Touchless tactile interaction with unconventional permeable displays

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Abstract

Unconventional displays, such as 3D displays, projection screens formed of flowing light-scattering particles (fogscreens), and virtual reality (VR) headsets, can create illusions of images floating in mid-air. Paired with hand-tracking, gestural interaction with floating user interfaces (UI) is possible on this permeable imagery, thus creating reach-through touchscreens that react and recover instantly from intersecting fingers and objects. The user can explore virtual environments and control floating UIs with hand gestures which could help, for example, in simulated training and in creating an improved feeling of immersion.

However, hand-based gestural interaction with such UIs can be difficult without haptic sensations typical in daily activities. Without haptics, the level of immersion and smoothness of interaction suffers if the hands can pass through virtual objects without triggering tactile sensations. Ultrasound haptics is a method to produce a focused airborne acoustic air pressure on a user's skin, thus creating an unobtrusive, mid-air sensation of touch.

Fogscreens, VR headsets, or some other unconventional displays together with ultrasound haptics enable tactile interaction with "touchless touchscreens". These tactile, floating UIs open new opportunities, e.g., for immersive interaction, advertisement, and entertainment. It can bring back the missing haptic feedback for these displays.

1 Introduction

Displays are everywhere, not just on phones and computers. Ubiquitous displays range from washing machines and other home appliances to public screens in venues such as shopping malls, movie theaters, etc., each requiring specific input modalities.

Unconventional displays, such as various kinds of stereoscopic, volumetric, or holographic displays (Benzie et al., 2007), fogscreens, and virtual reality (VR) headsets, can create illusions of images floating in mid-air, but they do not provide any sensation of touch, thus reducing the level of immersion. Ultrasound haptics is a method to produce an unobtrusive, mid-air sensation of touch on a user's skin.

We will focus on two types of unconventional displays, which can employ this mid-air tactile feedback: fogscreens and head-mounted displays (HMD). While appearing dissimilar at first glance, both displays share certain permeability – in fogscreens the display surface is permeable and in VR the presented virtual environments are permeable. This causes them to share also similar usability issues.

When compared with traditional touchscreens or the computer mouse, these displays do not provide the inherent tactile sensation of touching solid surfaces. Tactile sensations are important in interaction, as these sensations can affirm to the user that, e.g., a selection was indeed made. Without them, the user may be left wondering if the gesture was registered or were they simply waving their hands in front of the control.

Extended reality (XR) typically employs vision and audition. If any form of haptics is used, it is often obtrusive. The missing or weak sense of touch in most XR systems is a clear deviation from the real world. It can be disappointing and confusing to reach towards a visually accurate virtual object and then feel rudimentary (or no) tactile signals. Furthermore, the fidelity of current tactile display technologies is very low compared to audio-visual displays or to the capabilities and complexity of human tactile sensing. These tactile shortcomings amount to several orders of magnitude (Biswas & Visell, 2019). Haptics can enhance immersion, performance, and interaction of XR and user interfaces (UI).

Traditional, widely used commercial approaches to haptic feedback have been mostly limited to simple surface-based vibrotactile stimuli. Most VR headsets come with hand-held controllers housing vibration motors. This approach provides simple vibrotactile feedback with little precision and is not ideal for sensing surface textures, for example. Specialized and cumbersome haptic devices, gloves, and suits disrupt the feeling of presence even more. While wearable haptic devices (Pacchierotti et al., 2017) could be used to solve the issue of missing tactile feedback with permeable screens, they have not yet been a commercial success. Such devices, using many actuators, could offer a richer set of haptic sensations, but with current technology, they are expensive and cumbersome. In any case, wearable haptic devices might not be a good companion for permeable displays in a public setting, as touch-based tactile feedback is not hygienic.

VR headsets with hand trackers allow the user to interact with virtual objects using gestures. Luckily, the missing haptic feedback is no longer confined on a surface but is available also in mid-air without contact. Tactile sensations can be added using acoustic pressure to the skin from several tiny, phased ultrasonic speakers. This ultrasound haptics could be an elegant solution to providing haptic feedback while interacting with permeable displays.

