User Experience and Mid-Air Haptics: Applications, Methods and Challenges

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Abstract Mid-air haptic feedback presents exciting new opportunities for useful and delightful interactive systems. However, with these opportunities come several design challenges that vary greatly depending on the application at hand. In this chapter, we reveal these challenges from a user experience perspective. To that end, we first provide a comprehensive literature review covering many of the different applications of the technology. Then, we present 12 design guidelines and make recommendations for effective mid-air haptic interaction designs and implementations. Finally, we suggest an iterative haptic design framework that can be followed to create a quality mid-air haptic experience.

1 Introduction

Interaction design for novel human-computer interfaces has been met with increasingly complex challenges due to the advancements made by novel input technologies. Keyboard and mouse input has in many cases been replaced or complemented by touchscreen input, while since 2010 with the release of Microsoft Kinect and Leap Motion in 2014, advances in hand-tracking algorithms and devices (mostly camera based) have been challenging developers and interaction designers to explore the use of 3D mid-air hand gestures and their capabilities in a range of products and services. For example, hand and finger tracking sensors have been embedded in car infotainment systems for a more intuitive and comfortable input that is also less visually distracting; in virtual and augmented reality (VR/AR) head mounted displays (HMDs) for

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controller-free games and more immersive experiences; and in digital signage or self-service kiosks for a more hygienic and pleasant touchless operation.

All these touchless technologies enable novel and more natural interactions with the digital world, however they lack physicality as they do not stimulate our sense of touch. Ultrasonic mid-air haptic technology is a direct response to this *touch gap*, aiming to not only re-instill physicality to touchless user interfaces, thereby improving their functionality, but also to enhance user experience (UX), thereby improving various non-functional aspects of the interface.

Since the early prototypes emerging out of academic research labs in Japan [1] and later in the UK [2], ultrasound mid-air haptics has received a lot of academic and commercial interest and is an active area of research in the HCI and haptics communities (see recent survey here [3]). The main advantage of this technology compared to other mid-air haptic alternatives such as air jets, plasmas, and lasers, is that ultrasound mid-air haptics hardware platforms can be electronically programmed to display multiple points of vibrotactile stimulation with a high degree of spatial and temporal resolution and can do so in a controllable and safe manner [4]. Moreover, the tactile sensation is presented almost instantaneously and can be accurately targeted to the users' palms, fingers, face, lips, forearms and chest in the form of a short burst, or continuously over a large 3D work-space. Finally, various modulations and rendering techniques of the ultrasound waveforms can be used to further imbue the tactile sensation with rich touch information such as shape, stiffness, curvature, and roughness.

Many of these aspects and associated challenges are discussed in more detail in the following chapters of this book. In this chapter, we will instead approach the topic from a UX perspective, by first giving an overview of the different applications of the technology (Sec. 2), and then presenting some guidelines (Sec. 3) and methods (Sec. 4) for the design of useful mid-air haptic enabled interactive systems. Finally, we will discuss future challenges and give our vision for mid-air haptic user experience enhancement (Sec. 5).

2 Applications

2.1 Automotive

The global automotive human machine interface (HMI) market size was valued at USD 14.8 billion in 2017, and was projected to reach USD 33.6 billion by 2025, registering a compound annual growth rate (CAGR) of 11.1% from 2018 to 2025. According to market research reports, the key drivers behind this projected growth are observed to be enhanced UX and entertainment in vehicles and an increased focus on driver assistance systems. To that end, haptics have traditionally been applied in the automotive domain in many forms, notably the steering wheel, the seat, and the foot pedals, primarily for providing safety related benefits to the driver. Increasingly however, and in line with the market research reports, haptics are also applied in other interactive areas of the car, such as surfaces and touchscreens to improve UX, to enable new features, and to improve the perceived quality of the car itself [5]. Despite their ability to emulate, e.g., a ‘click’ touch sensation when in contact with a screen, haptic-enabled touchscreens are absent of contours and hence lack genuine tactile guidance, resulting in them being visually demanding during operation. This is also the main reason why touchscreen use in vehicles have been shown to increase driver distraction and crash-risk [6, 7, 8, 9, 10].

Therefore, a lot of research has in recent years focused on In-Vehicle Infotainment Systems (IVISs) and how to make large touchscreens more usable while driving, without taking the driver’s visual attention away from the road [11]. One promising alternative has been the use of touchless gesture input technologies [12, 13], with several car manufacturers like BMW, VW, Jaguar, Mercedes-Benz, Cadillac, PSA, and Hyundai, all investing in mid-air gesture interfaces [14]. The key advantage of gesturing in mid-air is that it engages our proprioception (kinesthetic haptics [15]), thereby potentially enabling eyes-free operation interaction with the IVIS, especially when feedback is provided through a multimodal combination of visual, audible and/or tactile information [16]. Gesture interfaces are also more hygienic, leaving no fingerprints or dirt transfer onto the centre console of the car.

Despite the core advantage of relieving visual distraction, gesture input technology in cars comes with its own challenges, such as potential cultural nuances [17], the learning associated with more complex gestures [18], the lack of a standard gesture set [19], a restricted 3D interaction space above the gearshift [20], the need for user acceptance [21], the reliability of the gesture recognition system itself, and of course the loss of haptic feedback [22], a key ingredient towards the sense of agency (SoA) - the subjective experience of voluntary control over your actions. Meanwhile, speech and non-speech audio feedback have been proposed to offset this lack of tactile feedback [23], however, these methods are not as effective and also interfere with other audio signals and external noise (e.g., due to an open window) while also disrupting passenger conversations.

Currently, most interactive hand-gesture input implemented in prototypes, concepts, and production IVIS’s include the index pointing gesture, pinch and drag, palm-swipe to reject, rotating index finger to adjust volume, downward push, grab and pull, and the “v” for victory gesture being user-defined. It has been argued that adding mid-air haptic feedback to these and/or other gestural interactions in cars can add value by: increasing interface usability, improving gesture learning and recall, reducing cognitive load, enhancing a sense of agency, reducing visual distraction, reducing eyes-off-road time especially during target locating, supporting error recovery, providing an experiential alternative to audio feedback, enabling new IVIS features and applications,

Fig. 1: Experimental set ups from [28] (left), [26] (middle), and [29] (right).

and being more inclusive to deaf or hard-of-hearing drivers. In addition to all these potential functional and usability benefits, there are experiential aspects such as expressivity, immersion, realism, autotelic and harmony as presented by Kim et al. [24] that can enhance how the IVIS feels to the user, and not just how well it works.

Research efforts in better understanding and establishing some of the above claims are underway, with automotive being an active yet currently under-explored use case of mid-air haptics. Here we briefly review some of the reported literature on the topic, and highlight some gaps and unanswered questions.

Georgiou et al. presented a first prototype demo created by Ultrahaptics (now Ultraleap) for a mid-air haptified hand gesture IVIS using just two input functions and hand gestures (Volume and Fan speed up/down and a switch between the two) [25]. Harrington et al. and Large et al. explored the human factors and benefits associated with adding mid-air haptics to gesture interfaces through user studies in a high fidelity driving simulator [26, 27]. Importantly, they showed the potential of haptified hand gestures towards reducing visual demand and perceived workload, improving secondary task performance and vehicle control when gesturing at the IVIS while driving, as compared to the non-haptic gesture and touchscreen input cases. It should be stressed that their results were not unanimous in all test cases, however they were generally encouraging and positive, indicating that if designed and implemented properly, mid-air haptic gesture input could indeed mitigate many of the key concerns about touchscreens and gesture input for human-car interactions. The study by Shakeri et al. echoed many of these encouraging findings, while also further arguing in favor of multimodal feedback (auditory and peripheral vision) in combination to mid-air haptics [28]. The experimental set ups of these studies are shown in Figure 1.

A study by Korres et al. used a holographic (floating) interactive display (rather than a standard LCD) together with mid-air haptic gesture input and showed that the addition of mid-air haptic feedback to the interactions with the IVIS improved driving performance (the average speed error, spatial deviation, and the number of off-road glances), improved the secondary task of IVIS interaction (reach time), and improved overall quality of user experience, as compared to no tactile feedback. [30]. Also using floating displays, Rümelin et al. studied pointing gestures with haptic feedback directed onto the index finger [31]. This interaction and a mid-air haptic display were prototyped and built into BMW's concept car shown at CES 2017 in Las Vegas that was branded as 'HoloActive Touch' [32]. Rümelin's work varied the amplitude modulation (AM) frequency and stimulus duration of the feedback presented during a holographic button press. Subjective ratings scored 200 Hz as the best stimulus frequency combined with a duration between 50 and 130 ms.

Motivated by former evaluations of button sounds and their perceived associations with the quality of a product, Rümelin's paper also looked at evaluating a vocabulary of adjectives used to describe the presented mid-air feedback pointing gesture and grouped them under: valence precision, attractiveness, resolution, and intensity. The most descriptive words that emerged were: effortless, sharp, desirable; deep; pleasant; artificial, coarse; and strong.

Combining prior results and knowledge from prototypes, psychophysical, and human factors studies, Young et al. [29] developed a more advanced mid-air haptic gesture-enabled user interface for human-vehicle-interactions. The prototype comprised of a graphical user interface and information architecture (i.e., a menu) with four functions (1. Music control, 2. Temperature and Fan control, 3. Navigation map control, and 4. Phone-call answer/reject), while using just 5 hand gestures (Pinch and move, Tap, Grab-Release, Swiping, and Hand-Twist) to ease learnability [33], and applied multimodal feedback (visual and audio) in combination to a variety of haptic feedback and feedforward sensations. The paper did not only present the prototype but also proposed a set of UX requerements for the mid-air haptic IVIS called REQUEST (REliable, Quick, Useful, Easy, Safe, and realisTic), and documented the design process considerations during the development process. These included an online survey, business development insights, background research, and three agile prototype iterations and user-testing on a simplified driving simulator.

Finally, motivated by human centred design, the expressivity afforded by mid-air haptics and the need to improve the learnability of IVISs, Brown et al. proposed a method to design an exemplar set of robust, function-associated haptic gestures, aka Ultrahapticons, that leverages drivers' mental models of interactions [34]. This work is further described in Chapter 5.

