and moderate workload conditions but significantly less effective in a high workload condition (complex phone conversation).

An important issue related to workload is whether the semantic content and delivery method of the warning should change as a function of operator workload. In the anesthesiology study by Ferris and Sarter (2011), multimodal displays that provided continuous tactile information concerning the patient's health resulted in better performance than warning signals that were only active when the situation became critical, presumably because the continuous signals allowed the operator to anticipate critical situations and respond more rapidly. However, these results were only observed under low operator workload. Under high workload, the continuous signals tended to be ignored, resulting in better performance with discrete warnings. To our knowledge, applied studies directly assessing whether an operator can utilize semantic information from auditory or haptic icons under high workload have yet to be conducted.

Since workload tends to vary greatly in complex real-world environments, it will be difficult to design a multimodal interface that performs well under all conditions. As a possible solution, Ferris and Sarter (2011) proposed adaptive systems in which the information presented to the user changes as a function of workload. However, this presupposes that adequate methods of detecting and/or predicting operator workload are developed. Further, research in adaptive systems for aviation suggests that they can serve to increase workload and reduce situational awareness (Kaber, Perry, Segall, McClernon & Prinzel, 2006). The much-maligned adaptive menus of Microsoft Office 2003 are a well-known example of how implementation of such a display can go wrong.

Another topic that has not been well studied is how the level of experience or training of the operator may affect performance with multimodal displays. Typically, participants in lab and simulator studies are given limited training prior to collection of data. However, training to asymptotic performance would likely be too cumbersome to be practical in conducting experiments. Further, if a given display requires much training it is less likely that it will be adopted as a good solution. In addition, unlike real world scenarios with unpredictable events, lab studies must necessarily test multimodal displays under simplified and controlled conditions in order to obtain results that can be statistically analyzed. It is unclear how well people can respond to many different warning signals that may not occur with any degree of regularity.

It is also unclear whether highly experienced operators who have developed complex mental representations of their operating environment would benefit from many of the relatively simple multimodal displays like those developed so far. Similar to pilots subjected to multiple alarms during an emergency situation with poorly designed cockpit displays, experienced users may simply find them annoying and turn them off. One experimental approach would be to directly compare performance for novice and expert participants, such as pilots, astronauts or doctors, although this is not always a practical possibility for many researchers.

7.5. Relevance to Space Applications

While many of the results discussed above will be relevant to space applications, conditions specific to space environments such as degraded sensory cues and the impact of micro- and macro-gravity conditions will need to be carefully considered when designing displays for spacecraft systems, EVA missions, and astronaut support. Compared to the earth environment, such factors may alter the relative reliability of individual sensory systems, the manner in which they integrate, and the way in which factors like workload impact performance. Although some conclusions may be drawn from simulation studies or buoyancy tank and centrifuge studies mimicking altered gravity conditions, investigation in a true space environment will remain the best test of display effectiveness.

8. The Forgotten Dimension: Depth

Of all our senses, only vision and audition allow us to perceive information that is currently out of reach. Whereas vision enables us to determine the spatial location of something that can be seen in frontal space only, audition helps with localizing sounds in all directions. Conversely, the sense of touch is relatively constrained in terms of depth perception as one can only feel things that are within reach. Perceiving touch is thus bound to the body. One aspect that has received little to no attention in the literature on multisensory integration is how the distance between multisensory stimuli and an observer affects multisensory integration.

8.1. Peripersonal vs. Extrapersonal Space

A few studies have provided neurophysiological and neuropsychological evidence indicating that information presented at different distances from the observer, or in different regions of space, is processed differently in the brain (Previc, 1998; Graziano, Reiss, & Gross, 1999). Objects at a distance can naturally be perceived through a limited number of senses, namely vision, audition, and olfaction. By contrast, objects nearer to, and therefore within reach or in contact with the body can impact upon all sensory systems, including gustation and all the sub-modalities of touch (see Craig & Rollman, 1999 for a review). There seems to be a clear distinction between the region of space directly surrounding different body parts (peripersonal space, near) and the space that is out of reach (extrapersonal space, far) in terms of multisensory interactions occurring in these regions of space (Occeli et al., 2011; Van der Stoep, Nijboer, Van der Stigchel, & Spence, 2015). Representations of peripersonal space are body-centered or body part-centered (see Làvadas, 2002 for a review), restricted to the space immediately surrounding the body (~70cm in humans), and involve the integration of information from multiple sensory modalities (somatosensory, proprioceptive, visual and auditory. The brain's representations of the visuotactile peripersonal space can be modulated to incorporate mirror images, inanimate objects, and tools held in the hand (Austen, Soto-Faraco, & Kingstone, 2001; Pavani, Spence, & Driver, 2000). Tool use seems to "capture" extrapersonal space and results in it being incorporated into peripersonal space. The question remains whether this applies to tools that are teleoperated, such as a robotic arm or rovers on a planetary surface.

8.2. Visuotactile and Audiotactile Interactions in Frontal Peripersonal Space

The majority of studies of multisensory interactions in the depth plane have focused on visuotactile and audiotactile interactions in frontal peripersonal space. In such studies, tactile stimuli are often delivered to the hands while the other parts of the skin surface are largely ignored. Neurophysiological evidence appears to support the notion that space is divided into several distinct regions and suggests that both audiotactile and visuotactile interactions are more pronounced in the space directly surrounding the body. In a 2012 study, Canzoneri et al. demonstrated that participants responded more rapidly to the tactile targets when the simulated sound location was situated close to their hand as compared to when it appeared further away. Similar results have been reported with vision and touch (Gray & Tan, 2002).

The specific spatio-temporal properties of dynamic stimuli can also influence the strength of multisensory interactions. When visual stimuli approach the body at a certain speed, predictions concerning the location of a tactile stimulus in 3D space can be made (e.g., when and where contact with the body is expected), thus enhancing the speed with which stimuli at the expected time and location are processed relative to other times and locations. Similar results have been observed in a study of visuotactile interactions, where responses to tactile targets were fastest to tactile stimuli presented at the same time at which contact with the face was expected, based on the speed of a reaching movement (Kandula et al., 2015).

Given that tactile perception is inherently bound to the body, the stronger multisensory interactions involving touch in peripersonal space require stimuli from different modalities to not only be aligned at any particular depth but also specifically to be aligned with the body (or extensions of the body in the case of tool-use).

