#### FORUM Short Paper

# Perspectives on the Evolution of Tactile, Haptic, and Thermal Displays

Editors' Note: To celebrate Presence's 25th year of publication, we have invited selected members of the journal's original editorial board and authors of several early articles to contribute essays looking back on the field of virtual reality, from its very earliest days to the current time. This essay comes from founding editorial board member Lynette Jones, who highlights the fundamental research that is still needed to make haptic and thermal devices light, energy efficient and intuitive to use.

## I Introduction, History, and Discussion

The field of haptics has matured considerably over the past 25 years as reflected in the evolution of articles published in Presence. Several themes in the hapticsrelated articles published in the early days of the journal such as the development of tactile and haptic interfaces based on novel actuator technology and the optimization of force feedback in teleoperated systems (e.g., Buttolo, Braaathen, & Hannaford, 1994; Ishii & Sato, 1994; Kontarinis & Howe, 1995; Monkman, 1992) continue to be a major research focus in the field (Abuhamdia & Rosen, 2013; Yang, Ryu, Park, & Kang, 2012). New areas of research have emerged with the increasing dominance of touch screen devices in human-computer interactions which lack tactile feedback. To address this limitation, considerable effort has been expended to make these surfaces tangible so that the virtual objects represented visually can also be experienced tactually (Vezzoli et al., 2015; Wiertlewski & Colgate, 2015). There has also been a resurgence of interest in the creation of wearable haptic displays with the advent of new head-mounted displays, such as Oculus Rift and Microsoft HoloLens, so that there is a physical connection to the virtual world.

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Attempts to use tactile displays and the sense of touch as a medium of communication date back to the late 1950s; progress was relatively slow over the next 35 years in part due to the size and power requirements of the actuator technology. However, with the widespread availability of small, low-cost actuators and controllers in the 1990s, the potential of wearable tactile displays became evident (Gallace, Tan, & Spence, 2007; Jones & Sarter, 2008). By the early 2000s, numerous studies had been conducted to evaluate the effectiveness of tactile displays in a variety of contexts from teleoperation (Kontarinis & Howe, 1995; Massimino & Sheridan, 1993) to navigation (Jones, Kunkel, & Piateski, 2009; van Erp, van Veen, Jansen, & Dobbins, 2005) and surgical training (Santos-Carreras, Leuenberger, Samur, Gassert, & Bleuler, 2012). Many of these studies demonstrated that vibrotactile displays are effective in assisting with spatial orientation and navigation in both real and virtual environments. In virtual training environments such as those simulating cloud flying or flying under high-G load conditions, vibrotactile stimuli have been shown to be effective in providing information about the intended direction of movement and the pitch and roll of an aircraft (Rupert, 2000; van Veen & Van Erp, 2000). In more general applications, such as moving through a virtual environment, tactile displays can provide information about potential collisions and obstacles (Bloomfield & Badler, 2008; Lindeman, Templeman, Sibert, & Cutler, 2002). The tactile displays used in these applications are typically belts or vests attached to

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the torso and so the spatial information comes from the location of the activated motor on the body. It appears to be very intuitive for people to perceive an external direction emanating from a single point of stimulation on the skin or from a directional sequence of mechanical inputs across the skin surface.

Over the past 15 years, we have seen an expansion in the range of applications of tactile and haptic displays with more robust, compact, and easily controllable actuators becoming readily available. For tactile displays, small vibrating motors dominate many of these applications due to their size, availability, cost, and low power requirements. Such motors are now pervasive in consumer electronic devices such as cell phones, watches, fitness trackers, and gaming controllers and are increasingly used in other applications (Koskinen, Kaaresoja, & Laitinen, 2008). For example, vibrotactile actuators affixed to steering wheels or seats in vehicles provide tactile cues that are used to alert drivers regarding the safety of impending lane changes or the proximity of other vehicles or obstacles in both real and virtual environments (Gallace & Spence, 2014; Ho, Reed, & Spence, 2006; Scott & Gray, 2008).