Automotive brands, OEMs, suppliers, and HMI design agencies want to create in-car experiences which are differentiating, easy to use and update, are cost-appropriate and safe. Mid-air haptic technology presents a compelling solution to the automotive use case wants, however most published research studies to date have largely focused on validating the technology and its associated benefits. They are essentially singular findings that do not naturally generalize to a broader automotive user context; perhaps such activities are better suited to industrial R&D settings. Going forwards, studies should shift their focus on optimizing both individual parts of mid-air haptic integration into IVIS but also how they all fit and work together. For example, there are no studies on the optimal set of ergonomic product design and placements of ultrasonic arrays within a car dashboard. With the exception of Young et al. [29], there are no studies on how best to design and implement mid-air haptic sensations (along with any accompanying sounds and visuals) to support the user in searching and operating IVIS control elements. To that end, the methods we will present in Sec. 4 could be followed to map out the interaction design and how mid-air haptics can be better leveraged to add value to IVISs and their users. Moreover, while much of the haptic use cases in automotive have been limited to the finding and confirmation of input control actions, other use cases could also be explored such as warning mechanisms during high visually and cognitively loaded conditions such as high traffic density [35].

2.2 Touchless displays in public spaces

2.2.1 Digital signage, pervasive and accessible displays

Digital signage and pervasive displays use technologies such as LCD, LED, projection and e-paper to display things like images, video, web pages, weather data, restaurant menus, or text, usually in public spaces like train stations, airports, malls and theaters. Making these large screens interactive has promised to transition such platforms from simple broadcast systems to rich digital media for targeted and bi-directional communication, e.g., through interactive experiences that enhance brand engagement. However, touchscreen technologies do not naturally lend themselves to this use case due to the need to ensure: hygiene and cleaning requirements, robustness against extended use and potential damage, needs for securing access to the display control panel, responsiveness, and finally reachability requirements that compromise viewability and location [36].

It is worth noting here that the global digital signage market was estimated at USD 16.3 billion in 2021 and projected to reach USD 27.8 billion by 2026, rising at a CAGR of 11.2% during the forecast period. According to market research reports, much of this growth is driven by an increasing adoption of digital signage in commercial applications and settings, while a key opportunity observed is the growing demand for contactless engagement in the post COVID-19 era. Advances in computer vision (face, gaze, facial expression, body and hand-gesture recognition) and mid-air haptics have thus stepped in to enable new ways of distal interactivity with digital content. These however also come with their own challenges. Namely, it is not clear how the interactivity of these displays is communicated to the passer-by audience and future user, how to initialize an interaction, and once the

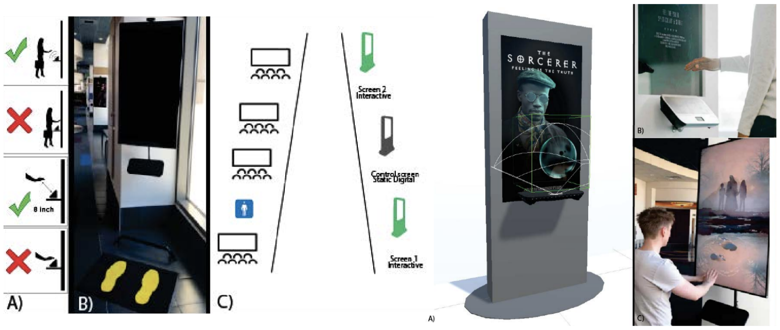


Fig. 2: Left: Instructional panel images shown on side of screen. B) Footprints on the floor beneath the interactive poster C) Layout of the deployment interactive posters (green) and the control poster (black) in movie theatre corridor. Right: A) Example with interactive poster set up, haptic interaction zone in green, hand tracking zone within white sphere. B) Example of hand location for interaction. C) Example of two-handed interaction. Reproduced from [37].

audience have engaged, how the interactive affordances are communicated across, both of which are fundamental UX questions. Sub-challenges that permeate and affect the above aspects include display blindness, interaction blindness, interaction design, awkward or embarrassing gestures in public, ergonomic design and the spatial positioning of the signage. Many of these were explored by Limerick [37] during an 8-week in-the-wild experiment in LA that led to a set of solutions and design guidelines, e.g., the use of animated idle screens showing hand gestures that people would mirror to initiate interaction, simplified instructional panels, footprints on the floor to signify where users should stand, but also the use of mid-air haptics to enhance user engagement and help offer more compelling experiences (see Figure 2). In a different but similar study, also by Limerick et al. [38], participants reported significantly more focused attention and experienced greater levels of reward when mid-air haptic feedback was present than without it.

Rutten et al. challenged the sustained positive UX effect of mid-air haptic to such experiences [39]. They found that the added value of valence was due to a novelty effect as it was only significantly elevated during initial use and fell after repeated use. However, the added value of mid-air haptic feedback in terms of enjoyment, engagement and arousal remained elevated over the course of their study (five weeks).

Corenthy et al. presented a demonstrator further including gamification aspects to the touchless experience, while using different mid-air haptic stimuli to indicate discrete events that were congruent with audio-visual stimuli (e.g., as laser blasts) but also haptic-only stimuli that conveyed hidden signals to the user (e.g., the direction of an incoming asteroid) [40]. Notably, continuous haptic stimuli were also displayed to indicate system responsiveness and the invisible tethered control of a user's hand and the game on the screen. Finally, an initialization haptic was used to guide the user towards positioning their hand in the right place and height, approximately at the centre of the interaction zone in front of the display.

Kim et al. presented a demonstrator for a new retail shopping experience which they called Refinity [41] (see also Chapter 7). In their vision, customers could directly select and explore realistic virtual products using auto-stereoscopic 3D displays combined with mid-air haptics and hand and finger tracking. Haptic gestures were introduced to enable natural interaction with products: point to identify, grab to select, rotate to preview, swipe to browse other options and push back to place the items back in the virtual shelf. Notably, sensory substitutions via haptics and audio were used to tackle the visual-physical conflict when interacting with the 3D screen. Further, in addition to the visual and mid-air vibrotactile haptic feedback presented by the ultrasonic arrays in the Refinity prototypes, Kim et al. also explored a variety of multisensory combinations like different smells, heat flow and rich interactive auditory cues to create a memorable and joyful multisensory shopping experience which was easy to walk up and use, i.e., not requiring any additional wearables, headsets, or instrumentation, while simulating the different functionalities of the displayed products.

Gaining maximum attention from passerby audiences and delivering a strikingly novel experience can be achieved through the use of permeable displays consisting of tiny, flowing, light scattering particles, such as dust, smoke, or fog. Rakkolainen et al. have worked on a variety of such systems (see also Chapter 8 of this book) where a thick laminar air flow is created along a plane within which particles are injected and are protected by the surrounding air flow, thus keeping the screen flat and enabling high-quality images and videos to be projected onto them thus creating a hovering holographic effect [42]. While images floating in thin air are a common theme in science fiction, they are still relatively rare in everyday life and are thus easily noticed by the audience whose attention and imaginations are intrigued. Enhancing such floating displays with ultrasound haptic feedback can be utilized for the efficient information transfer on tactile displays, e.g., the presentation of interactive buttons or tactile images through tapping, swiping, grasping and dwell time gesture input. To that end, Shinoda et al. [43, 44, 45] have been using floating images produced by projecting through transmissive mirrors, also referred to as aerial imaging plates which double up as a reflector of ultrasound waves that focus and provide tactile feedback to the optical holographic images. These techniques and challenges are further discussed in Chapter 12 of this book.

Finally, motivated by the increased unwillingness to touch self-service touchscreens in public places due to the COVID-19 pandemic, Huang et al. presented a touchless Customer Feedback Kiosk (happy, OK, bad, terrible), like those deployed after security checks at airports [46]. Their study results pointed out that even for simple touchless interfaces like these, there are many new and unexplored design questions that present implementation challenges such as the optimal distance between buttons, the size of the virtual hands to reduce error rates, and the need for training instructions, akin to those presented by Limerick et al. [37] but further appropriated for the quick and direct input interactions necessitated by self-service touchless kiosk interfaces.

Also motivated by COVID-19, Singhal et al. designed an interactive simulation of a contactless elevator panel with mid-air touch feedback and comprehensive accessibility considerations [47]. Users could not only feel mid-air haptic feedback on contact with the panel buttons corresponding to the different floors, but could also feel their Braille representations using a similar implementation to that described by Paneva et al. [48]. Additional interactions such as responsive button magnification to assist people with low vision, intuitive gestures for opening or closing doors, and audio feedback where also presented in their prototype.

2.2.2 New media, art, science communication and museums

Museums and art galleries have traditionally been at the forefront of integrating and stimulating multiple human senses, not only to explore new ways of representing arts, but also to increase the wider public interest in the artifacts being displayed. Within this context, Vi et al. worked with a team of curators artists and designers to create and deploy a six-week multisensory display called Tate Sensorium that was exhibited to over 2500 people at the Tate Britain art gallery in London [49]. This was the first time that mid-air haptic technology was used in a museum context over a prolonged period of time and integrated with sound to enhance the experience of visual art. Participants expressed that experiencing art with the combination of mid-air haptics and sound was immersive, memorable and provided an up-lifting experience of touching without touch.

Trotta et al. created a multisensory science exhibit that was presented at the London Science Museum aimed at communicating abstract concepts in cosmology and astrophysics in a more accessible and inclusive manner [50]. Different experiences evoking all five of our senses were designed, with touch and particularly the malleability offered by mid-air haptics were used for producing tactile sensations that represented the change in dark matter wind during an earth-year, and its density profile in our galaxy. Participants voted on which of the five sensory channels had the most significant influence on one of five personal responses: Awareness, Enjoyment, Interest, Opinion forming, and Understanding (also known as the AEIOU framework) with the touch experience performing comparatively well in the Awareness, Enjoyment and Understanding dimensions.