Canzoneri et al.'s results (2012) suggest that the presentation of sensory information from slightly beyond the border of peripersonal space does not result in the sudden absence of audiotactile interactions, but rather shows a more gradual decline in performance, as expressed by a gradual increase in RTs. This effect appeared to be the most pronounced for sounds that are perceived to be approaching the participants and less for sounds that appear to recede from the participant. Drawing a distinction between the space that is reachable and that which is not would appear to be useful in terms of the possible (motor) interactions with the environment and the perception of stimuli that are somehow relevant in terms of their proximity to the body of the observer. The existence of two different spatial representations (dichotomous vs. continuous) has been supported by the results of several studies (Caggiano et al., 2009; Makin et al., 2008). A study of sound localization in depth (Canzoneri et al., 2012) indicates that participants perceived the location of simulated approaching or receding unimodal stimuli in terms of a spatial continuum in depth. During audiotactile stimulation, however, RTs showed a somewhat steeper decrease at a certain distance from the observer, indicative of there being some kind of boundary in peripersonal space. Such a border was not observed when audiovisual stimuli were used (Teneggi et al., 2013), underlining the idea that multisensory interactions that involve tactile stimulation may display a dichotomous border for peripersonal space, perhaps due to the asymmetric nature of tactile perception.

Unlike tactile perception, auditory and visual perception are not constrained by the distance at which stimuli are presented. Consequently, audiovisual interactions do not show the same asymmetric effects as audiotactile and visuotactile interactions. Thus, multisensory interactions involving touch may be especially pronounced close to the body, given that spatial alignment in depth will always require that all unimodal component stimuli be presented in peripersonal space in alignment with the body.

8.3. Rear Peripersonal and Extrapersonal Space

The area of space behind the observer, which cannot be seen directly, provides an interesting opportunity to investigate the interactions taking place between auditory and somatosensory information. The distinction between peripersonal and extrapersonal space can also be made when it comes to the space behind the observer. The results of neurophysiological (Graziano & al., 1999) and neuropsychological studies (Farnè & Làvadas, 2002) have suggested that audiotactile spatial interactions may be more prevalent in near rear space than in frontal space. Kitagawa et al. (2005) have similarly shown that audiotactile interactions were greater when the auditory stimuli were presented close to (i.e., 20cm) rather than far from (i.e. 70cm) the back of the participant's head. Farnè and Làvadas (2002) have argued that this is because people will typically perceive an object's approach from behind by means of auditory cues (see also Kitagawa & Spence, 2006). It will be particularly important for future research to:

- assess whether spatial influences on audiotactile interactions are dependent on the particular body surface stimulated
- investigate the impact of spatial distance between auditory and somatosensory stimuli, particularly within rear space
- determine to what extent auditory-somatosensory interactions are coded in terms of the egocentric and/or external spatial position of the stimulated body surface

8.4. Body Posture and Sensory Deprivation

Tactile location has been demonstrated to be represented both in skin-based anatomical and external reference frames in a variety of tasks (Heed & Azañón, 2014; Overvliet, Azañón & Soto-Faraco, 2011; Harrar & Harris, 2010). Spatial transformations in touch are impaired by limb-crossing but are consistent with tactile location being recoded rapidly and efficiently, followed by integration of skin-based and external reference information to specify the reach target (Brandes & Heed, 2015). A 2016 study (Noel et al.) investigating the relative contribution of the different sensory systems under different body postures in a tactile temporal order judgment (TOJ), showed that mechanisms governing the alignment between somatotopic and external reference frames extend beyond those imposed by body posture to include spatial features conveyed by the auditory and visual modalities, with a heavier weighting of auditory than visual spatial information. More specifically, auditory, and auditory-visual deprivation exacerbated the difference in tactile temporal acuity between uncrossed to crossed leg postures, an effect not seen for visual-only deprivation. Furthermore, the effects under combined visual-auditory deprivation were greater than those seen for auditory deprivation. This result is of particular interest in the context of space operations where sensory cues are altered or missing.

9. Research Needs

9.1. Tactile Display Issues

While tactile technologies in some form have been developed for nearly 100 years, there are a number of research issues that still need to be addressed regarding the design and effectiveness of tactile feedback by itself as well as its integration with information presented in other modalities.

Current tactile devices have proven to be useful but are still largely limited to vibrotactile tactors like the ERM or pager motor type, and the LRA as used in the TSAS system. These devices have been used due to their low cost, smaller size, and relatively good control qualities. Future displays would greatly benefit from the development of tactors that have a wider dynamic range in terms of frequency and amplitude control, are power efficient, and are physically robust. In many of the complex task environments in which tactile displays are likely to be needed, the human user will be physically active and will need to be able to perform a wide range of different body motions and positions. Examples include impoverished and difficult task environments in military and aerospace applications such as helicopter flight during brown out conditions, soldiers conducting combat sorties, or EVA and planetary exploration tasks during space operations. Tactile displays under these conditions will need to be designed to maintain continuous contact with the skin, be well integrated with current combat gear or spacesuits, and present tactile signals of sufficient magnitude that they are readily attended to but not aversive.

Important questions also remain for the design and implementation of current tactile technologies, such as the optimal dimensions and configuration of tactile arrays and how they should change as a function of the display's purpose and the locus of presentation on the body. Array size has varied considerably and has often been determined by trial and error or practical limitations. High-density arrays have been used for systems that involve the densely innervated fingers such as reading aids for the blind. More spatially diffuse devices are typically used on less sensitive areas of the body such as the torso or arm. However, even on the torso the number of elements in the displays has ranged from 8 to 128 (Jones, Kunkel, & Piateski, 2009; Rupert, 2000; van Veen & van Erp, 2000). Psychophysical studies have shown that using larger arrays does not necessarily lead to superior perceptual performance in localization tasks, while using anatomical reference points such as the spine when positioning the tactile display does enhance localization accuracy (Cholewiak et al., 2004; van Erp, 2001). Given the range of possible users' body sizes, an important research question is whether it is better to use the available sensory area by adjusting intertactor distances to cover the skin surface or to maintain the same display dimensions for all users. The answer to this question will also likely depend upon the properties of the specific tactor being used.

Another issue for tactile display design is the trade-off between selecting the best body locus for the display and the constraints of real-world feasibility and user acceptance. Using sites with the highest cutaneous sensitivity, i.e., the fingers, tongue, and lips, is often not possible due either to interference with user tasks or the intrusiveness of such a display. Tactile patterns presented across a larger surface such as the back are easier to recognize than similar patterns presented on a smaller surface like the forearm (Jones, et al., 2006), although high recognition accuracy can be achieved for both with the careful selection of tactile patterns (Jones, et al., 2009). One possible solution to locating displays is to create wearable displays that integrate tactile technologies with devices that users already use such as headsets, seat surfaces, seatbelts, and combat gear. Particularly for military and aerospace applications, it may be desirable to integrate sensor and tactor technology into garments made with woven conductive fabrics that can be used for power and data transmission (Wade & Asada, 2006; Stoppa, & Chiolerio, 2014; Zeng, Shu, Li, Chen, Wang & Tao, 2014).