2 Unconventional display devices

Display technologies usually take much longer than anticipated to reach maturity (Jepsen 2005). The time from the first prototypes to high-volume sales was around 50 years for the CRT and around 20 years for LCOS. The first HMD was introduced in 1968 (Sutherland, 1968), and only now have they started to appear in our homes.

Many display devices have at first been unconventional, but with time have either become more mainstream or forgotten. They can have a good run but become obsolete, like the View-Master by William Gruber, which captivated and immersed its viewers from 1939 to at least the 1990s. Displays can often find a niche market in which to thrive. For example, 3D display devices may be valuable tools for architects or medical professionals, as well as some researchers and data analysts. It is likely that there will never be a universal display for all purposes. Overall, novel display technologies can bring advanced features that in some cases end up competing with traditional lower cost displays if the added value or demand surpasses the added expense. For example, VR headsets are now experiencing a new wave of popularity. Where VPL Research, Sega, and Nintendo failed commercially in the 1980s, it is not exceptional to find HMDs in homes today.

2.1 Permeable displays

Mid-air and holographic displays have dominated the display imagery in science fiction movies for decades. Ranging from Forbidden Planet to Star Wars to Minority Report and Iron Man, they have captivated the media and the general public's attention. But the idea of an immersive, permeable, or "holographic" display has intrigued people for centuries before any movies. Dioramas (a mobile theatre device) immersed the general public into a variety of scenes ever since the early 19th century, whereas wide mural scenic paintings could have filled the viewer's entire field of view.

Permeable imagery floating in mid-air is even more magical and intriguing. Images have been projected to various kinds of water, smoke, haze, or fog screens since at least the 15th century. The concept gained popularity and birthed commercial viewings in which attendees would sit in a darkened room occupied by flying demons, hellish scenery, and appropriate audio effects (**See Figure 1**). Belgian inventor Étienne-Gaspard Robert coined the term *fantascope* for these "magic" lanterns used to project the images. The macabre atmosphere in the post-revolutionary city of Paris combined with the novelty of moving mid-air projections made Robert the best-known phantasmagoria showman.

Figure 1. Fantasmagorie de Robertson at Cour des Capucines in 1797.

Images apparently floating in free space can be generated in numerous ways, e.g., with stereoscopic or multiview displays, or with the old Pepper's ghost illusion (Benzie et al., 2007) but most of them only create illusions of objects in midair and they are not truly in air or penetrable. Volumetric displays emit light from the actual 3D positions, but the images are usually in a confined display volume, and interaction with them is limited.

Various water and fogscreens are used for example in theme parks and they can create impressive shows (e.g., Disney's Fantasmic show), but they are not walk-through. Most fog and water screens are wet projection surfaces. Alternatively, thin particle clouds have been used, but they need to be planar to create sharp images, except when viewed from afar and directly towards the projector. Smoke is opaque and usually darker, requiring more illumination and resulting in less-than-optimal contrast. Fog machines in concerts can create fine particles from chemicals. However, they accumulate haze after prolonged use in enclosed spaces, which may float around for long periods of time and may have adverse effects on humans.

An unprotected fog flow disperses rapidly due to the turbulence induced by the dynamic pressure differences between the flow and the surrounding air, disrupting the desired smooth and planar surface and thus severely distorting the image. In contrast, the FogScreen (**See Figure 2**) uses a thick, nonturbulent (laminar) airflow around a thin, nonturbulent fog flow (both around 1 m/s). The injected particle flow is protected by the surrounding airflow, thus keeping the screen flat and enabling high-quality projected images hovering in thin air.

Figure 2. A large fogscreen hanging from the ceiling can show a clear projected image on a thin layer of fog.

The FogScreen is thus a great method to create a light scattering particle screen in terms of high-quality, dry images hovering in mid-air. However, water screens, 3D illusions, volumetric displays, and other types of displays are better than fogscreens for some purposes. There is not a universally best display technology, but all of them have their uses.

The FogScreen creates a concise and thin particle projection screen and produces an image quality superior to previous methods. Eventually, the fog flow tends to get slightly turbulent farther away from the device and increasingly starts to break up before reaching the floor. Multiprojector systems can make free space fogscreens appear volumetric (Yagi et al., 2011).