Going beyond this single exhibit, Hajas et al. explored how mid-air haptics technology could play a role in communicating a variety of scientific concepts [51]. In their work, they prototyped six mid-air haptic probes for three thematic areas: particle physics, quantum mechanics and cell biology, and also describe guidelines on how to do so most effectively through the use of cognitive and tactile metaphors. Then, through three qualitative focus group sessions with domain experts and science communicators, the team identified how dynamic features afforded by mid-air haptics could convey scientific concepts through metaphors and stories. For example, dynamic tactile feedback on the palms of both hands was presented to simulate the process of particle collisions in the large hadron collider (LHC). Similarly, a growing haptic sensation that then splits into two smaller haptic sensations was used to simulate the process of Meiosis (a type of cell division). It was further discovered that dialogue around the haptic probes (post-experience) naturally resulted in a co-discovery process and that shared exploration of scientific phenomena contributed to the enjoyment of mid-air haptics technology for public engagement therefore complementing formal learning.

In contrast to previous studies where the haptic experience was created to match a specific graphic or semantic interaction space, Ablart et al. designed generalized mid-air haptic patterns to enhance movie experiences [52]. The authors then assessed their effects through physiological measurements (respiration, heart rate, skin conductance level) and questionnaires (SAM and Immersion Questionnaires) which hinted towards increased immersion, improved overall UX, and potentially the ability to influence the viewer's emotions. The latter opportunity (emotions) with the exception of the work by Obrist et al. [53] has yet remained largely unexplored due to the complexity and difficulty of customising the haptic stimulus and presenting it at the right time and place. The former opportunity (immersion) was further developed and successfully deployed by O'Conail et al. who created an immersive yet accessible (blind, deaf, or wheelchair) movie experience that is currently (2021) in use at the Aquarium of the Pacific in LA [54]. Their development process followed agile and design thinking principles, cycling through design, implementation and user testing at each phase or cycle, resulting in both a finished installation and valuable insights about how to design and match haptic sensations to different environmental themes (here aquatic) and using audio-visually synchronised dynamic haptic patterns that achieve semantic congruence (similar to Hajas et al. [55]). An unexpected finding of their study was a role reversal, where deaf or blind viewers who observed the mid-air haptic-enhanced experience of the movie would enthusiastically explain or describe their experience to family members.

Fig. 3: Left: Tactile bio-hologram by [58]. Middle: AR car design simulation and customization demo by [59]. Right: VR with a head mounted mid-air haptic array by [57].

2.3 Augmented, Virtual, and Mixed Reality

With AR and VR finally breaking through the novelty barrier and reaching increasingly more markets and applications (gaming, employee training, healthcare, education, and entertainment), almost all major HMD vendors are beginning to integrate outward facing camera systems into their headsets in what appears to be an effort to unlock a controller-free interaction paradigm. One reason for this is that the capabilities offered by hand tracking technologies in AR and VR environments have demonstrated remarkable advancements in the last few years with tracking accuracies down to just a few centimeters [56] and latencies of less than 20 ms. Another reason is that hand controllers are an added cost to the HMD.

With virtual and physical worlds merging into the metaverse, and with hand and gesture interactions in AR/VR becoming increasingly feasible, the opportunity to physicalise and enrich virtual and augmented content through mid-air haptics has been identified and explored by several authors. Perhaps one of the earliest efforts was that by Sand et al. who built an ultrasound mid-air haptic device and mounted it onto a VR HMD (see Figure 3) [57]. Through their testing of that new hybrid platform, it was not observed that the inclusion of tactile feedback resulted in interaction speed or accuracy improvements, but rather that the key benefits of this technology in this use case was a qualitative improvement in UX. Participants reported that they preferred to experience mid-air tactile feedback, rather than not, and felt slightly less mentally and physically tired.

Similar observations were made by Pinto et al. who explored pick-and-place tasks within a mixed reality robotic teleportation environment [60]. In their implementation, the authors were looking to teach a robotic arm how to perform such tasks without using any kinematic or programming languages, but instead through human hand guidance, i.e., mimicking of user movements. In order to replicate the experience of physical hand-guidance more closely, ultrasonic mid-air haptics were introduced since hand grasping movements are reported to be more realistic and ergonomic in the presence of tactile feedback. Pick and place grasping tasks in VR were also studied by Frutos et al. [61], who concluded that while task completion time was mostly unaffected through the addition of mid-air haptics to the interaction, grasping accuracy, UX and overall preference was improved, particularly for small objects.

2.3.1 VR Instruments and Games

Motivated by the prospect of enhancing UX, Hwang et al. developed a musical piano in VR whose keys were emulated through ultrasonic mid-air haptic feedback [62]. Follow-up user studies of their AirPiano VR prototype, confirmed that adding mid-air haptic feedback significantly improved the UX. Their adaptive tactile intensity feedback during key pressing further increased clarity, reality, enjoyment, and user satisfaction.

In a similar musical VR environment, Georgiou et al. presented a rhythm game akin to playing the bongo drums that leveraged hand tracking and mid-air haptic technologies [63]. It is worth noting here that VR rhythm games are very popular, with the likes of the Beat Saber rhythm game achieving sales of up to USD 180 million as of February 2021 since its launch in May 2018. In their implementation of the VR bongo rhythm game, the mid-air haptic stimuli were not designed to accurately mimic the physical shape of what was seen on the screen during the game, but rather to convey its dynamics and motion. For instance, tapping tactile sensations presented at the middle of the palm were synchronized with tapping gestures and congruent audio-visual effects, while moving stimuli where presented during swiping gestures (similar to those used in automotive IVISs [29]).

Following a similar approach, where dynamic haptic stimuli are used to accompany and enhance VR experiences, Martinez et al. sought to haptify abstract and supernatural notions like the shooting of lightning bolts from the user's hands [64] (so called "Special Effects" as discussed in Chapter 3). The challenge there was to design haptic sensations that were temporally congruent with audio-visual cues, and that felt somehow similar to what one might expect or imagine such supernatural experiences should feel like on their hands. To that end, four tactile stimuli were designed and projected to the centre of the user's palm during a variety of interactions to represent the touching of a magic orb (a tactile focal point skipping through multiple random haptic points), casting a lightning spell (rapidly moving the haptic point from the wrist to the index fingertip) and finally casting a fire spell (spiral following the infinity path).

2.3.2 AR/VR/MR Training and Simulation

Looking beyond gaming and entertainment use cases, perhaps the most pivotal VR application is that of training and simulation. According to market research, the virtual training and simulation market size was valued at USD 262.36 million in 2020 and projected to reach USD 628.62 million by 2028, growing at a CAGR of 13.30% from 2021 to 2028. A key driver to this projected growth has been the ability of VR simulators to include human action recognition methods, which provide students with an engaging and immersive training environment. To that end, Balint et al. have presented a VR training procedure to palpate the body with one hand and place the stethoscope with the other hand on different body parts [65]. During this interaction, mid-air haptics were used to convey touch sensation to a health care trainee while they would touch and feel the body of a virtual patient (e.g., to examine the size, consistency, texture, location, and tenderness of different organs and body parts). To further heighten user immersion, their VR system was programmed in a way that the user's hands cannot penetrate the patient's body or other objects in the simulated world. This pseudo haptic effect (i.e., the visual illusion of a solid object), combined with the vibrotactile haptic feedback generated by the ultrasound device was argued to adequately create the illusion of a physical interaction as required during a VR medical simulation and training environment.

While no prototype was created nor tested, the concept and premise for a mid-air haptically enhanced VR flight simulator was proposed and discussed for the first time by Girdler et al. [66]. Indeed, while an entire industry exists that installs real-life flight decks, displays and visual systems that replicate flight conditions for pilot training, novel mixed reality alternatives have been stepping in to provide low-cost, flexible and more accessible simulation environments. Already, mixed reality display products such as Collins Aerospace's Coalescence or CAE's Sprint VR Trainer, for example, allow not only a synthetic environment to be viewed, but also the user's hands, props and real world view. The authors argue that the number of props can be significantly reduced, virtualized and mid-air haptified therefore reducing cost, and increasing flexibility and accessibility of the training and simulation platform. Note that the Airbus A330 has over 200 buttons on the overhead panel alone, whilst the Boeing 737 cockpit has undergone dozens of iterations over the past 50 years. Haptic feedback in training and simulation environments can aid in the learnability of a specific cockpit layout, facilitate for faster and more accurate hand interactions within the peripheral visual field of the pilot. While such hypothesis need to be vigorously tested, mid-air haptic enhanced VR simulators also need to be FAA certified before trainees and pilots can officially log flight training time and maintain instrument flight rules (IFR) currency.

On a slightly less stringent road map, AR headsets and their ability to overlay digital content and virtual user interfaces on top of real environments have presented interesting new opportunities for product design and brand engagement, among many others. Here, users can see and interact with AR holograms, receive additional information, select actions by tapping on virtual screens, use hand gestures or verbal commands to interact with the digital content while also being able to interact with the real world around them. To that end, Dzidek et al. presented a prototype AR car design simulation and customization demo, and describe five mid-air haptic sensations that were applied to different hand gesture interactions [59] (see also Figure 3). Each haptic sensation was further customized to better match the intended interaction. For example, during the demo the user could reach out, touch, feel and hear the car engine rev. During that interaction, the audio waveform was used to dynamically modulate the base envelope of the mid-air haptic intensity profile, aiming to achieve good audio-haptic congruence.

External sensory data can also be used to alter the haptic sensation; for example, Romanus et al. [58] (see also Figure 3) used an expanding haptic circle sensation that was displayed at the same frequency as the heart-rate recorded by a wearable sensor (60-100 beats per minute). An AR hologram of a beating heart was also shown to the user in synchrony with the haptics and measured heart-rate, thus creating a so called tactile bio-hologram.

Finally, while all previously described AR, VR and MR mid-air haptic experiences are table-top and therefore suffer from reduced interaction volumes, Brice et al. and Howard et al. have proposed and demonstrated methods of mounting ultrasound mid-air haptic devices on robotic arms or rotating platforms, thus enlarging the effective work space for room-scale mixed reality experiences [67, 68].