Many different actuator technologies have been used to create tactile and haptic displays including eccentric rotating mass motors, linear resonant actuators, voice coil motors, shape memory alloy actuators, piezoelectric actuators, and electroactive polymer actuators (Jones & Held, 2008; Yao & Hayward, 2010). These actuators vary with respect to their bandwidth, response times, capacity to generate different waveform profiles, and power requirements. The specific properties of the actuators have often determined their domain of application such as the use of piezoelectric actuators and electroactive polymers in refreshable braille displays that require compact placement of the actuators that drive each of the pins in the braille cell over relatively small distances (Ren, Liu, Lin, Wang, & Zhang, 2008; Russomanno, O'Modhrain, Gillespie, & Rodger, 2015). For vibrotactile displays, most of the actuators have been used to produce forces normal to the skin surface, although some devices have been developed to generate lateral skin deformation using shear force (Gleeson, Horschel, & Provancher, 2010; Levesque, Pasquero, Hayward, &

Legault, 2005). This enables the presentation of friction forces that can be applied through the movement of actuated sliding plate contactors. Both force and torque cues are available with this type of device which provides the user with a realistic experience of grasping an object.

The demonstrated efficacy of tactile displays for spatial cuing as described previously leads to an exploration of how more complex cues could be presented to a user. Here the interest was in creating tactile communication systems based on vibrotactile signals. The advantage of vibration is that stimuli generated vary along a number of dimensions such as frequency, waveform, intensity, and duration, each of which can be used to create a range of inputs (Jones, 2011; MacLean & Enriquez, 2003). These tactile stimuli are often referred to as tactons and represent the basic unit of a tactile communication system (Azadi & Jones, 2014; Barber, Reinerman-Jones, & Matthews, 2015; Brown, Brewster, & Purchase, 2005). To date, variations in the temporal profile of stimuli (e.g., duration, pulse repetition rate) and the site on the body stimulated have been the most effective dimensions for generating different tactile patterns (Jones et al., 2009). There continues to be active research in this area to determine how tactile vocabularies can be created and easily learned so that an avenue of communication is available in situations where the visual and auditory systems are overloaded or unreliable.

In addition to tactile displays that mechanically stimulate the skin, there have been a number of electrotactile displays developed that create tactile sensations by passing a small electric current through surface electrodes attached to the skin (Kaczmarek & Haase, 2003; Kajimoto, 2012). The advantage of this type of display are that it does not contain any moving parts and so is relatively simple to control and maintain. The displays are also usually compact and have lower power requirements than electromechanical actuators. However, they have a rather limited dynamic range in comparison to electromechanically based displays which means that the difference between threshold levels of stimulation and the onset of pain is rather small. One area of application that has been actively pursued and shows promise is their use as sensory substitution systems for the blind and visually impaired and for those with vestibular deficits. For this purpose, an electrotactile tongue display has demonstrated potential in conveying information from image sensors mounted on glasses to aid blind users while navigating (Kaczmarek, 2011), and from accelerometers on the heads of people with vestibular impairments to help them maintain upright posture (Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007).

One of the more recent application domains of tactile displays has been in the creation of programmable haptic effects, known as surface haptics, on flat physical surfaces such as touch screens. Unlike conventional haptic devices, force feedback on touch screens cannot be conveyed through a handheld interface such as a stylus or glove; the forces must be applied directly to the bare fingertips. Various approaches have been explored to control the friction forces on the fingertip as it moves across the screen, including electro-adhesion and ultrasonic vibration (Chubb, Colgate, & Peshkin, 2010; Giraud, Amberg, & Lemaire-Semail, 2013). By controlling the friction force between the fingertip and the surface, these devices are capable of creating shapes and textures that are perceived as the finger moves across the surface.

Haptic displays are distinguished from tactile displays in that there is bidirectional communication between the operator and the environment being controlled (a robot, computer-generated virtual environment) through the device. This means that both tactile and kinesthetic (i.e., haptic) feedback is available to the user. The direct human interaction with a haptic device, which may be worn as an exoskeleton or thimble or held like a stylus, means that the device's performance measures are critical to its domain of application. In contrast to visual rendering, force reflection for both real and virtual surfaces requires high servo rates, in the order of 1 kHz, in order to maintain stability and represent transients to the user such as collisions with stiff walls. In addition to servo rates, haptic devices are differentiated on the basis of the number of controlled mechanical degrees of freedom, their work space, bandwidth, sensor resolution, and peak force (Hayward & MacLean, 2007). The application areas for these devices extend from the provision of force feedback during remote manipulation tasks such as hazardous materials handling and controlling a surgical

robot, to simulating contact with virtual objects during surgical training or virtual assembly (Okamura, 2004).