Research on tactile patterns and tactons has focused on their use in facilitating interactions with graphical interfaces (Brewster & Brown, 2004), for navigation and communication in hazardous environments (Jones, Kunkel, & Torres, 2007) and for human-robot interactions (Barber, Reinerman-Jones & Mathews, 2015). The number of tactons that are potentially available in these contexts will need to be determined from analyses of how the basic parameters of vibrotactile signals can be combined to create unique icons. Parameters, such as stimulus waveform, that may be useful for tactons displayed in handheld devices (Brown et al., 2005) may be ineffective in displays on other body sites. Further, the number of tactons that can be accurately identified depends on the degree of similarity among the various tactons (Enriquez et al., 2006; Jones, et al., 2009).

Another important issue is how individual differences impact the design of tactile displays that are intended for a wide range of users. For example, studies of the effect of aging on tactile perception indicate that older people have a reduced spatial acuity for most body locations (Stevens & Choo, 1996). In a study of narrowing of cross-modal attention, Hess and Sarter (2007) found that under conditions of high visual load, older drivers were significantly more likely to miss tactile cues than younger drivers. Such differences have important implications for the design of automotive or other in-vehicle interfaces.

Finally, it is necessary to develop ways of overcoming known limitations and breakdowns in tactile information processing related to factors such as masking and change blindness. Masking refers to a situation in which a tactile stimulus is not perceived when another tactile stimulus is presented immediately preceding or following that stimulus (Evans, 1987; Tan, Reed, Delhorne, Durlach, &Wan, 2003). Change blindness is a failure to detect a change in a tactile pattern when it is presented repeatedly in between other stimuli (Gallace, Tan, & Spence, 2006). The skin is highly subject to sensory adaptation and very little is known about the long-term effects of prolonged, but intermittent, cutaneous stimulation in tactile displays.

9.2. Multimodal Integration for Space Applications

NASA has identified a number of potentially significant biomedical risks that may limit deep space missions, including missions to the Moon and Mars. Among them, and relevant for the present report, are changes in eye-head-hand control, gaze function, postural and/or locomotor ability and perception (Bloomberg et al. 2015). Evidence from space flight research has demonstrated that the function of each of these subsystems is altered by removing gravity, a fundamental orientation reference for vestibular, proprioceptive, and haptic receptors used in the control of orientation, posture, navigation and coordination of movements. The decrement in sensation, and their consequences for perception and action, affects all the senses, although hearing function under microgravity has received little attention.

Space activities are also highly constrained by the affordances of the environment. In flight, the crew may experience a visual reorientation illusion (VRI) induced by the architectural symmetries of the cabin interior that typically defines multiple “visual vertical” directions, usually separated by 90º. When VRI occurs, crews lose their sense of direction with respect to the entire vehicle and reach or look in the wrong direction for remembered objects. Distortions of the visual space have also been reported and may influence astronauts’ ability to accurately perform cognitive and sensorimotor tasks, such as those involved in robotic operations. In space, the environment is not structured with a gravitational reference and a visual horizon, so perspective is irrelevant and astronauts perceive heights and depths of objects as taller and shallower on orbit, respectively (Clement et al., 2013). On surface, low visibility conditions and non-earth gravitational forces will likely impact inertial navigation. EVAs in space are uniquely defined by the loss of information normally provided by the auditory and somatosensory systems, and a restricted field of view. In this hostile environment, astronauts may not be able to keep a six-DoF situational awareness, in particular regarding potentially life-threatening objects approaching at high speed (extrapersonal space). Another critical aspect of EVAs in space is the absence of tactile feedback associated with operations, whether directly guided by hand or mediated by tool use (peripersonal space).

Therefore, different types of risks will be associated with different types of activities: rendezvous/docking and remote manipulator system operations, piloted landing, vehicle egress and extravehicular activities, and rover operations. Although the decrement in sensations under microgravity, and their consequences for perception and action, is relatively well documented at the level of each sensory system individually, less is known about interactions between the senses.

Furthermore, the role of tactile displays for space activities has been primarily investigated as a substitutive device for orientation and navigation within the spaceship.

The potential roles for the tactile inputs (redundancy, complementarity or substitution) need to be addressed in context (task and environment specific) and in interaction with the other senses. The first important aspect here is that there is a significant decrement in sensation associated with space operations. As a consequence, the normal contribution (weight) of each sensory modality to multimodal perception experienced on Earth will not be relevant in space, since the reliability of the different senses will change. In other words, the usual dominance of the visual cues in multisensory perception may be challenged, and the role of auditory and tactile cues may increase. It is, thus, fundamental to determine the role of each sensory modality, alone and in combination, for very specific tasks where multisensory information presentation would lead to performance and safety improvement. Last, the combined presentation of “real” and “virtual” information may also affect the way sensory modalities are integrated, and this aspect should be investigated.

References

Adelstein, B. D., Ho, P. & Kazerooni, H. A. **(1996) Kinematic design of a three degree of freedom parallel hand controller mechanism,** *Fifth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. Proceedings, Dynamic Systems and Control, DSC-Vol. 58, American Society of Mechanical Engineers, New York, 1996, pp. 539-546.*

Adelstein, B. D., Gayme, D. F., Kazerooni, H. A. & Ho, P. **(1998) Three degree of freedom haptic interface for precision manipulation**, *Proceedings, Dynamic Systems and Control, DSC-Vol. 64, American Society of Mechanical Engineers, New York, 1998, p. 185.*

Adelstein, B. D., Begault, D.R., Anderson, M. R. & Wenzel, E.M. (2003). Sensitivity to Haptic-Audio Asynchrony, *Fifth International Conference on Multimodal Interfaces*, November 5-7. Vancouver, British Columbia, Canada, pp. 73-76.

Adelstein, B. D., Lee, T. G. & Ellis, S. R. (2003) Head Tracking Latency in Virtual Environments: Psychophysics and a Model. *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting,* pp. 2083-2087.

Allison, R. S., Harris, L. R., Jenkin, M., Jasiobedzka, U., & Zacher, J. E. (2001) Tolerance of temporal delay in virtual environments. *Proceedings of Virtual Reality*, pp. 247-253.

Austen, E. L., Soto-Faraco, S., Pinel, J. P. J., & Kingstone, A. F. (2001). Virtual body effect: factors influencing visual-tactile integration. *Psychonomic Society*, *6*(2).

Azañón, E., & Soto-Faraco, S. (2008). Changing reference frames during the encoding of tactile events. *Current Biology*, 18(14), 1044-1049.

Bach-y-Rita, P., Collins, C. C., Saunders, F. A., White, B., & Scadden, L. (1969). Vision substitution by tactile image projection. *Nature*, 221, 963–964.

Barber, D. J., Reinerman-Jones, L. E. & Matthews, G. (2015). Toward a Tactile Language for Human–Robot Interaction: Two Studies of Tacton Learning and Performance, *Human Factors,* 57(3), 471-490.

Bau, O., Poupyrev, I., Israr, A. & Harrison, C. (2010). TeslaTouch: Electrovibration for Touch Surfaces. *User Interface Software and Technology*, October 3-6, 2010, New York: New York, USA.

Békésy, G., von. (1955). Human skin perception of traveling waves similar to those on the cochlea. *Journal of the Acoustical Society of America*, 27, 830–841.