2.4 Touchless computer interfaces in hospitals

Providing surgeons with control over medical images while maintaining sterility has motivated a number of research initiatives that explore novel ways of interacting with imaging technologies without touching them. Initially this was enabled through the use of gesture and voice control [69]. Many of these novel interface ideas and challenges were discussed by O'Hara et al. [70] under the theme of touchless interaction surgery, later expanded and reviewed by Cronin et al. [71] under the more general theme of touchless computer interfaces in hospitals. The four key motivators for introducing touchless control in medical environments according to the scientific literature have included, *i.* sterility (up to 95% of hospital keyboards have been shown to be contaminated), *ii.* enhanced 3D applications (e.g., navigating 2D and 3D data and images), *iii.* new and more efficient input methods (e.g., to speed up of specific tasks), and *iv.* tele-medicine and rehabilitation (e.g., using hand gesture recognition for post-stroke rehabilitation [72]). Recently, some of these use cases have taken on a whole new dimension enabled by HMDs such as the Hololens and Magic Leap that come with inbuilt hand tracking technologies enabling additional functions such as remote training of medical staff.

When designing touchless interfaces in medical environments for use by medical professionals, one needs to be very careful and aware of the key target

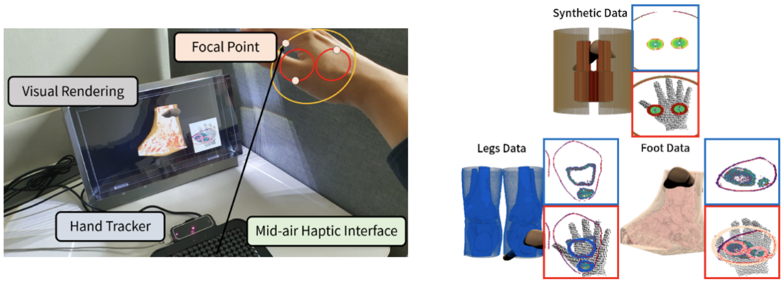


Fig. 4: Left: Experimental setup showing the user interacting with a 3D hologram of a CT scan. First, the user defines a region of interest, then a haptic rendering algorithm produces a set of tactile patterns which represent the internal structures of the region selected that can be explored and felt in real time by the user. Right: The volumetric data is converted into a tactile periphery render and is displayed to the user's hand. Reproduced from [75].

outcomes and expectations of the user that if adequately met will accelerate the introduction and integration of the proposed new technology into the realms of standard practice. From Cronin et al. [71], some of the key metrics and target outcomes stated include: ease of use, task completion time, accuracy, reliability, scalability, learnability, responsiveness, and UX. While many of these key targets relate to the overall touchless system's performance, and therefore depend on a complex set of sub-components and their interactions, several UX studies of ultrasound mid-air haptics have reported relevant benefits thus motivating their use in touchless medical prototype systems with haptic enhanced gesture input. For example, studies have demonstrated how mid-air haptics can help localize and interact with floating widgets [49, 73], enhance grasping of virtual objects in VR [61] and AR [74], improve the sense of agency [22], enhance perceived physicality of holograms [60], and improve usability and aesthetic appeal [38].

Exploring the use of mid-air haptics in touchless computer interfaces in hospitals therefore makes sense, however is significantly under studied.

Hung et al. developed a mid-air haptic system in 2013 to train cardiologists to search for a pulse [76]. The prototypes called UltraSendo and UltraPulse were piloted at Glan Clwyd Hospital in Wales where multiple clinicians evaluated its efficacy with mixed responses [77]. Balint et al. [65] implemented a training and simulation setup in 2018 in VR using ultrasound mid-air haptics to emulate the palpation of a virtual patient and train staff. Romanus et al. [58] presented a mid-air haptic bio-hologram, where the user can see, touch and feel a holographic projection of a user's heart beating (see also Figure 3). Data about the heart rate were wirelessly streamed live from a wearable sensor. Finally, Jang et al. [75] presented a demonstrator that combined a 3D holographic display and mid-air haptics to enable users to explore anatomical data (CT scans of a human body), where elements like bones and vessels are rendered by different tactile effects in mid-air (see Figure 4).

In summary, the use of mid-air haptics for medical applications and training is very much in an exploratory phase, with a variety of one-off demonstrators and indirectly studied benefits. One reason for this is that this use case is highly interdisciplinary requiring a lot of medical or industry specific expertise and insights as well as the integration with a variety of immersive display technologies.

2.5 Neuroscience research studies

Neuroscience is the scientific study of the nervous system and is a hugely multidisciplinary science. The emergence of powerful new measurement techniques such as neuroimaging, EEG, MEG, electrophysiology, etc. have allowed scientist to probe and then measure so as to understand how cognition and emotions are mapped to specific neural substrates. Specifically for touch, neuroscientists are interested in understanding how the somatosensory system processes tactile information.

The ability of mid-air haptics to produce complex spatial and temporal tactile stimuli has thus presented neurscientists with uncharted new territories for research and knowledge generation. For example, Perquin et al. asked whether the tactile system can be used to perceive complex whole hand motion stimuli, and whether it exhibits the same kind of established perceptual biases as reported in the visual domain [78]. To that end, they designed user studies that confirmed human hand ability to discriminate tactile motion direction, and affirmed the presence of a tactile 'Oblique Effect' (analogous to that observed in vision) where users are both better and more confident at discriminating motion in the vertical and horizontal axes of the hand, compared to those stimuli moving obliquely. In another example, Karafotias et al. studied whether VR and mid-air ultrasound tactile stimulation could reduce perceived pain simulated via the cold pressor test [79] and showed that mid-air haptic stimulation plays a significant role in increasing pain tolerance time. In contrast, Nakajima et al. leveraged the thermal grill illusion together with mid-air ultrasonic haptics and some mist vapor to display tactile pain or cooling sensations to the forearm [80].

Lehser et al. used EEG recordings to demonstrate the feasibility of eliciting somatosensory evoked potentials (SEPs) with ultrasonic haptic stimuli in mid-air [81], and that more complex tactile stimuli (e.g., shapes) tend to elicit a larger EEG wavelet phase synchronization stability indicating that a greater attentional effort is needed to solve more complex tactile recognition tasks [82]. It is worth noting that Carcagno et al. who performed a similar study to see if people could hear the ultrasound emitted by a mid-air haptic device did not detect any EEG phase locked activity [83]. Therefore EEG and SEPs could potentially be used to provide objective evaluation metrics for mid-air haptic feedback in different HMI settings. To that end, Brice et al. created a mid-air haptically enhanced VR environment where users were exposed to virtual spiders (in jars, near them, or on their hands) and used EEG recordings and skin conductance levels to measure changes in anxiety and distress. Their results were then contrasted to self reported data obtained through the Fear of Spiders Questionnaire [84].

Going beyond EEG and in order to use advanced neural monitors such as microneurography, Hayward et al. developed an electromagnetic shielding (Faraday cage) that can encapsulate the ultrasonic mid-air haptic device therefore reducing any electromagnetic interference (EMI) [85]. This is important since microneurography uses metal microelectrodes to detect neural traffic in nerves leading to or coming from muscle and skin receptors, a process which is very sensitive to EMI. Moreover, microneurography can discriminate between the type of mechanoreceptors being stimulated by mid-air haptics (i.e., Merkel discs (SA1), Meissner corpuscles (RA1), Pacinian corpuscles (RA2), and Ruffini endings (SA2)) [86] but also help study afferent neural pathways relevant to affective touch [87].

Finally, to aid in the design of mid-air haptic stimuli, especially for research purposes, Mulot et al. developed an open-source framework called DOLPHIN that enables easy control of the different haptic rendering parameters [88].

3 Design guidelines for effective mid-air haptic interfaces

Clearly, mid-air haptic technology has been used in a variety of applications ranging from automotive, to VR, to public displays in retail, to touchless interfaces in hospitals and museums, and even in the home [89]. Moreover, it holds great research potential in deepening our understanding of how our brain works and interprets touch. Closing the loop and bringing that understanding back into the applications presented in the previous subsections and beyond is an even greater but highly desirable challenge. From a UX perspective however, it is paramount to extract design guidelines and best practices from the plethora of applications and prototypes built to date – which is the focus of the present section.

As shown in the previous section of this chapter, ultrasound mid-air haptic technology can be used in a variety of applications to enhance touchless control interfaces, by providing the end-user with a sense of touch in mid-air. In such settings, the sense of touch is vital for control in at least two key ways: *1) Confirmation* - conveying that an action has been recognised by the system, and *2) Presence and Affordance* - conveying information about the physical requirements of control, i.e., where the control is located (presence) and what actions are required from the user to assert control (affordance).

We can see both concepts embodied by physical controls in the real world, e.g., the tactile cues one experiences when pressing a light switch. Mechanical feedback from the switch confirms the action has taken place and the physical properties of the switch (e.g., its shape, current state) are the affordances that help the user discover how to use it. A good user interface should therefore aim to give confirmation feedback and convey affordances, while also supporting a user's internal locus of control (i.e., the degree to which people believe that they, as opposed to external forces, have control over the outcome of events in their lives) which is one of Shneiderman's 8 golden rules of interface design [90]).

Mid-air tactile cues can address the requirements for control (confirmation, presence and affordance) and therefore support the user's internal locus of control by 1) enabling control, and 2) enhancing the feeling of control (an idea explored further in Chapter 4). Moreover, repeated use of a new mid-air interface that combines multimodal feedback (e.g., visual, haptic, audio and olfactory) can result in the build up of a user's experience with the interface and can translate into a feedforward loop that primes their expectations for their next interactions and accelerates familiarization via muscle memory, interface learning, mental models, etc. [91]. Below, we present some of the ways that an interaction designer can leverage mid-air haptics to their advantage while also highlighting some of the key challenges and considerations. These design recommendations are derived from findings in the literature and best practices adopted by the ultrasound haptics community.

3.1 Presence of controls

> Guideline 1: use haptic feedback to convey the presence and location of mid-air controls (e.g., buttons, slider elements, dials).