The FogScreen is a permeable projection screen. The tiny micron-scale fog particles are dry to touch, and the screen feels just like air to the hand. The light-scattering fog particles serve as a rear-projected screen with the unconventional feature that the user can unobtrusively interact with the screen and walk or reach right through it.

The mid-air screen opens new use cases as it cannot be broken – it recovers automatically and instantly when penetrated. It also stays clean and hygienic, as there is no permanent surface for dirt, bacteria, and viruses to transfer. It enables also two-sided content, where the two sides do not visually interfere with each other. This can further add value in multi-user scenarios.

The technology enables both large and small screens. A smaller, laptop-sized screen can be used as a computer monitor, with the exception that physical objects can share space with the display medium, thus bringing, for example, augmented reality (AR) content close to the object of interest without any AR glasses. Furthermore, proximity to the screen will not harm delicate objects when used in that manner.

Gesture tracking can be used for interaction with the display and its content. Figure 3 shows two examples of educational applications using a small FogScreen with a hand tracker.

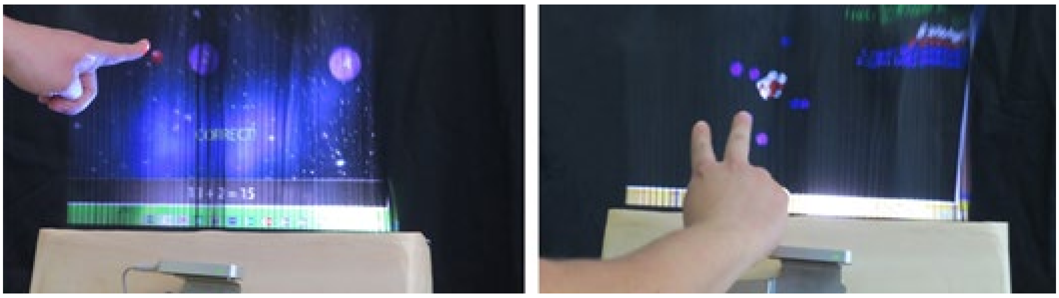

Figure 3. Left: an interactive math learning application on a 17″ desktop FogScreen with hand tracking. Right: an atomic model visualizer with gestural interaction.

While a small-size FogScreen could be used as a typical monitor with a keyboard and a mouse, the unique opportunities afforded by it are best employed when used with gestural interaction. This, however, comes with an issue of usability. Touching elements presented on a permeable screen do not provide the tactile sensation of solid touchscreens. With audiovisual feedback alone, the user might be uncertain on whether they performed the intended gesture correctly, or whether the system detected the performed gesture correctly. Wearable actuators, such as haptic gloves, could be used to alleviate the issue, but they may be cumbersome and obtrusive and are often tethered.

2.2 Head-Mounted Displays

The basic principle behind a device that would be called a head-mounted display was presented by Charles Wheatstone (Wheatstone, 1838) before the invention of photography. He used custom stereoscopic drawings that were viewable through a device called a stereoscope (**See Figure 4 Left**). This simple device was placed in front of the eyes of the user, had two mirrors at 45-degree angles to the user's eyes and stereoscopic picture card pairs on the sides. The drawings, and later photographs, had a slight offset in perspective to mimic the offset of the human eyes.

David Brewster improved on Wheatstone's design in 1849 by adding a pair of lenses (**See Figure 4 Left bottom**). This made the device much smaller and more portable. This device was later refined into the well-known View-Master in 1939, but the design remained very similar even in the smartphone-based HMDs, such as the Google Cardboard and Samsung Gear VR, some 200 years after Wheatstone's invention.