Békésy, G., von. (1959). Synchronism of neural discharges and their demultiplication in pitch perception on the skin and in hearing. *Journal of the Acoustical Society of America*, 31, 338–349.

Békésy, G. von. (1962). Can we feel the nervous discharges of the end organs during vibratory stimulation of the skin? *Journal of the Acoustical Society of America*, 34, 850–856.

Benjamins, J. S., van der Smagt, M. J., & Verstraten, F. A. (2008). Matching auditory and visual signals: Is sensory modality just another feature? *Perception, 37,* 848–858.

Berger, A., Henik, A., & Rafal, R. (2005). Competition between endogenous and exogenous orienting of visual attention. *Journal of Experimental Psychology: General*, *134*(2), 207.

Bertelson, P. (1999). Ventriloquism: A case of crossmodal perceptual grouping. *Advances in psychology*, *129*, 347-362.

Bliss, J. C., Katcher, M. H., Rogers, C. H., & Shepard, R. P. (1970). Optical-to-tactile image conversion for the blind. *IEEE Transactions on Man-Machine Systems*, MMS-11, 58–65.

Bloomberg, J. J., Reschke, M. F., Clement, G. R., Mulavara, A. P., & Taylor, L. C. (2015). Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight. NASA HRP HHC Report.

Bolanowski, S. J., Gescheider, G. A., & Verrillo, R. T. (1994). Hairy skin: Psychophysical channels and their physiological substrates. Somatosensory and Motor Research, 11, 279–290.

Brandes, J., & Heed, T. (2015). Reach Trajectories Characterize Tactile Localization for Sensorimotor Decision Making. *The Journal of Neuroscience*, *35*(40), 13648-13658.

Bresciani, J. P., Dammeier, F., & Ernst, M. O. (2008). Tri-modal integration of visual, tactile and auditory signals for the perception of sequences of events. *Brain research bulletin*, *75*(6), 753-760.

Brewster, S. A., & Brown, L. M. (2004). Tactons: Structured tactile messages for non-visual information display. In *Proceedings of the 5th Australasian User Interface Conference* (pp. 15–23). Sydney, Australia: Australian Computer Society.

Brewster, S. A., & King, A. (2005). The design and evaluation of a vibrotactile progress bar. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 499–500). Los Alamitos, CA: IEEE Computer Society.

Brill, J. C., Lawson, B. D., & Rupert, A. H. (2015). Audiotactile aids for improving pilot situation awareness. In *Proceedings of the International Symposium for Aviation Psychology*, May 4-7, Dayton, OH, 13-18.

Brown, L. M., Brewster, S. A., & Purchase, H. C. (2005). A first investigation into the effectiveness of tactons. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 167–176). Los Alamitos, CA: IEEE Computer Society.

Caggiano, V., Fogassi, L., Rizzolatti, G., Thier, P., & Casile, A. (2009). Mirror neurons differentially encode the peripersonal and extrapersonal space of monkeys. *Science*, *324*(5925), 403-406.

Canzoneri, E., Magosso, E., & Serino, A. (2012). Dynamic sounds capture the boundaries of peripersonal space representation in humans. *PloS one*, *7*(9), e44306.

Chan, A., MacLean, K. E., & McGrenere, J. (2005). Learning and identifying haptic icons under workload. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 432–439). Los Alamitos, CA: IEEE Computer Society.

Cholewiak, R. W. (1979). Spatial factors in the perceived intensity of vibrotactile patterns. *Sensory Processes,* 3, 141–156.

Cholewiak, R. W., Brill, J. C., & Schwab, A. (2004). Vibrotactile localization on the abdomen: Effects of place and space. *Perception and Psychophysics*, 66, 970–987.

Cholewiak, R. W., & Collins, A. A. (2000). The generation of vibrotactile patterns on a linear array: Influences of body site, time and presentation mode. *Perception and Psychophysics*, 62, 1220–1235.

Clément, G., Skinner, A., & Lathan, C. (2013). Distance and size perception in astronauts during long-duration spaceflight. *Life*, *3*(4), 524-537.

Cohen, Y. E., & Andersen, R. A. (2002). A common reference frame for movement plans in the posterior parietal cortex. *Nature Reviews: Neuroscience*, *3*(7), 553-562.

Colonius, H., & Diederich, A. (2012). Focused attention vs. crossmodal signals paradigm: deriving predictions from the time-window-of-integration model. *Frontiers in integrative neuroscience*, *6*(62).

Craig, J. C. (1972). Difference threshold for intensity of tactile stimuli. *Perception and Psychophysics*, 11, 150–152.

Craig, J. C., & Rollman, G. B. (1999). Somesthesis. *Annual Review of Psychology*, *50*(1), 305-331.

Culler, E., Coakley, J. D., Lowy, K., & Gross, N. (1943). A revised frequency-map of the guinea-pig cochlea. *The American Journal of Psychology*, *56*(4), 475-500.

Downar, J., Crawley, A. P., Mikulis, D. J., & Davis, K. D. (2000). A multimodal cortical network for the detection of changes in the sensory environment. *Nature neuroscience*, *3*(3), 277-283.

Driver, J., & Spence, C. (1998). Attention and the crossmodal construction of space. *Trends in cognitive sciences*, *2*(7), 254-262.

Ellis, S.R., Young, M.J., Ehrlich, S.M., & Adelstein, B.D. (1999a) Discrimination of changes of rendering latency during voluntary hand movement. *Proceedings, 43rd Annual Meeting HFES,* pp. 1182-1186.

Ellis, S.R., Young, M.J., Adelstein, B.D., & Ehrlich, S.M. (1999b) Discrimination of changes in latency during head movement. *Proceedings, Computer Human Interfaces,* pp. 1129-1133.

Enriquez, M., MacLean, K. E., & Chita, C. (2006). Haptic phonemes: Basic building blocks of haptic communication. In *Proceedings of the 8th International Conference on Multimodal Interfaces (ICMI'06)* (pp. 302–309). Los Alamitos, CA: IEEE Computer Society.

Eskildsen, P., Morris, A., Collins, C. C., & Bach-y-Rita, P. (1969). Simultaneous and successive cutaneous two-point threshold for vibration. *Psychonomic Science*, 14, 146–147.

European Telecommunications Standards Institute. (2002). *Human factors (HF); Guidelines on the multimodality of icons, symbols and pictograms (ETSI EG 202 048)*. Sophia Antipolis, France: Author.

Evans, P. M. (1987). Vibrotactile masking: Temporal integration, persistence, and strengths of representations. *Perception and Psychophysics*, 42, 515–525.

Farnè, A., & Làdavas, E. (2002). Auditory peripersonal space in humans. *Journal of Cognitive Neuroscience*, *14*(7), 1030-1043.

Ferris, T. K., & Sarter, N. (2011). Continuously informing vibrotactile displays in support of attention management and multitasking in anesthesiology. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *53*(6), 600-611.