Tactile cues can signal the presence and location of a mid-air control interface, subtly indicating to the user that their hand is in the correct location for making a particular action. Vo et al. [92], for example, showed that when providing haptic feedback to indicate the location of a mid-air control, users were able to find and interact with it about 50% more accurately compared to providing visual feedback alone. Such improvements afforded to touchless interfaces by mid-air haptics can decrease the minimum recommended widget size from 2 cm^2 to 1 cm^2; since users can more accurately localise controls with haptic feedback, touchless interfaces can provide more functionality within a given size of workspace. This is especially important if the use-case requires the user to be visually attending to another element of the interaction, such as during driving, or if the interaction volume is small or

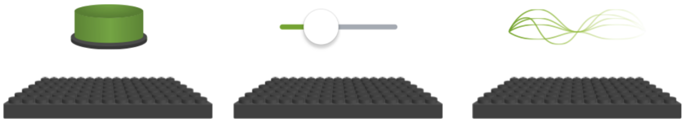


Fig. 5: Presence of controls. This image illustrates that a mid-air button, slider and general haptic feedback presence can be represented in mid-air making it easy for a user to find and interact with.

the input interface is dense, e.g., for a virtual keyboard such as in Hwang's AirPiano [62]. Figure 5 illustrates some example mid-air controls that can be displayed using ultrasound mid-air haptic feedback.

3.2 System status and changes

> Guideline 2: use haptic feedback to inform the user of system status and changes to system state.

The first principle in Nielsen's 10 usability heuristics [93] is to convey system status, so that the user understands the current state of the system. Adhering to this heuristic ensures that the user feels informed and in control. This is typically achieved in interface design by using Shniederman's third golden rule – offering informative feedback. Informing the user of ongoing operations and system state is important, especially when actions do not have an immediately noticeable outcome. For example, graphical user interfaces often employ progress indicators to show when the system is loading or carrying out lengthy operations, letting the user know they can expect a slight delay while the system processes information.

In a similar way, tactile feedback can be used to convey system status to users, e.g., through changes in haptic parameters and sensations. For example, a progress indicator can be represented haptically to a user by drawing a line or a circle on the palm of their hand, analogous to a graphical progress indicator (like in Figure 6). The chosen haptic sensation should aim to convey or trigger some kind of semantic meaning or relevance that is congruent to the action or system state itself. This is the principle behind the Ultrahapticons concept [34], further detailed in Chapter 5 of this book.

Fig. 6: The system status of a loading time being conveyed through tactile information.

3.3 Confirmation

> Guideline 3: use haptic feedback to give confirmatory feedback about input actions.

Tactile cues can be used to provide haptic feedback to confirm that the system has recognised the user's input actions. Confirmation is perhaps the most commonly considered and applied use of tactile cues in interface design, especially during user input as it can enhance the user's sense of agency. [22]. For example, haptic feedback during smartphone keypad input is now commonplace; a subtle 'buzz' or 'pop' vibration for every screen tap, or a burst of vibrations when adjusting a slider.

Intuitive confirmation haptics can improve the user experience and progressively establish trust between the interface and the user who feels in control. The same concept carries over to mid-air haptic feedback and gesture input and can be particularly useful in reducing the amount of time users need to perform the input accurately, or glance at the screen for additional visual feedback; reducing glance time is particularly important for car infotainment systems.

Martinez et al. [22] and Evangelou et al. [94] have studied the enhancements in the sense of agency imbued due to mid-air haptics during discrete input events in such as pressing a mid-air button followed by a haptic feedback confirmation sensation. Young et al. [29] have applied several such mid-air haptic feedback sensations, often enhanced with additional functional information such as directional and dynamic haptics to match the corresponding hand gesture. In a similar automotive setting, Georgiou et al. [25] considered agency and control during their haptic design of automotive touchless user interfaces by applying haptics throughout the interaction, not just during the input action. This was achieved by incorporating a solution for pre-emptive gestures: on entrance of a hand into the active interaction region of the interface, the user's palm is met with a continuous haptic sensation that fixes itself onto the palm and moves with the hand. Akin to lightly touching a keyboard key before pressing it, this sensation lets the user know that the system is engaged and ready for their input. Once the user initiates an action gesture (e.g., a tap or a swipe) the mid-air haptics delivers a powerful pulse to indicate confirmation of a click. Congruence between mid-air haptic design and hand gestures has been hypothesized to improve UX, but no evidence has yet been presented to support that.

3.4 Latency and timing

Guideline 4: aim to provide the *right haptic feedback* at the *right time* in the interaction.

Tactile cues must be well timed to facilitate effective control. We see from psychological studies that the perception of time and control are linked during our interaction with technology [95]. Therefore, one needs to consider two key timing questions: how much latency can the interaction afford, and should haptic cues be presented before, during, or after the interaction takes place?

The latency between when the user makes an action and when the feedback is actually provided is an important parameter to consider when designing for mid-air haptic control interfaces. As a general rule this latency should not exceed 100 ms, and should be as small as possible [96]. Excessive latency may lead the user to attempt an operation again because they were unsure if their action was recognised (i.e., missing confirmation feedback); for example, when a person continues pressing a button in a lift if the doors have not started to close.

In most gesture interaction scenarios, the computer must first recognise the user's action before it can generate a response, thus making it difficult to achieve instantaneous feedback, especially if the input gesture is long or complex. Therefore it is important to consider the type of gesture to be used in an interface, together with the type of mid-air haptic feedback that should be given, since these may sometimes be incompatible or result in excess latency due to the necessary gesture recognition time. This continues to be an issue, despite advancements and capabilities brought forward by machine learning approaches that enable the prediction of the intended gesture before the gesture completes [97]. Pickering et al. [98] for example classified gesture input into pre-emptive, function associated, context sensitive, global shortcut, and natural dialogue. From these, one might expect that functional, context sensitive and natural dialogue type of gestures will generally be more complex and take longer to complete or action, therefore delaying gesture recognition

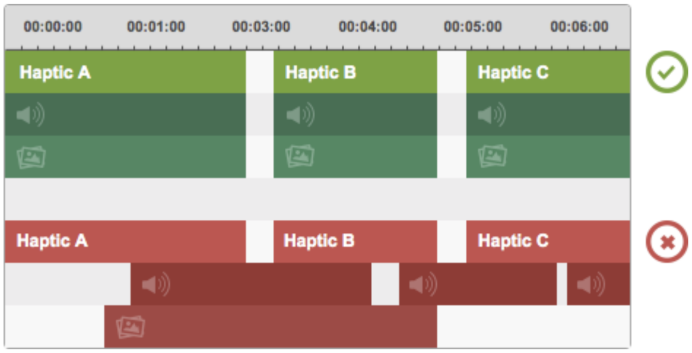


Fig. 7: Timing illustration of haptic, auditory and visual playback cues. Generally, these should be congruent in time and space, however sometimes applying a short delay can be beneficial.

and making the application of instantaneous haptic feedback difficult and prone to delays.

Choosing a suitable time to present tactile cues is also important and can be difficult to design for. If tactile cues are presented at the wrong time during the interaction, it can be confusing and frustrating to the user. Therefore, the best time to provide the tactile cue depends on the role it plays in the interaction. If its purpose is to guide or pre-empt the user prior to some input action, then providing tactile cues *before* their action begins can help indicate that their hand is in the correct location or that the system is engaged. If its purpose is to represent the physicality of the control interface (e.g., the size, shape or location of control elements) then feedback should be given instantaneously with as little delay as possible. If haptic cues are intended as confirmation feedback for an input action, e.g., pressing a button or adjusting a slider, then preliminary evidence suggests that a greater sense of agency is achieved when haptics are presented at the time of the *outcome* resulting from activation, as opposed to being presented at the time of the activating gesture itself. If the haptic interaction purpose is to represent the state or the function of a particular control element, then just like with hover-over gesture interactions, a small delay could be applied before haptics are displayed. Finally, how haptic feedback or feedforward stimuli are triggered and timed relative to other visual or audio stimuli is an important UX consideration (see Figure 7).

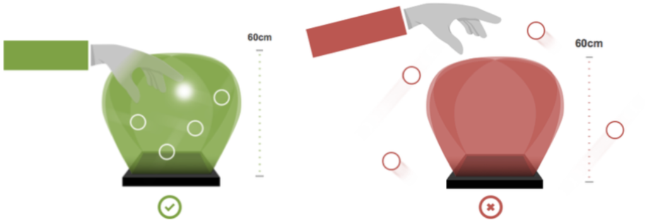


Fig. 8: The green diagram shows that the user's hand and the haptic interactive elements of the experience must be within the interaction zone to feel the optimum strength of haptic sensations. The red image shows a badly designed experience, where the interactive elements are outside the optimum interaction zone.

3.5 Interaction zone and hand positioning

> Guideline 5: use haptic feedback to reveal the interaction zone so users know where to provide input.

A key principle when designing a good interactive experience is that hand position and gesture are ergonomic for comfortable use [99]. Hand position also has important implications for the quality of input sensing and mid-air haptic feedback quality [73]. A well positioned hand can help to optimise the extent to which the user feels a haptic sensation. Ultrasonic mid-air haptic feedback requires a line of sight between the emitting phased array and the target region on the hand. Moreover, it is important that the hand is within range of both the tracking and haptic devices, otherwise input sensing is degraded. Therefore, one needs to choose hand gestures that expose the right parts of the hand in a suitable mid-air position, thereby enabling good tracking and good haptics. For example a fist/punch hand gesture is difficult to track by most gesture recognition algorithms, and will also occlude the palmar region of the hand which is the most sensitive to ultrasonic vibrotactile stimulation. One also needs to consider where the haptic and tracking devices are positioned relative to the interaction region while also considering any use case specific limitations and UX constraints.