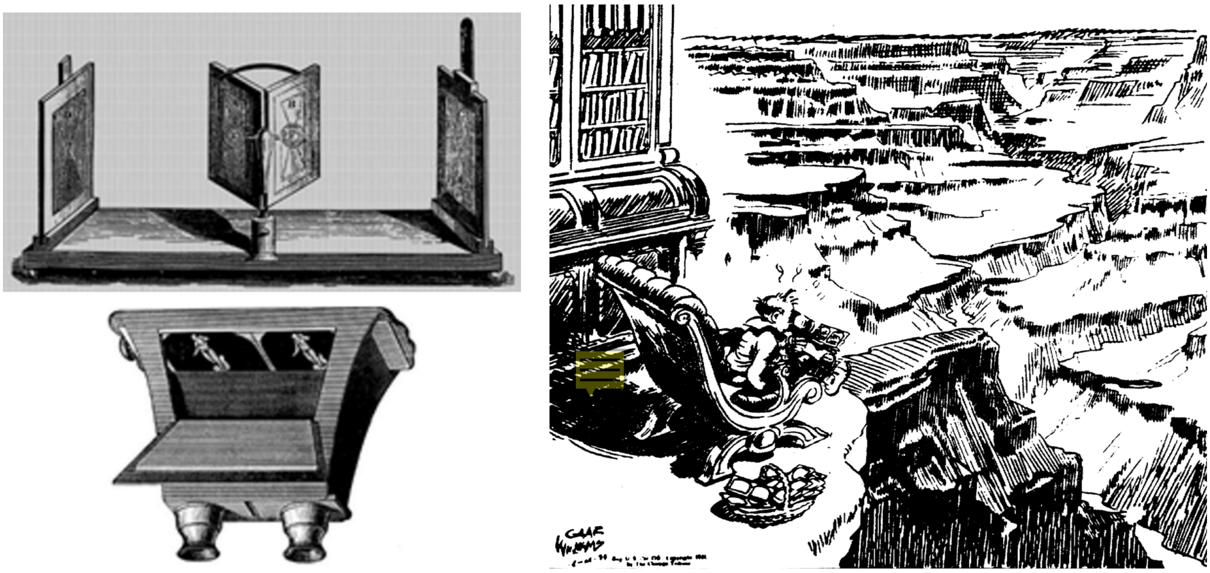

Figure 4. Left: Wheatstone's and Brewster's stereoscopes. Right: Immersion through stereoscopic image pairs in the early 20th century.

Comeau and Bryan (1961) created the first video-based HMD. In 1968 Ivan Sutherland presented an HMD with 3D graphics and head tracking (Sutherland, 1968). It is worth noting that the 3D graphics of that time consisted of mostly wireframe rooms and objects.

Today, HMDs take many shapes: AR glasses, VR headsets, head-mounted projector displays, etc. Sometimes a clear distinction between categories can be difficult to make. For example, the Varjo XR-3 HMD streams stereoscopic camera feed into human eye-resolution screens, thus allowing the level of augmentation to be anything from entirely un-augmented reality to a fully virtual environment.

VR headsets allow the users to explore virtual environments. These often come with hand-held controllers, but also hands-free interaction is possible with the use of hand trackers. The user can see their hands in the virtual environment and touch the virtual objects. They can receive audiovisual feedback on their interaction, but ultimately the hand will penetrate the virtual object without providing haptic sensations. This issue is perhaps most emphasized when trying to interact with UI elements using touch. Buttons, knobs, sliders, etc. can be difficult to operate when the hand can slide through them. Wearable controllers could provide coarse vibrotactile feedback, but this would limit hands-free interaction. Some form of touchless tactile interaction could make touching virtual elements easier and more immersive.

3 Touchless tactile interaction

Unconventional displays, such as fogscreens, 3D displays, and VR headsets, open new opportunities for gestural interaction. User interfaces on these displays create reach-through touchscreens but tapping on a UI element or a virtual object on such a display would leave the finger intersecting the display surface without any tactile stimulation. This feels unnatural, as visible objects usually feel tactile. It lessens the immersion and makes manipulation of virtual objects cumbersome.

Surface haptics is the traditional method for generating haptic feedback. Smartphones, smartwatches, tablet computers, and gaming controllers house tiny actuators that vibrate the entire device. They are simple, inexpensive, and effective, but the information they can provide is very limited. Further, a high spatial resolution would also require new methods to propagate the haptic stimuli at a specific location and not to the whole device, such as using constructive wave interference from several actuators (Coe et al., 2021).