Fong, T., Abercromby, A., Bualat, M. G., Deans, M. C., Hodges, K. V., Hurtado Jr., J., Landis, R., Lee, P., & Schreckenghost, D. (2010) Assessment of robotic recon for human exploration of the Moon. *Acta Astronautica,* Vol. 67, pp. 9-10.

Foster, B., Cavina-Pratesi, C., Aglioti, S. M., & Berlucchi, G. (2002). Redundant target effect and intersensory facilitation from visual-tactile interactions in simple reaction time. *Experimental Brain Research*, **143**, 480–487.

Fujisaki, W., & Nishida, S. Y. (2005). Temporal frequency characteristics of synchrony–asynchrony discrimination of audio-visual signals. *Experimental Brain Research*, *166*(3-4), 455-464.

Fujisaki, W., & Nishida, S. Y. (2009). Audio–tactile superiority over visuo–tactile and audio–visual combinations in the temporal resolution of synchrony perception. *Experimental brain research*, *198*(2-3), 245-259.

Gallace, A., Tan, H. Z., & Spence, C. (2006). Failure to detect tactile change: A tactile equivalent to the change blindness phenomenon. *Psychonomic Bulletin and Review*, 13, 300–303.

Geldard, F. A. (1957). Adventures in tactile literacy. *American Psychologist*, 12, 115–124.

Geldard, F. A. (1960). Some neglected possibilities of communication. *Science*, 131, 1583–1588.

Geldard, F. A. (1975). *Sensory saltation*. Hillsdale, NJ: Erlbaum.

Geldard, F. A., & Sherrick, C. E. (1972). The cutaneous "rabbit": A perceptual illusion. *Science*, 178, 178–179.

Germani, M., Mengoni, M., Peruzzini, M. (2013) Electro-tactile device for material texture simulation. *International Journal of Advanced Manufacturing Technology*, 68(9), 2185–2203.

Gescheider, G. A. (1965). Cutaneous sound localization. *Journal of Experimental Psychology*, 70, 617–625.

Gescheider, G. A., Bolanowski, S. J., Pope, J. V., & Verrillo, R. T. (2002). A four-channel analysis of the tactile sensitivity of the fingertip: Frequency selectivity, spatial summation, and temporal summation. *Somatosensory and Motor Research,* 19, 114–124.

Giang, W., Santhakumaran, S., Masnavi, E., Glussich, D., Kline, J., Chui, F., Burns, C., Histon, J. & Zelek, J. (2010). *Multimodal Interfaces: Literature Review of Ecological Interface Design, Multimodal Perception and Attention, and Intelligent Adaptive Multimodal Interfaces.* Defence R&D Canada Contract Report DRDC Toronto CR 2010-051

Gilson, R. D., Redden, E. S., & Elliott, L. R. (2007). *Remote tactile displays for future soldiers*. (Tech. Rep. ARL-SR-0152.) Aberdeen Proving Ground, MD: Army Research Laboratory.

Goff, G. (1967). Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology*, 74, 294–299.

Gray, R., & Tan, H. Z. (2002). Dynamic and predictive links between touch and vision. *Experimental Brain Research*, *145*(1), 50-55.

Gray, R., Spence, C., Ho, C. & Tan, H. Z. (2013). Efficient multimodal cuing of spatial attention. *Proceedings of the IEEE,* 101(9), 2113-2122.

Graziano, M. S., Reiss, L. A., & Gross, C. G. (1999). A neuronal representation of the location of nearby sounds. *Nature*, *397*(6718), 428-430.

Hairston, W. D., Wallace, M. T., Vaughan, J. W., Stein, B. E., Norris, J. L., & Schirillo, J. A. (2003). Visual localization ability influences cross-modal bias. *Journal of cognitive neuroscience*, *15*(1), 20-29.

Hale, K. S., & Stanney, K. M. (2004). Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundation. *IEEE Computer Graphics and Applications*, 24, 33–39.

Hameed, S., Ferris, T., Jayaraman, S., & Sarter, N. B. (2006). Supporting interruption management through informative tactile and peripheral visual cues. In *Proceedings of the Human Factors* *and Ergonomics Society 50th Annual Meeting* (pp. 376–380). Santa Monica, CA: Human Factors and Ergonomics Society.

Harrar, V., & Harris, L. R. (2010). Touch used to guide action is partially coded in a visual reference frame. *Experimental brain research*, *203*(3), 615-620.

Harrington, L. K., & Peck, C. K. (1998). Spatial disparity affects visual-auditory interactions in human sensorimotor processing. *Experimental Brain Research*, *122*(2), 247-252.

Heed, T., & Azañón, E. (2014). Using time to investigate space: a review of tactile temporal order judgments as a window onto spatial processing in touch. *Front. Psychol*, *5*, 76.

Hess, W. J., & Sarter, N. B. (2007). Crossmodal and intramodal attentional narrowing and its interaction with aging. Unpublished Manuscript.

Ho, C., Reed, N. & Spence, C. (2007). 'Multisensory in-car warning signals for collision avoidance. *Human Factors*, 49, 1107–1114.

Holmes, N. P. (2009). The principle of inverse effectiveness in multisensory integration: some statistical considerations. *Brain topography*, *21*(3-4), 168-176.

Hughes, H. C., Reuter-Lorenz, P. A., Nozawa, G., & Fendrich, R. (1994). Visual-auditory interactions in sensorimotor processing: saccades versus manual responses. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(1), 131.

Jones, L. A., Kunkel, J., & Piateski, E. (2009). Vibrotactile pattern recognition on the arm and back. *Perception,* 38, 52-68..

Jones, L. A., Kunkel, J., & Torres, E. (2007). Tactile vocabulary for tactile displays. In *Proceedings of the Second Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 574–575). Los Alamitos, CA: IEEE Computer Society.

Jones, L. A., Lockyer, B., & Piateski, E. (2006). Tactile display and vibrotactile recognition on the torso. *Advanced Robotics*, 20, 1359–1374.

Jones, L. A. & Sarter, N. B. (2008). Tactile Displays: Guidance for Their Design and Application, *Human Factors*, 50(1), 90-110.

Kaaresoja, T., & Linjama, J. (2005). Perception of short tactile pulses generated by a vibration motor in a mobile phone. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 471–472). Los Alamitos, CA: IEEE Computer Society.

Kaber, D. B., Perry, C. M., Segall, N., McClernon, C. K., & Prinzel, L. J. (2006). Situation awareness implications of adaptive automation for information processing in an air traffic control-related task. *International Journal of Industrial Ergonomics*, *36*(5), 447-462.

Kaczmarek, K. A., & Bach-y-Rita, P. (1995). Tactile displays. In W. Barfield & T. A. Furness (Eds.), *Virtual environments and advanced interface design* (pp. 349–414). New York: Oxford University Press.