Some of the early applications of haptic displays involved telemanipulation in which a hand-mounted master controlled a slave manipulator (robot) and force information sensed at the slave fingertips were fed back to the operator (Hannaford, Wood, McAffee, & Zak, 1991). There was often direct mapping from the human hand to the robot hand and so finger positions measured on the human master were translated to robot hand movements, and forces were fed back from the robot to the master. Wearable systems such as force-reflecting hand exoskeletons in which the actuators are mounted directly on the hand were developed around this time to provide force feedback (Bergamasco et al., 1994; Burdea et al., 1992).

In the late 1990s, desktop haptic displays became commercially available with devices such as the SensAble PHANToM, a point contact device, and the Force Dimension Omega, a force feedback gripper. These devices provided a critical resource that enabled researchers to examine a wealth of issues using a consistent hardware platform. Topics such as the effect of time delays on human performance in teleoperated systems and the importance of synchronizing visual and haptic feedback could be explored by different research groups (e.g., Abuhamdia & Rosen, 2013). Over the years, many studies have used these commercial devices to examine how best to render stable contact during surface exploration and manipulation with dynamic objects in real and virtual environments. We continue to see the development of new haptic displays at the research level that make use of novel actuators; the importance of making such devices light-weight, wearable and energy efficient will be critical to their longer term success.

Tactile and haptic displays make use of the sensory processing capacity of the skin and muscles to encode displacement and force. In addition to the skin's tactile sensors, it also houses thermal receptors that respond to changes in skin temperature and convey information about the magnitude and rate of change in temperature. Over the past 20 years, thermal displays have been developed to explore how changes in skin temperature can be used to provide information about objects in a virtual

environment or to create a more realistic sense of presence in the environment by incorporating thermal cues (Yamamoto, Cros, Hashimoto, & Higuchi, 2004; Jones & Ho, 2008). Thermal displays designed to facilitate object recognition in virtual environments attempt to reproduce the thermal sensations associated with making contact with the real object (Guiatni, Benallegue, & Kheddar, 2009). Thermal models are developed that capture the responses of the skin on contact with different materials (e.g., ceramic, plastic, aluminum) and the models are then implemented in a thermal display typically consisting of thermoelectric coolers, thermal sensors, and a temperature control system (Bergamasco, Alessi, & Calcara, 1997; Ho & Jones, 2007). The results from studies on virtual object recognition using thermal cues indicate that model-based displays are able to present cues that can be used effectively to identify and discriminate between materials and that performance on these tasks is comparable to that achieved with real materials (Ho & Jones, 2007; Yang, Jones, & Kwon, 2008).

Larger-scale thermal displays have been developed for use in virtual environments in which there is no physical contact between the device and the user. In this situation the thermal display is designed to create a sense of realism or "presence" using heat transfer methods such as convection and radiation. For example, infrared lamps have been used with visually impaired individuals to convey cues about the location of a virtual sun as they are being trained to navigate in unfamiliar environments (Lecuyer, Mobuchon, Megard, Perret, Andriot, & Colinot, 2003). Similarly, lamps and ventilators have been used to simulate the effects of walking past a fire blazing in a fireplace or an open window in a virtual environment (Dionisio, Henrich, Jakob, Rettig, & Ziegler, 1997). In comparison to the critical evaluations of thermal displays used to facilitate virtual object recognition (Ho & Jones, 2007; Kron & Schmidt, 2003), there are few quantitative studies that have demonstrated the importance of incorporating thermal stimuli in large-scale virtual environments. It is anticipated that with the advent of technology that is focused on new materials and more efficient cooling strategies, some of the traditional limitations of thermal displays in terms of their

wearability, mass, and safety will be overcome and novel applications of thermal displays will arise.

In summary, there is a burgeoning field of applications for tactile, haptic, and thermal displays. This is in part driven by the growth in wearable technology that has come to rely heavily on the visual and auditory systems for the provision of information and the need to find other less invasive ways of communicating with a user. The challenge in developing these haptic and thermal systems is the need to make them light, energy efficient, and intuitive to use.

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