Another option is to mediate the sensation in mid-air, without the need for wearable devices. This allows for hands-free interaction and in some cases offers a significantly higher spatial resolution. The ability to 'feel' content in mid-air addresses fundamental usability challenges with gestural interfaces (Freeman et al. 2014; Rakkolainen et al. 2020). It helps users to overcome uncertainty about gestures, improves user engagement, immersion, etc.

Mid-air haptics is a group of different technologies that allow for haptic feedback on touchless interaction. Some techniques use directed air jets to create a sensation of touch from a distance, others can produce thermal sensations, but none of them is very accurate or fast. Currently, the most promising approach is using ultrasound haptics.

3.1 Ultrasound haptics

Focused airborne acoustic air pressure produced by ultrasonic phased arrays can provide mid-air tactile feedback (Iwamoto et al., 2008; Rakkolainen et al., 2020) without mechanically moving parts and with much greater speed and precision. As an ultrasonic actuator matrix can remain at a distance and requires no tethering on the user, this approach is unobtrusive, maintaining the user's freedom to move in the target area.

Compared to wearable vibrotactile actuators, ultrasonic mid-air haptics has some clear benefits. It does not require any wearable actuators or the user to be tethered to the device. It has spatial freedom as the acoustic pressure focal point can be translated quickly inside the interaction volume. It can be used to create volumetric shapes and surfaces and to present surface textures (e.g., Freeman et al., 2017). It can feel like magic to the user.

Ultrasound haptics is particularly good at generating a range of tactile stimuli on the user's palm or fingertips (Sand et al., 2020). For example, a 200 ms burst has been described as "unmistakably a mouse click" (Palovuori et al. 2014).

Common ultrasonic phased arrays offer interaction volumes suitable for desktop use, as the range is limited to tens of centimeters. For large public displays, this is unfeasible. Lately, a solution has been proposed in the form of rotating the array around the pan and tilt axes (Howard et al., 2020). Workspace can also be expanded with a long-distance midair haptic display using a curved reflector (Ariga et al., 2021).

Ultrasound haptics is fast and relatively accurate, it offers untethered hands-free interaction, it can present shapes and surfaces to a degree, and it can be a natural transition from traditional input feedback. For these reasons ultrasound haptics could be a natural match for touchless tactile permeable displays.

4 Touchless tactile permeable displays

Mid-air tactile feedback systems can benefit interaction with displays. They can be used as tactile displays (Sand et al., 2020), and be merged with 3D displays (Hoshi et al., 2009; Inoue et al., 2014; Long et al., 2014; Monnai et al., 2014) or fogscreens (Sand et al., 2015). Stationary ultrasonic arrays require the user to stay close to the array to receive tactile feedback.

The transducer arrays can also be fitted onto an HMD. An HMD with an ultrasound array in a fixed position (Kervegant et al., 2017; Martinez et al., 2018) severely limits the working range.

If the array is mounted to the front of an HMD (Sand et al., 2015b), the tactile feedback is always directed outwards to the visual working area of the user, thus its range is mobile and adequate in the range of convenient reach of the arm (**See Figure 5**), thus somewhat circumventing the issue of limited interaction volume. For this reason, HMDs match well with mid-air tactile feedback.

Figure 5. An ultrasonic mid-air haptics device attached to a head-mounted display always keeps the feedback oriented to the facing direction. The hand tracking sensor on top of the matrix allows the focal point to be directed at the fingertip.

This setup allows touchless tactile stimulation when touching virtual objects with one's hands. It has the potential to take VR to a whole new level of immersion. In addition to touching UI controls, such as buttons, the user could also experience ephemeral elements, such as wind and rain, feel a butterfly landing on their hand, etc.

Ultrasound haptics can also go inwards from the HMD to the face (Gil et al., 2018) or lips (Jingu et al., 2021). It can guide the user's attention or evoke emotions. In a teleconference a mother could caress her child with a hand gesture, to be sent to the child's cheek. To accomplish this, short-range low-powered ultrasound haptics could be used towards skin areas adjacent to the HMD.

Permeable screens such as the FogScreen (**See Figure 6**), make the mid-air gestural interaction significantly easier, as the user has a visual reference on roughly where the interaction should take place, for example, how far they need to reach to make a tap gesture. This allows the system to only regard gestures made in a shallow depth volume and frees the user to move and gesture at will without having to worry about unintentional selections.