Kaczmarek, K. A., & Haase, S. J. (2003). Pattern identification as a function of stimulation current on a fingertip-scanned electrotactile display. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 11, 269–275.

Kaczmarek, K. A., Webster, J. G., Bach-y-Rita, P., & Tompkins, W. J. (1991). Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Transactions on Biomedical Engineering,* 38, 1–16.

Kandula, M., Hofman, D., & Dijkerman, H. C. (2015). Visuo-tactile interactions are dependent on the predictive value of the visual stimulus.*Neuropsychologia*, *70*, 358-366.

Keetels, M., & Vroomen, J. (2005). The role of spatial disparity and hemifields in audio-visual temporal order judgments. *Experimental Brain Research*, *167*(4), 635-640.

Keetels, M., & Vroomen, J. (2008). Tactile—visual temporal ventriloquism: No effect of spatial disparity. *Perception & Psychophysics*, *70*(5), 765-771.

Kitagawa, N., Zampini, M., & Spence, C. (2005). Audiotactile interactions in near and far space. *Experimental Brain Research*, *166*(3-4), 528-537.

Klein, R. M. (2000). Inhibition of return. *Trends in cognitive sciences*, *4*(4), 138-147.

Kleiner, J. S. (2011). Somatotopic Organization. *Encyclopedia of Clinical Neuropsychology*.

Làdavas, E. (2002). Functional and dynamic properties of visual peripersonal space. *Trends in cognitive sciences*, *6*(1), 17-22.

Laurienti, P. J., Kraft, R. A. Maldjian, J. A., Burdette, J. H. & M. T. Wallace, M. T. (2004). Semantic congruence is a critical factor in multisensory behavioral performance. *Experimental Brain Research,* 158, 405–414.

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in cognitive sciences*, *9*(2), 75-82.

Lee, J. D., McGehee, D. V., Brown, T. L. & Marshall, D. (2006). Effects of adaptive cruise control and alert modality on driver performance. Transp. Res. Record, 1980, 49–56.

Lester, D. & Thronson, H. (2011) Low-Latency Lunar Surface Telerobotics from Earth-Moon Libration Points. *Proceedings of the AIAA SPACE 2011 Conference & Exposition,* Long Beach, California, September 27-29.

Lévesque, V., Pasquero, J., Hayward, V., & Legault, M. (2005). Display of virtual Braille dots by lateral skin deformation: Feasibility study. *ACM Transactions on Applied Perception*, 2, 132–149.

Lindeman, R. W., Sibert, J. L., Lathan, C. E., & Vice, J. M. (2004). The design and deployment of a wearable vibrotactile feedback system. In *Proceedings of the Eighth International Symposium on Wearable Computers* (pp. 56–59). Los Alamitos, CA: IEEE Computer Society.

Lindeman, R. W., & Yanagida, Y. (2003). Empirical studies for effective near-field haptics in virtual environments. In *Proceedings of the IEEE Virtual Reality Conference* (pp. 287–288). Los Alamitos, CA: IEEE Computer Society.

Lindeman, R. W., Yanagida, Y., Noma, H., & Hosaka, K. (2006). Wearable vibrotactile systems for virtual contact and information display. *Virtual Reality*, 9, 203–213.

MacGrath, B. J., Estrada, A., Braithwaite, M. G., Raj, A. K., & Rupert, A. H. (2004). Tactile situation awareness system flight demonstration final report (USAARL Rep. 2004-10). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.

MacLean, K., & Enriquez, M. (2003). Perceptual design of haptic icons. In *Proceedings of Eurohaptics* (pp. 351–363). Dublin, Ireland: Trinity College.

MacLean, K. E. (2008). Foundations of transparency in tactile information design. *IEEE Transactions on Haptics*, *1*(2), 84-95.

Mahns, D. A., Perkins, N. M., Sahai, V., Robinson, L., & Rowe, M. J. (2006). Vibrotactile frequency discrimination in human hairy skin. *Journal of Neurophysiology*, 95, 1442–1450.

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: dummy hands and peripersonal space. *Behavioural brain research*, *191*(1), 1-10.

Mengoni, M., Colaiocco, B., Peruzzini, M., & Germani, M. (2010). Design of a Tactile Display to Support Materials Perception in Virtual Environments. *IEEE Virtual Reality 2011,* 19 - 23 March, Singapore, 227-228.

Meredith, M. A., & Stein, B. E. (1983). Interactions among converging sensory inputs in the superior colliculus. *Science*, *221*(4608), 389-391.

Mohebbi, R., Gray, R., & Tan, H. Z. (2009). Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *51*(1), 102-110.

Morley, J. W., & Rowe, M. J. (1990). Perceived pitch of vibrotactile stimuli: Effects of vibration amplitude, and implications for vibration frequency coding. *Journal of Physiology*, 431, 403–416.

Mowbray, G. H., & Gebhard, J. W. (1957). Sensitivity of the skin to changes in rate of intermittent mechanical stimuli. *Science*, 125, 1297–1298.

Myles, K. P. & Binseel, M. S. (2015). Exploring the tactile modality for HMDs. In *Helmet-Mounted Displays: Sensation, Perception and Cognition Issues.* Rash, C. E., Russo, M. B., Letowski, T. R. & Schmeisser, E. T. (Eds.), Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory, 849-875.

Naumberg, R. E. (1931). Apparatus for translating impressions. *U.S. Patent No.* 1828198 A. Washington, DC: U.S. Patent and Trademark Office.

Ngo, M. K., Pierce, R. & Spence, C. (2012). Utilizing multisensory cues to facilitate air traffic management. *Human Factors,* 54, 1093–1103.

Noel, J. P., Łukowska, M., Wallace, M., & Serino, A. (2016). Multisensory simultaneity judgment and proximity to the body. *Journal of vision*, *16*(3), 21-21.

Oakley, I., Kim, Y., Lee, J., & Ryu, J. (2006). Determining the feasibility of forearm mounted vibrotactile displays. In *Proceedings of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 27–34). Los Alamitos, CA: IEEE Computer Society.

Occelli, V., Spence, C., & Zampini, M. (2011). Audiotactile interactions in front and rear space. *Neuroscience & Biobehavioral Reviews*, *35*(3), 589-598.

Oskarsson, P.-E., Eriksson, L. & Carlander, O. (2012). Enhanced perception and performance by multimodal threat cueing in a simulated combat vehicle. *Human Factors*, 54, 122–137.

Overvliet, K. E., Azañón, E., & Soto-Faraco, S. (2011). Somatosensory saccades reveal the timing of tactile spatial remapping. *Neuropsychologia*, *49*(11), 3046-3052.

Pasquero, J. (2006). *Survey on communication through touch* (Tech. Rep. TR-CIM 06.04). Montreal, Canada: McGill University, Department of Electrical and Computer Engineering, Center for Intelligent Machines.

Pavani, F., Spence, C., & Driver, J. (2000). Visual capture of touch: Out-of-the-body experiences with rubber gloves. *Psychological science*, *11*(5), 353-359.

Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain: A journal of neurology*.

Persterer, A., Opitz, M., Koppensteiner, C., Nefjodova, M., Müller, C., & Berger, M. (1993). Audimir: Directional hearing at microgravity. *Journal of the Audio Engineering Society*, *41*(4), 239-247.

Podnar, G. Dolan, J. & Elfes, A. (2010) Telesupervised Robotic Systems and the Human Exploration of Mars. *Journal of Cosmology*, Vol. 12, pp. 4058-4067.

Popper, K. R., & Eccles, J. C. (1977). The self and its brain. *Springer International*.

Poupyrev, I., Maruyama, S., & Rekimoto, J. (2002). Ambient touch: Designing tactile interfaces for handheld devices. In *Proceedings of the ACM Symposium on User Interface Software and Technology* (Vol. 4, pp. 51–60). New York: Association for Computing Machinery Press.

Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological bulletin*, *124*(2), 123.

Priplata, A. A., Niemi, J. B., Harry, J. D., Lipsitz, L. A., & Collins, J. J. (2003). Vibrating insoles and balance control in elderly people. *Lancet,* 362, 1123–1124.

Reed, C. M., & Delhorne, L. A. (1995). Current results of a field study of adult users of tactile aids. *Seminars in Hearing*, 16, 305–315.

Reed, C. M., & Delhorne, L. A. (2003). The reception of environmental sounds through wearable tactual aids. *Ear and Hearing*, 24, 528–538.

Rinker, M. A., Craig, J. C., & Bernstein, L. E. (1998). Amplitude and period discrimination of haptic stimuli. *Journal of the Acoustical Society of America*, 104, 453–463.

Roberts, J. C., & Franklin, K. (2005). Haptic glyphs (Hlyphs) – Structured haptic objects for haptic visualization. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 369–374). Los Alamitos, CA: IEEE Computer Society.

Rochlis, J. L., & Newman, D. J. (2000). A tactile display for International Space Station (ISS) extravehicular activity (EVA). *Aviation, Space, and Environmental Medicine*, 7, 571–578.

Rollman, G. B. (1973). Electrocutaneous stimulation. In F. Geldard (Ed.), *Cutaneous communication systems and devices* (pp. 38–51). Austin, TX: Psychonomic Society.

Rothenberg, M., Verrillo, R. T., Zahorian, S. A., Brachman, M. L., & Bolanowski, S. J. (1977). Vibrotactile frequency for encoding a speech parameter. *Journal of the Acoustical Society of America,* 62, 1003–1012.

Rupert, A.H., et al. (1996). Tactile Interface to Improve Situation Awareness. *Aviation, Space, and Environmental Medicine.* 67(A10): p. 53.

Rupert, A. H. (2000). An instrumentation solution for reducing spatial disorientation mishaps: A more "natural" approach to maintaining spatial orientation. *IEEE Engineering in Medicine and Biology Magazine,* March/April, 71–80.

Santangelo, V., & Spence, C. (2009). Crossmodal exogenous orienting improves the accuracy of temporal order judgments. *Experimental brain research*, *194*(4), 577-586.

Sarter, N. B. (2006). Multimodal information presentation: Design guidance and research challenges. *International Journal of Industrial Ergonomics*, 36, 439–445.

Saunders, F. A. (1973). Electrocutaneous displays. In F. Geldard (Ed.), *Cutaneous communication systems and devices* (pp. 20–26). Austin, TX: Psychonomic Society.

Sheridan, T., (1993) Space Teleoperation Through Time Delay: Review and Prognosis." *IEEE Transactions of Robotics and Automation*, Vol. 9, No. 5, pp. 592-605.

Sherrick, C. E. (1985). A scale for rate of tactual vibration. *Journal of the Acoustical Society of America*, 78, 78–83.

Schmidt, G. R., Landis, G. A & Oleson, S. R. (2012) HERRO Missions to Mars and Venus Using Telerobotic Surface Exploration from Orbit. *43rd Lunar and Planetary Science Conference.*

Spence, C. (2010). Crossmodal spatial attention. *Annals of the New York Academy of Sciences*, *1191*(1), 182-200.

Spence, C. (2013). Just how important is spatial coincidence to multisensory integration? Evaluating the spatial rule. *Annals of the New York Academy of Sciences*, *1296*(1), 31-49.

Spence, C., & Driver, J. (2000). Attracting attention to the illusory location of a sound: reflexive crossmodal orienting and ventriloquism. *Neuroreport*,*11*(9), 2057-2061.

Spence, C., & Gallace, A. (2007). Recent developments in the study of tactile attention. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *61*(3), 196.

Spence, C. &. Ho, C. (2008). Tactile and multisensory spatial warning signals for drivers. *IEEE Transactions on Haptics,* 1(2), 121–129, Jul.–Dec. 2008.

Spence, C., & McDonald, J. (2004). *Of the Exogenous Spatial Orienting of Attention*. *The handbook of multisensory processes*, 3.

Spence, C., Shore, D. I., & Klein, R. M. (2001). Multisensory prior entry. *Journal of Experimental Psychology: General*, *130*(4), 799.

Spirkovska, L. (2005). *Summary of Tactile User Interfaces, Techniques and Systems.*NASA Technical Memorandum, TM-2005-213451.

Stein, B. E., Meredith, M. A., Huneycutt, W. S., & McDade, L. (1989). Behavioral indices of multisensory integration: orientation to visual cues is affected by auditory stimuli. *Cognitive Neuroscience, Journal of*, *1*(1), 12-24.

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. The MIT Press.

Stein, B. E., London, N., Wilkinson, L. K., & Price, D. D. (1996). Enhancement of perceived visual intensity by auditory stimuli: a psychophysical analysis. *Cognitive Neuroscience, Journal of*, *8*(6), 497-506.

Stein, B. E., & Stanford, T. R. (2008). Multisensory integration: current issues from the perspective of the single neuron. *Nature Reviews Neuroscience*, *9*(4), 255-266.

Stevens, J. C., & Choo, K. K. (1996). Spatial acuity of the body surface over the life span. *Somatosensory and Motor Research,* 13, 153–166.

Stevens, S. S. (1968). Tactile vibration: Change of exponent with frequency. *Perception and Psychophysics*, 3, 223–228.

Stoppa, M. & Chiolerio, A. (2014). Wearable Electronics and Smart Textiles: A Critical Review. *Sensors*, *14*(7), 11957-11992. www.mdpi.com/journal/sensors; doi:10.3390/s140711957

Summers, I. R. (2000). Single-channel information transfer through the skin: Limitations and possibilities. In *Proceedings of the 6th International Conference on Tactile Aids, Hearing Aids and Cochlear Implants* (pp. 105–108). Exeter, UK: University of Exeter.