The interaction zone is the volume of space above the ultrasound array in which the haptic sensation can be felt and where the hand tracking device will track the hand. The haptic designed thus must ensure that the interactions and the haptic objects in the experience are within the interaction zone, anything outside of this zone will be weak or not felt at all. Figure 8 shows the typical interaction zone for a 16 × 16 transducer phased array. The interaction

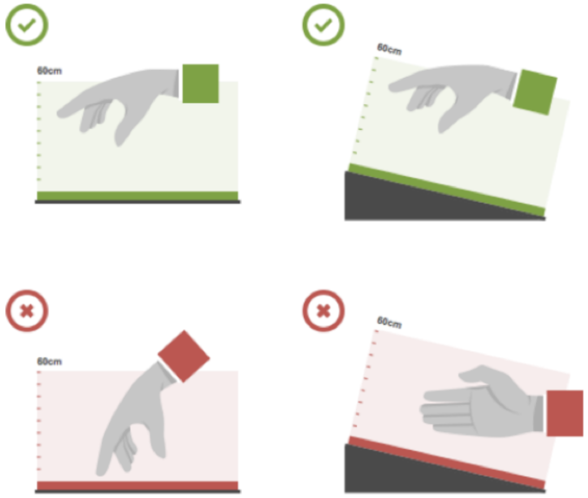


Fig. 9: Green images show the correct hand positioning within the interaction zone with the palm open and facing the array. Red images showing sub-optimal hand positioning.

volume increases with transducer count, and can take different shapes when multiple non-planar arrays are used.

The angle at which the focused pressure interacts with the hand is also an important consideration. Roughly, the acoustic radiation pressure applied to the hand will vary with $\cos^2\theta$, where θ is the angle between the source and the target surface on the hand, and is equal to $\theta = 0$ when they are parallel. Therefore, to ensure maximum haptic sensation, the experience design should encourage the user to have an open hand with their palm facing the array when inside the interaction zone. For example, if the array is placed pointing upwards on a table, the palm faces down. Conversely, if the array is facing downwards, acoustic pressure is directed downwards and the user should place their hand with their palm facing up. More complex gestures can of course be used and the angle θ need not be exactly zero. For example, a swipe gesture that exposes the palm to the haptic source is preferred to one that does not. Therefore, the UI/UX and haptic designer need to consider this limitation during both the interaction design and the physical design (where to place ultrasound emitters) of the experience (see Figure 9).

3.6 Haptic congruence

Guideline 6: maximize congruence between haptic sensations and other sensory modalities.

Ensuring that there is good congruence between haptic sensation and audio-visual cues, as well as being congruent with the system status, is an important and challenging consideration. In the simplest case, one should aim to match primary interface properties such as the interactive object's location, size and function. Virtual buttons or widgets for example should look, sound, feel and react similarly, e.g., they can be 'snappy' and 'clicky'. The mid-air haptics applied should therefore also imbue a similar 'click' or 'pop' sensation and should be fairly localized, either as a single focal point on the fingertip or somewhere on the palm. Detailed consideration and suggestions about the different haptic design patterns and when or how they relate to different types of interaction are discussed in more detail in Chapter 3 of this book.

Mid-air haptic sensations stimulate our cutaneous haptic sense (i.e., are vibrotactile) and lack a strong kinaesthetic force, a crucial element in our interactions with the physical world captured by Newton's third law. Thus, mid-air haptics will by definition fail to recreate accurate physical touch sensations of a holographic object. Despite this, mid-air haptics, together with audio and visual feedback can create 'good enough' representations of 3D touch interactions, especially if we follow some basic guidelines. For instance, when manipulating or grasping 3D holographic objects in AR/VR, haptic feedback should be applied to the contact regions of the hand and fingers intersecting the object [100], salient features such as corners and edges should be haptically emphasized [101, 55] (see Figure 10), the intensity of the ultrasound haptics can be modulated to adjust the perceived changes in stiffness when an object is pressed or squeezed [102], and visual cues can be used to further indicate when a grip is formed successfully [61]. It has also been argued that applying some semi-transparency shaders onto the graphical representation of a virtual object in AR/VR can help maintain congruence between a penetrable holographic object and a vibrotactile mid-air haptic interaction that lacks force feedback. This is already observed when contrasting AR and VR with a force feedback apparatus of equal intensity where VR graphics led to them being perceived as 60% stiffer than the equivalent AR ones [103].

Following this line of thought, Beattie et al. [104] proposed that the visually inferred tactile expectations of a virtual object, i.e., how we imagine that an object will feel before actually touching it, should be congruent to with the mid-air haptic effect applied. Beattie et al. [104] demonstrated this idea by using machine learning to match the visual perception of roughness to haptic rendering algorithm to produce visuo-haptic congruent textures. It is expected that visuo-haptic and audio congruence would further enhance the

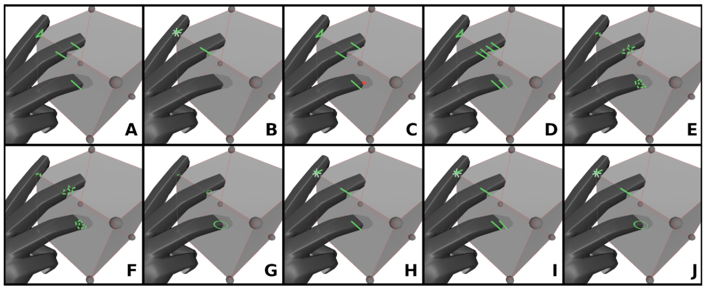


Fig. 10: Image showing where mid-air haptic feedback should be applied during hand-object interactions while also emphasizing salient features of the object. Reproduced from [101].

tactile reproduction of textures [105] and of other hand-object interactions, with audio in particular influencing how some mid-air haptic sensations are perceived [106]. In fact, through multimodal synthesis and haptic design, it is possible to supplement or augment a number of tactile and haptic experiences to either create supernatural experiences of abstract notions such, e.g., magic spells [64] or can lead to the creation of so called tactile illusions [107].

3.7 Improving perceived haptic intensity

> Guideline 7: use knowledge of haptic perception to maximize perceived intensity of haptic stimuli.

As with other perceptual modalities (e.g., visual, auditory) the perceived intensity (strength) of the haptic stimulus is primarily due to the maximal stimulation of the corresponding sensory receptors, which in this case depend on frequency selectivity, and spatial and temporal summation effects [108]. It is therefore important to know how one should modulate and leverage the available control parameters of mid-air haptics to maximize the perceived strength of the tactile stimulus. When using amplitude modulation, a stationary amplitude modulated (AM) focal point is felt stronger at frequencies of about 150–200 Hz [31, 109], which corresponds to the peak sensitivity of the PC mechanoreceptors. Also, similar to visual and auditory stimuli, the duration and intensity of mid-air haptics can be interchanged for a similar perceptual outcome. In fact, according to Driller et al. [110] who tested short impulses of a mid-air haptic point presented for 100–700 ms, it was observed that longer duration stimuli were generally perceived as more intense than shorter duration stimuli, i.e., a *temporal summation* effect was observed. Similarly, when utilizing more advanced haptic rendering techniques like lateral modulation (LM) and spatiotemporal modulation (STM), described in more detail in Chapter 9, one can take advantage of the so-called *spatial summation* effect, where the size of the mid-air haptic stimulus being presented will impact its perceived strength: i.e., the larger the stimulus against the hand, the stronger it will feel. Care needs to be taken here, however, as a larger stimulus will reduce the total pressure output capacity of a mid-air haptic device, resulting in a trade-off between the applied radiation pressure (Newtons per square meter) and the stimulus area.

To address this trade-off, LM and STM techniques propose to rapidly move a single focal point along a trajectory (e.g., a line or circle) thereby increasing the effective stimulus area while maintaining the instantaneous total applied radiation pressure. Further optimizing the sampling interval of STM paths can maximize the perceived strength of the vibrotactile stimuli [111]. Additionally, optimizing the focal point motion speed to match the surface wave velocity of vibrations on human skin (in the range of 5 to 8 m/s) can cause wave-front constructive interference, thereby increasing skin indentation and amplifying the perceived intensity of the stimulus [112]. Known characteristics of haptic perception like these can be used to increase perceived intensity, without any changes to the haptic device or its driving software.

3.8 Shape recognition

Guideline 8: select an appropriate rendering approach for the desired haptic shapes.

Accurate shape representation has been one of the earliest and most studied challenges associated with this technology, motivated through the presentation of haptic icons in car interfaces [34], science communication [51], menu navigation [113] and interaction with AR/VR digital and immersive worlds [114]. As such, there are multiple approaches towards the rendering of haptic shapes, which can be generally grouped under three distinctly different approaches: (1) placing multiple AM focal points along the perimeter of the shape [115]; (2) using a single STM focal point to rapidly trace out the shape [101], and (3) using a single AM focal point that moves to dynamically draw the intended shape while briefly pausing at salient features such as the shape corners [55]. In the following sections, we review each of these in more detail.

Multiple refinements and modifications to these methods exist and are also ongoing in state-of-the-art research, while their implementations differ in complexity, effectiveness, and suitability to each specific use case. Note that the difference in the three implementations can be illustrated when the

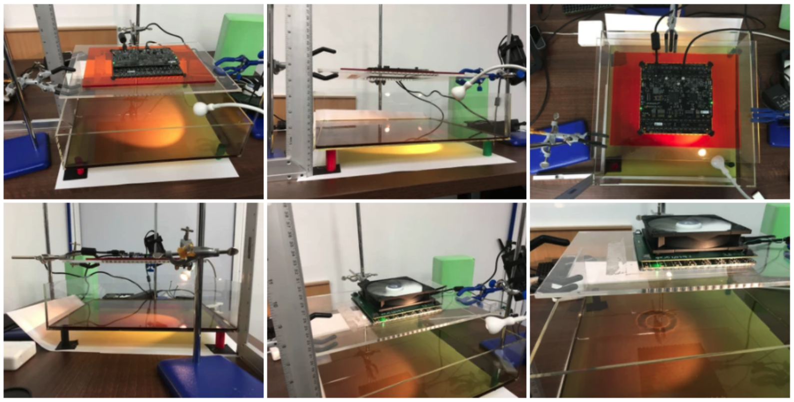


Fig. 11: Oil bath apparatus for visualising mid-air haptic shapes and sensation. An array is suspended approximately 15 cm above the oil bath. The oil is between 2 and 5 mm deep and of the correct consistency: viscous enough to show dispersion, fluid enough to be responsive. We have found that a 50:50 mix of olive oil and pumpkin seed oil give good results. The oil bath must be level and raised approximately 3 cm above a white surface or table. A bright single light source is used from above or at an angle to project the shadow of the distorted oil onto the white surface. If the light is bright enough, it can reflect onto a wall to create a screen. The room must be as dark as possible to achieve the best effect. If operating the array for long, it is advisable to use a cooling fan to suck out hot air and avoid over heating.

acoustically rendered shape is projected onto an oil bath using the apparatus described by Abdouni et al. [116]. Figure 11 shows a similar apparatus to that of [116]. In the bottom right sub-figure one can clearly observe an STM circle pressure field being applied to the thin layer of oil bath. The caption of Figure 11 describes how one can reproduce this apparatus and view mid-air tactile holography.