Figure 6. From front left to back right: Leap Motion controller, FogScreen, phased ultrasonic 16x8 array, and projector (masked with an R2D2 printout) (Sand et al., 2015a).

Challenges of touchless interaction

When touching or tapping with mid-air gestures, there are still some tradeoffs due to technological limitations. It can be difficult to tap on a virtual target in such a uniform way that it can be reliably recognized by the system between various gestures and users.

Many technological challenges can be alleviated with good design, while others require less than optimal interaction methods. One of the most prominent technological challenges related to mid-air gesturing is commonly known as the Midas touch (Kjeldsen & Hartman, 2001). Because the gesture tracking technology is constantly tracking the user, there can often be a disparity in what the system detects as a gesture and what the user intends as one. This can lead to constant unintentional selections making the use of the system a very frustrating endeavor. The user might be communicating to another person and, perhaps subconsciously, move their hands, or engage in other physical tasks in the tracking system's interaction space (Walter et al., 2014).

Common remedies for the Midas touch problem include the use of extra actions. In whole-body interaction the user might be required to take a special body pose, such as a "teapot" (Walter et al., 2013), meaning that the user must place their hands on their hips to indicate to the tracking system that they wish to begin the interaction. When using just pointing and tapping, the user might be required to make a fist or other special gesture to confirm the selection of the pointed object. This can, however, result in the virtual cursor moving away from the intended target as the hand tends to move slightly while the gesture is being made.

The system can analyze also the user's posture and gaze to guess when the user wants their movements to be considered as interacting with the system (Schwarz et al., 2014). However, the Midas touch issue is not limited to just gestural interaction but is prominent in most interaction methods that rely on continuous tracking, for example, in using eye gaze to select targets in gaze-based interfaces (Vrzakova & Bednarik, 2013).

The Midas touch phenomenon is worsened by the inherent lack of tactile feedback associated with permeable and virtual displays, as well as mid-air gestural interaction. Traditional physical input devices come with built-in haptic feedback and also inherent limitations – a button can only be pressed so far, and a knob can only be turned one way or the other.

From what we have observed, the Midas touch phenomenon is greatly reduced with fogscreens as the user can have a shallow interaction depth with a clear visible indicator of where it starts. Yet, fog and other common light-reflecting particles reduce the tracking accuracy of many common tracking methods, such as time-of-flight sensors and depth cameras, justifying the need for haptic feedforward. Moreover, users may be wary of gestural interfaces, at least initially, worrying if the system is working or not, and haptic feedback could work to reassure the user that the system is indeed tracking the selections reliably.

To make gesture recognition more reliable, many systems opt for dwelling the pointing finger or hand on top of the target for a certain duration of time. This can help to eliminate unintentional selections but is often much slower and more tiring for the user (van de Camp et al., 2013; Yoo et al., 2015). For example, with a two-meter-wide public fogscreen, a dwell-timer combined with extreme hand extrusion could quickly lead to severe physical strain. In this case, it would perhaps make more sense to interact with the display from a distance as one would with a typical large public display. While the dwell-based selection method has clear drawbacks (time consumption and physical strain) it might still require more technical advances before simple pointing and tapping becomes reliable enough to surpass the need for such clutch actions. One such technical advance could be the addition of ultrasonic actuators to provide the tactile sensation of touching solid surfaces to interact with permeable displays.

Ultrasound haptics suffers also from some limitations, mainly from noticeably weaker feedback compared with standard haptic actuators, as well as from a relatively short interaction distance. The interaction distance with current ultrasound haptics hardware is functional for small-size fogscreens but won’t work with larger fogscreens of over one meter of width.

Experimental results

In our preliminary testing, providing ultrasonic tactile feedback to interaction with a fogscreen on a numerical input task (**See Figure 6**) did not result in significant differences in the rate of numbers entered or the error rate compared with use without haptic feedback, but the addition of tactile feedback was preferred by the users (Sand et al., 2015a). However, this experiment was conducted using a small 16x8 transducer array. A larger ultrasonic array would produce stronger feedback. Further, both the display and the feedback device were novel to the participants and that novelty may also have distracted the participants from the actual task, maximizing their interaction with the tactile feedback instead of optimizing their performance.