Summers, I. R., Cooper, P. G., Wright, P., Gratton, D. A., Milnes, P., & Brown, B. H. (1997). Information from time-varying vibrotactile stimuli. *Journal of the Acoustical Society of America*, 102, 3686–3696.

Summers, I. R., Dixon, P. R., Cooper, P. G., Gratton, D. A., Brown, B. H., & Stevens, J. C. (1994). Vibrotactile and electrotactile perception of time-varying pulse trains. *Journal of the Acoustical Society of America*, 95, 1548–1558.

Tan, H., Lim, A., & Traylor, R. (2000). A psychophysical study of sensory saltation with an open response paradigm. In S. S. Nair (Ed.), *Proceedings of the Ninth (9th) International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, American Society of Mechanical Engineers Dynamic Systems and Control Division*, 69(2), 1109–1115.

Tan, H. Z., Gray, R., Young, J. J., & Traylor, R. (2003, June 11). A haptic back display for attentional and directional cueing. *Haptics-e*, 3, Article 1. Retrieved May 16, 2016, from http://haptics-e.org/Vol_03/he-v3n1.pdf

Tan, H. Z., Reed, C. M., Delhorne, L. A., Durlach, N. I., & Wan, N. (2003). Temporal masking of multidimensional tactual stimuli. *Journal of the Acoustical Society of America*, 114, 3295-3308.

Teneggi, C., Canzoneri, E., Di Pellegrino, G., & Serino, A. (2013). Social modulation of peripersonal space boundaries. *Current biology*, *23*(5), 406-411.

Traylor, R., & Tan, H. Z. (2002). Development of a wearable haptic display for situation awareness in altered-gravity environment: Some initial findings. In *10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperation Systems* (pp. 159–164). Los Alamitos, CA: IEEE Computer Society.

Valinia, A., Garvin, J. B., Vondrak, R., Thronson, H., Lester, D., Schmidt, G., Fong, T., Wilcox, B., Sellers, P. & White, N. (2012) Low-Latency Telerobotics from Mars Orbit: The Case for Synergy Between Science and Human Exploration, *First Exploration Telerobotics Symposium,* NASA Goddard Space Flight Center.

Van der Stoep, N., Nijboer, T.C.W., Van der Stigchel, S. & Spence, C. (2015). Multisensory interactions in the depth plane in front and rear space: A review, *Neuropsychologia, 70,* 335-349. https://doi.org/10.1016/j.neuropsychologia.2014.12.007 https://www.sciencedirect.com/science/article/abs/pii/S0028393214004618?dgcid=api_sd_search-api-endpoint

van Erp, J. B. F. (2001). Tactile navigation display. In S. Brewster & R. Murray-Smith (Eds.), *Haptic HCI 2000* (pp. 165–173). Berlin: Springer-Verlag.

van Erp, J. B. F. (2005). Presenting directions with a vibrotactile torso display. *Ergonomics,* 48, 302–313.

van Erp, J. B., Eriksson, L., Levin, B., Carlander, O., Veltman, J. A., & Vos, W. K. (2007). Tactile cueing effects on performance in simulated aerial combat with high acceleration. *Aviation, Space, and Environmental Medicine*, *78*(12), 1128-1134.

van Erp, J. B. F. & Self, B. P. (Eds.) (2008). *Tactile Displays for Orientation, Navigation and Communication in Air, Sea and Land Environments.* NATO RTO Technical Report, TR-HFM-122.

van Erp, J. B. F., van Veen, A. H. C. (2003). A Multi-purpose Tactile Vest for Astronauts in the International Space Station. *Proceedings of EuroHaptics*, Dublin, Ireland, Trinity College, 405-408.

van Erp, J. B. F. & van Veen, H., (2004). Vibrotactile in-vehicle navigation system. *Transportation Research Part F: Traffic Psychology and Behavior,* 7, 247–256.

van Erp, J. B. F., van Veen, A. H. C. (2006). Touch down: The effect of artificial touch cues on orientation in microgravity. *Neuroscience Letters*, 404, 78–82

van Erp, J. B. F., van Veen, A. H. C., Jansen, C., & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception*, 2, 106–117.

van Erp, J.B.F., Van Veen, H.A.H.C. & Ruijsendaal, M. (2007). More than a feeling: bringing touch into astronauts' spatial orientation. *Microgravity Science and Technology*. 19 (5), 108-112.

van Veen, H. A. H. C., & van Erp, J. B. F. (2000). Tactile information presentation in the cockpit. In S. Brewster & R. Murray-Smith (Eds.), *Haptic HCI 2000* (pp. 174–181). Berlin: Springer Verlag.

van Veen, H. A. H. C., & van Erp, J. B. F. (2003). Providing directional information with tactile torso displays. Eurohaptics, 471–474.

van Wassenhove, V., Grant, K. W., & Poeppel, D. (2007). Temporal window of integration in auditory-visual speech perception. *Neuropsychologia*, *45*(3), 598-607.

Verrillo, R. T., & Chamberlain, S. C. (1972). The effect of neural density and contactor surround on vibrotactile sensation magnitude. *Perception and Psychophysics*, 11, 117–120.

Verrillo, R. T., Fraioli, A. J., & Smith, R. L. (1969). Sensation magnitude of vibrotactile stimuli. Perception and Psychophysics, 6, 366–372.

Weinstein, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. R. Kenshalo (Ed.), *The Skin Senses* (pp. 195–222). Springfield, IL: Charles C. Thomas.

Wenzel, E. M. (2001). Effect of increasing system latency on localization of virtual sounds with short and long duration*. Proceedings of the International Conference on Auditory Display, ICAD 2001,* Espoo, Finland, July 29-August 1, pp. 185-190.

Wenzel, E. M. & Godfroy-Cooper, M. (2015). Multimodal augmented displays for surface telerobotic missions. NASA HRP-SHFH Report.

Woods, D. D. (1995). The alarm problem and directed attention in dynamic fault management. *Ergonomics,* 38, 2371–2393.

Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: a tutorial review. *Attention, Perception, & Psychophysics*, *72*(4), 871-884.

Yost, W.A. (2000). *Fundamentals of hearing*, Academic Press, New York.

Zampini, M., Guest, S., Shore, D. I., & Spence, C. (2005a). Audio-visual simultaneity judgments. *Perception & psychophysics*, *67*(3), 531-544.

Zampini, M., Brown, T., Shore, D. I., Maravita, A., Röder, B., & Spence, C. (2005b). Audiotactile temporal order judgments. *Acta psychologica*, *118*(3), 277-291.

Zampini, M., Torresan, D., Spence, C., & Murray, M. M. (2007). Auditory–somatosensory multisensory interactions in front and rear space. *Neuropsychologia*, *45*(8), 1869-1877.

Zeng, W., Shu, L., Li, Q., Chen, S., Wang, F. & Tao, X. M. (2014). Fiber-Based Wearable Electronics: A Review of Materials, Fabrication, Devices, and Applications. *Advanced Materials.* 2014, 26, 5310–5336.