3.8.1 Multiple AM points forming a perimeter

Long et al. [115] presented the first implementation and successful user study of volumetric rendering of 3D shapes (e.g., cube, cone, pyramid, etc.) with an 80% recognition rate using a novel multi-point solver of ultrasound mid-air haptics. While the user was unable to enclose a 3D shape in a traditional sense due to the lack of force feedback, the 3D object, such as a sphere or pyramid, could be explored from all sides using the palm and fingertips. In their implementation, the user's hand was represented as sixteen planes (a palm polygon and three separate polygons for each finger). When some of these planes intersect an object in the 3D scene, the hand-object intersections are found as line segments and processed into continuous arcs. Multiple ultrasonic focal points are then sampled along the arcs at appropriate spacings and presented onto the user's hand by a 320x phased transducer array. Repeating this procedure which takes a few milliseconds to compute would re-position the focal points dynamically during active exploration or manipulation of 3D digital objects by the user's hands therefore enabling real-time haptic sensations and dynamically changing shapes. Each focal point was amplitude modulated (AM) at 200 Hz, however multiple focal points were grouped together into two groups, with one of the groups modulation pattern shifted by $\pi/2$ as to improve the array efficiency.

In a different setting where participants were prohibited to move their hand freely during the mid-air tactile interaction (passive touch) and using just a 100x transducer phased array, Korres et al. [117] used a similar implementation to Long et al. and studied 2D shape recognition (circle, triangle, line, and plus sign) and reported an average accuracy of about 60% with a mean recognition time being 14 seconds. In yet a slightly different setting Rutten et al. also used a similar implementation to Long and studied how identifiable mid-air haptic shapes (4 static and 4 dynamic) were [118]. These were presented to an older group of people than in previous studies for just 1 second using a 196x transducer phased array. They observed a 44% recognition rate which is quite low, thus suggesting that participant age, the short stimulus time, a smaller array and the large variety of shapes presented could all have a negative impact on shape recognition. However, they also concluded that line based patterns were generally better recognised than circular ones and that dynamic sensations made of a moving focal point were more accurately recognised than static shapes made by multiple focal points. Further improvements have been reported when the acoustic pressure distribution applied to different parts of the hand surface is controlled to mimic the contact area with the virtual object [119]. This however requires larger transducer counts capable of more precise control of the acoustic fields and more complex computations of the hand-object interactions.

A slightly different approach is that achieved by Morales et al. [120] where a modified Gerchberg–Saxton algorithm is used to produce a target acoustic amplitude field by iteratively back- and forward-propagating with a discretization masking step in between. Even though the mathematical algorithm is very different from that of a multi-focal point solver, the resulting acoustic field resembles that of densely-packed AM points. User studies on the ability of such algorithms to produce well-recognisable tactile shapes in mid-air have not yet been conducted.

3.8.2 Single STM point rapidly tracing out a shape

Mid-air haptic devices utilising phased arrays are limited in the amount of acoustic energy they can output thus limiting the number of focal points they can display simultaneously. To mitigate this shortcoming, STM rendering techniques were proposed by Kappus et al. [121] whereby a single focal point at maximum pressure output is rapidly (~ 7 m/s) moved along a path or a set of so called polylines which trace a geometric shape resembling the hand-object intersection profile [101]. Howard et al. studied the ability of people to discriminate the orientation of a haptic STM straight line presented at different angles ($\alpha = \{0°, 45°, 90°, 135°\}$) to the palm of a user and observed quite high recognition rates of 92% to 99.3% [122]. When displaying more complex shapes however such as a circle, a triangle or a square, Hajas et al. observed a shape recognition of just 51.7% and 57.3% for passive and active touch explorations, respectively [55]. These studies seem to suggest that the STM shape rendering approach is not robust enough and therefore not well suited for the tactile presentation of 2D and 3D shapes in mid-air. However the above studies have only considered holographic shapes which are of diameters of a few centimeters being projected onto the user's palm during active or passive explorations. In contrast, Matsubayashi et al. applied STM rendering along micro-paths tracing the perimeter of finger-object contact cross-sections and observed an avergae shape recognition of 65% [123], an improvement of about 25% compared to a stationary AM focus point located at the centre of the finger-object contact point. It should be stated however that Matsubayashi et al. were using a very large array with 3984 transducers and only compared between four local shapes (curved, flat, edge, corner).

3.8.3 Single AM point dynamically drawing a shape

Currently, the most effective method for presenting complex tactile shapes using ultrasound mid-air haptic devices (84.7% and 88%) has been reported by a dynamic rendering method described by Hajas et al. [55] and Rocchesso et al. [113], both of which leverage AM points to dynamically draw a given shape or icon on the user's palm, akin to a pencil writing on paper. This method is known as *dynamic tactile pointer* (DTP). Slowing down the speed of the DTP according to the curvature of the trajectory, or even pausing completely for $300-450$ ms at corners, helps the user identify salient features of the shape or count its corners. Note that corner identification was a key failure point mentioned by users in a study by Marti et al. [124] who used a 196 transducer array to project static tactile shapes (circle, square, point) and match them to visual or verbal representation probes. While DTP successfully manages to convey corners thus helping with the discrimination between circles and polygons, one issue with this method is that it can take a few seconds for the icon/shape to be fully dynamically rendered, thus introducing a minimum delay in recognition time. Adding a second AM focal point that draws on the palm simultaneously can address that in some cases, depending on the path being drawn, e.g., for the equals and times symbols ($=$ and $\times$). Indeed it was recently shown that it was significantly easier to identify stimuli that are rendered at a slower pace (i.e., longer duration) regardless of the number of draw repetitions [125]. It is noted that recognition accuracy and time can be improved when the set of icons chosen are somehow meaningful to the actions they are supposed to trigger or relate to specific mental models of their application [34]. Therefore, the choosing and the design process of the specific icons that constitute a mid-air haptic interface is as important as the rendering method used.

3.9 Haptic switching duration

> Guideline 9: use a brief gap between different haptic sensations to help users recognise change.

Pauses between mid-air haptic sensations can be as noticeable and perceptible as the sensation itself. Rather than presenting a series haptic effects in sequence, brief pauses or gaps can be used to increase impact and make changes more noticeable, e.g., when moving from one button on a mid-air control interface to another. This delay, known as the *haptic switching duration*, can support better recognition of the change in haptic sensation. When switching between haptic patterns, leaving a delay of at least 200 ms is advisable, however a rigorous investigation of the optimal gap duration has not yet been conducted.

3.10 Haptic sensation priority

> Guideline 10: prioritise haptic sensations so that users receive the most important or salient feedback.

When multiple haptic sensation need to be presented simultaneously, it is logical to only present the one which is most dominant or important to the user experience. This is similar to visual hierarchy principles in visual design, when dominance conveys something critical about the experience. For example, the mid-air game experience described by Corenthy et al. [40] used the hand's movements to represent the position of a spaceship, and applied different mid-air haptic effects to present a number of different game actions and events, such as lasers fired from the user's space ship, entering or jumping between scenes, etc. However, when the spaceship got hit by enemy fire, its haptic sensation was prioritised over others to represent the explosion,

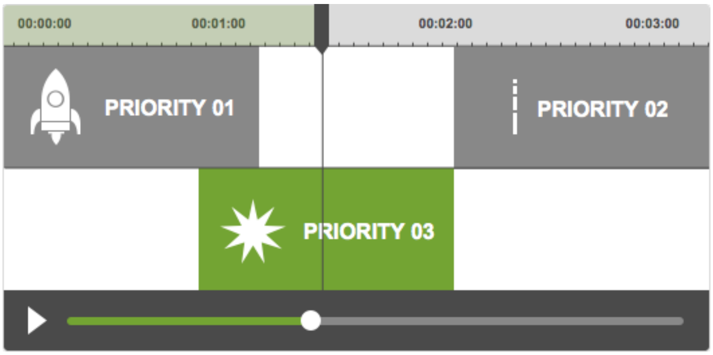


Fig. 12: Illustrating the haptic priority principle where the highest priority haptic will play.

which was a more important and rare game event, as illustrated in Figure 12. Therefore, depending on different events in and during an interaction, the priority will shift and should be considered by the UX and haptic designer.

3.11 Static or moving?

Guideline 11: consider if your mid-air haptic interface should remain in position, or follow the user's hand movements.