In a later study, a similar experiment was repeated using an HMD with the transducer array mounted on the front panel of the HMD (**See Figure 5**). While we did not find a significant difference on entered characters per second or error rate compared with use without haptic feedback, subjective values collected using NASA TLX revealed that ultrasonic haptic feedback lessened the perceived temporal, physical, and mental demand as well as effort with temporal demand having a statistically significant change in t-test ($t12=4.38$, $p<0.001$) (**See Figure 7**). Further, the preference for the tactile feedback was clear with 11 out of 13 participants reporting they preferred having the tactile feedback (Sand et al., 2015b).

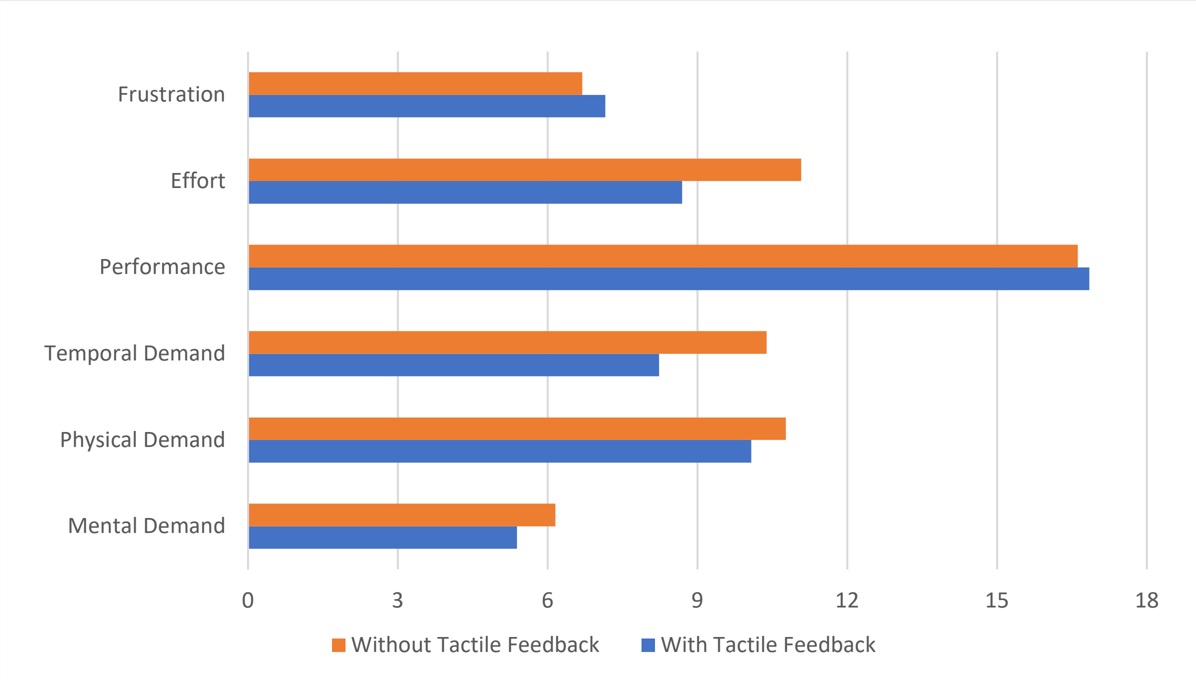

Figure 7. TLX averages with and without tactile feedback (smaller is better, except in performance, where larger is better).

Permeable displays have several benefits. In AR use, they allow delicate objects to be placed within the display volume, thus bringing the AR content seamlessly close to the object of interest. As dirt or bacteria can't catch on, the display is suitable for bakeries, operating rooms, factories, and other places where the user's hands may be dirty. The hygienic aspect makes it suitable also generally during pandemics.

5 Discussion

Ultrasound haptics offers potential for controllable and expressive touchless tactile feedback. It is a natural match for permeable screens, VR headsets, and other virtual UIs that do not provide inherent tactile sensations. Compared with traditional surface haptics, it allows, for example, rapid translation of the focal point, easy creation of multiple simultaneous focal points, and presentation of shapes and textures.

However, the small range and the strength of stimulation limit its usefulness in many scenarios. Very large permeable screens, such as the one shown in Figure 2, are not a good match for ultrasound haptics. This is due to the large interaction volume, which would be difficult to serve with ultrasonic actuators. Rotating the array around the pan and tilt axes (Howard et al., 2020), using massively scalable arrays (Suzuki et al., 2021), or using long-distance curved ultrasound reflectors (Ariga et al., 2021) could remedy the issue to a degree, but the dissipation of acoustic radiation over distance would still be problematic. A wearable actuator might still be required for use with large interaction volumes, but the combination of touchless and wearable haptics is not extensively studied.

The strength of stimulation can be affected by the number of transducers, but it is a path of diminishing returns and increasing cost and complexity. Different frequencies can be utilized for stronger stimulations, but current research has focused mainly on 40 kHz (Iwamoto et al., 2008) or 70 kHz (Ito et al., 2016). It is important to note that the size of the focal point is determined by the wavelength of the carrier frequency so that 70 kHz allows a more precise focal point than 40 kHz. More research and technological advancements, such as different transducers, transducer layouts/board designs, and transducer frequencies are needed to improve the strength of the stimulation.

Based on the results of the evaluations described in the previous section, we assume that the best use of mid-air haptic feedback with unconventional permeable displays could be in situations emphasizing user experience: entertainment technology, games, and other user interfaces meant for fun could potentially be even more fun with mid-air haptics. However, in productivity applications, the measurable performance benefits may turn out to be small. At least amplifying an art exhibition with ultrasound haptics left the visitors feeling more immersed and uplifted (Vi et al., 2017). It seems within reason to assume that the same could happen with unconventional displays, but further studies would be needed.

Ultrasound haptics remains an interesting topic for further studies. Little is known about emotional responses to ultrasonic stimulations, and most research has focused exclusively on the palmar side of the hands as the receiving skin location. Ultrasound haptics can create more subtle sensations compared with traditional vibrotactile actuators. This could be useful in therapeutic touch, or wider emotional response invocation, as well as remote touch.

Focusing research on the palmar side of the hands has made sense since it is an area with a high density of mechanoreceptors, which is important given the relatively weak feedback amplitude. The human face, especially the lip area, has also a high density of mechano-receptors, making it somewhat an obvious research interest, but possibly researchers have thus far avoided focusing the feedback on the face for safety concerns.

Touchless interaction has clear benefits in environments where touch-transferred dirt, viruses, or bacteria might pose harm to others or the system they are interacting with – environments such as operating rooms, factories, bakeries, etc. Further, during pandemics, people might appreciate hygienic “touchless touchscreens” on public interfaces.

Great interest in ultrasound haptics has recently arisen from the automotive industry. As VR gains popularity for simulated training, remote participation, and entertainment, touchless tactile feedback can allow for hands-free interaction and exploration. All of these are fascinating avenues of future research.

6 Conclusions

Unconventional displays, such as fogscreens, various types of 3D displays, and VR headsets, open new opportunities for interaction. Paired with hand-tracking they allow for gestural interaction. User interfaces can be presented on permeable screens to create reach-through touchscreens that react and recover instantly from intersecting objects. The user can explore virtual environments and control floating UIs with hand gestures.

Merging touchless interaction with ultrasound haptics enable the user to better interact with and feel virtual objects, as well as experience ephemeral elements. The visual reference provided by fogscreens together with confirming tactile sensation of ultrasound haptics could be one solution for the Midas touch issue of gestural interaction.

Floating UIs using unconventional displays, hand tracking, and ultrasound haptics enable more immersive interaction and enhanced simulated training, and entertainment. However, it has also its limitations, such as limited range, extra weight, relatively weak feedback, etc.

The effects of mid-air haptics on interaction have not been extensively studied, but initially it looks like the technology improves user experience and entertainment more than the performance of tasks. The technology is still relatively young, and we expect that many improvements will make it a very intriguing element for many kinds of interaction in the future.

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