This question refers to the way that mid-air haptics are applied to the user's hand while also leveraging the capabilities of the hand-tracking system. A static control panel composed of a matrix of buttons for example was implemented in the automotive study by Harrington et al. [26] where the driver would feel the relative locations of buttons arranged in a 2×2 grid and then choose which one to activate via a pressing down gesture. Such an implementation is robust and does not require advance hand tracking algorithms as a simple proximity sensor could suffice. In contrast, a moving control panel where the buttons 'come to you' was implemented in an automotive setting by Young et al. [29] where a gesture was detected and a set of haptic sensations were accurately projected towards the user's palm or fingers as long as they were within a predefined interaction region. The two scenario are illustrated in Figure 13. Static mid-air haptic interfaces are therefore generally easier and more straight forward to implement and comprehend as they represent a more direct one-to-one, mapping between physical space and holographic touch interactions, while dynamic ones require a robust implementation of gesture input yet facilitate for a more natural 3D spatial interaction. Choos-

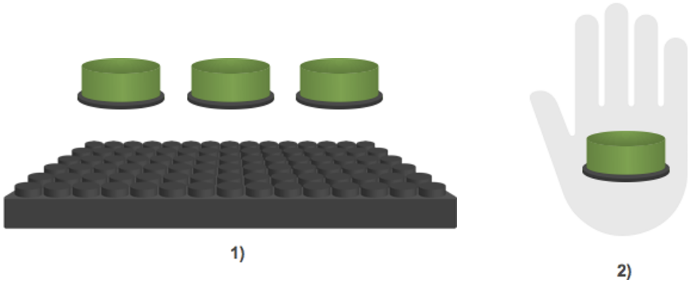


Fig. 13: 1) *Static:* three buttons fixed in space within the interaction zone. The user will move their hand between these buttons, but the haptic for each button will be fixed in space. 2) *Dynamic:* the button follows the user's hand. The user will feel a button wherever their hand is located within the interaction zone. The a 'click' sensation is projected when the user taps one of the three static buttons or the dynamic button.

ing which of the two types of haptics is more suitable will strongly depend on the use case and available hardware capabilities. Chapter 3 further considers the use of static vs moving haptic interfaces.

3.12 Multimodal feedback and synthesis

Guideline 12: combine mid-air haptics with other sensory modalities to create a richer user experience.

Other sensory modalities (visual, audio, olfactory and even gustatory) can be combined with that of haptics to enhance utilitarian or functional aspects of an interaction, as well as its experiential qualities. For example, peripheral visual feedback can be leveraged to aid users in finding where to place their hand for improved mid-air interaction (better accuracy and faster interaction time) [73]. Here, the authors used an LED strip that interpolated between green and white hues as a function of the proximity distance between a target and the user's hand position. A similar arrangement was used by Shakeri et al. in an automotive setting, where the LED strip would pulse briefly in white when the user's hand would enter the interaction region, blue lights would animate from the ends of the strip towards its centre during a 'v' gesture, while yellow and blue lights would animate to the left or right during a swipe or circular gesture [28]. The inclusion of such peripheral visual feedback together with mid-air haptics was shown to significantly reduce the average eyes-off-the-road time and the subjective workload during a driving task. Even better results were however reported for the combination of haptics plus audio feedback which were ranked as the most preferred form of feedback in their study [28]. These examples leveraged multiple sensory modalities to make user interface feedback more salient.

In a different, more immersive setting, mid-air haptic feedback was combined with different sound cues that were triggered by tapping and swiping hand gestures to create a VR rhythm game for playing the bongo drums [63]. As rhythm games in general require tight synchronicity between visual, audio, and haptic cues, the author's demonstrator showed that mid-air haptics can be reliably and pleasantly displayed in real-time and in sync with audio visual cues in an immersive VR setting thereby increasing the user's sense of being in control and feeling of interacting with a a more responsive system [22]. This example used multimodal feedback for a higher quality user experience.

Mid-air haptics can also have a significant effect on several experiential and perceptual dimensions (e.g., intensity, roughness, regularity, roundness, and valence) when displayed in conjunction with different audio and visual stimuli. Early evidence by Albart et al. suggested that when congruent stimuli, e.g., mid-air haptics and audio stimuli that were rated as both being quite 'round' are presented simultaneously a general enhancement effect was reported, while incongruent stimuli could alter or augment the perception of the bi-modal (audio/visual plus haptic) stimuli [126]. Indeed, in a recent study by Freeman it was shown that adding white noise audio (emanating from the haptics device itself) increased the perceived roughness of a mid-air tactile sensation, while pure audio tones had a small but opposite effect [106]. These examples demonstrate the potential benefits of using congruent, or deliberately incongruent, sensations from different modalities to influence the haptic experience.

Additional guidelines on how to best combine auditory and mid-air haptic feedback in a simple light-switch interaction was recently presented by Ozkul et al. [127]. Not only did they demonstrate the added value of multimodality with mid-air haptic feedback in influencing pleasantness, the authors results also suggested that adding more sensory components resulted in more pleasantness (trimodal > bimodal > unimodal) while mid-air haptics and visual feedback was the preferred bimodal pair composition. Further, it was shown that longer haptic stimuli and the use of designed sounds (as opposed to digital click sounds) led to higher perceived pleasantness and clarity.

In a more creative yet real world setting (i.e., outside of a controlled laboratory) comprising interactive art installation, Vi et al. reported on how to design art experiences whilst considering all the senses (i.e., vision, sound, touch, smell, and taste) [49]. The authors identify that touch, as displayed through a mid-air haptic device, was rated by the 2500 visitors as the most important sense during the whole experience, as opposed to scent and taste, and that the combination of mid-air haptics and sound was immersive and provided an up-lifting experience of an art painting. Thus, as more such findings are explored and documented for different use cases, we can anticipate that UX and haptic designers will be able to tailor the parameters of different mid-air haptic stimuli (size, shape, frequency etc.) to deliver richer tactile and multimodal experiences that better reflect the desired outcome effect and will be potentially able to modulate and control various experiential aspects of the different interactions and applications. While this is a fascinating future vision with great potential, guidelines of exactly how one should synthesize multimodal feedback are however still in an early exploration phase with very few clear cut examples. Namely, while mid-air haptics have been integrated in short movie experiences and have been shown to improve valence, arousal and liking ratings, design guidelines on how to best present and time them is still under explored.

3.13 Summary

In this section we have reviewed numerous aspects of mid-air haptic design and presented 12 guidelines, which make recommendations for effective haptic design and prompt designers to consider how to make the best use of mid-air haptic technology for their intended user experience. In the following section, we suggest an iterative haptic design process that can be followed to create a quality mid-air haptic experience.

4 Methods

When designing a mid-air haptic experience, you can follow a general interaction design process and employ methods and techniques used in other areas of UX design. However, there are additional special challenges to be considered, which may not be encountered in other fields of interaction design. In this section, we review some of these challenges and make recommendations about how to overcome them.

Our general process follows the four key activities often found in a typical interaction design process, specifically based on the model by Sharp, Preece, Rogers [128]: 1) establish requirements, 2) design alternatives, 3) prototype solutions, and 4) evaluate them (see Figure 14). Hapticians can use this section as a crash course in how to think about interaction design, and interaction designers can use this section to adapt their craft when designing for a mid-air haptic interface. While this section is described in the order one might encounter these activities, the overall process is highly iterative and can be blended or rearranged as needed.

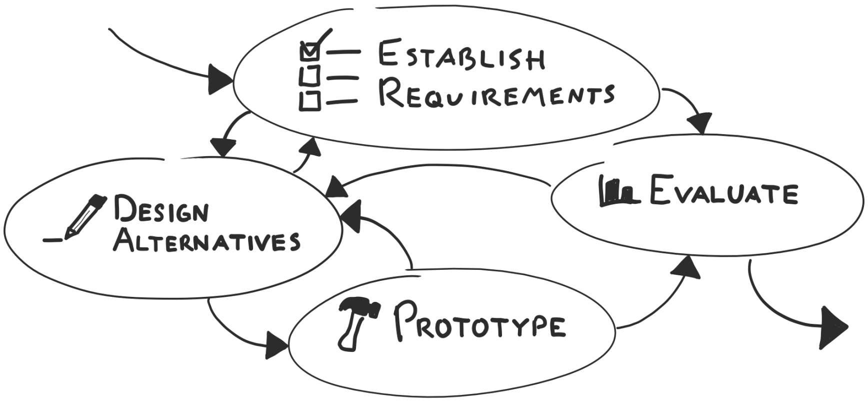


Fig. 14: The major interaction design activities, as adapted from Sharp, Preece, Rogers [128]. Interaction designers rapidly iterate between gathering requirements, designing alternatives, prototyping potential designs, and evaluating those prototypes.

4.1 Why care about user experience design?

Haptic technology often faces a crisis of justification. The costs are high, and in many application areas the main added value comes from subtle experiential benefits that are difficult to link to the bottom line [129]. However, recent work has started to study the impact of haptic feedback on experience, especially in digital media. Work by Maggioni et al. [130] showed that adding mid-air haptic or vibrotactile feedback can improve UX as measured by the AttrakDiff questionnaire [131]; specifically, movies with mid-air haptic and vibrotactile feedback were rated as more pleasant, unpredictable, and creative than movies without haptic feedback. Other recent studies highlight the benefits of haptic feedback from other types of haptic device. For example, Pauna et al. worked with motion seat feedback in movies, finding physiological signals of positive emotions increased [132]. Singhal and Schneider [133] examined video games, showing that vibrotactile feedback can improve player experience as measured by the Player eXperience Inventory (PXI) questionnaire [134] - specifically increasing measures of appeal, immersion, and meaning, with some moderation by visual effects.

Ultimately, haptic feedback, including mid-air haptics, can enable more tasks, make many interfaces more usable, and have value simply by being a better experience, if designed correctly.

4.2 Establish Requirements

The commonly stated first step in any interaction design process is to engage with stakeholders and understand their needs, and then use this to establish requirements [128]. Doing this step early is essential, otherwise you might design a solution to the wrong problem, and fixing core design problems after delivery is more costly than addressing them during the requirements and design phase [135]. From a design standpoint, immediately jumping to a solution risks 'tunnel vision', and can limit the number of solutions considered, potentially missing out on more suitable alternative designs. Most design processes advocate starting by considering as many options as possible.

However, when hapticians talk to people, there are major barriers to communication. Interviews with expert hapticians tells us that people "don't really know what to do with [haptics]", even though there's an expectation that it will add value to the user experience [129]. Similarly, it can be challenging to communicate about haptics because there is such a varied (and ambiguous) vocabulary used to talk about tactile experiences [136]. When clients do come in with questions, they are often inscrutable, such as creating the design as being "variable". To that end, it is essential that hapticians have existing demos and examples to help communicate with the various stakeholders of their projects and establish their understanding of what tactile experiences are (and are not) possible.

After engaging the various people involved in your project, an important activity early in the interaction design process is to consolidate the project's goals. In interaction design, these goals are often split into pragmatic goals (utility and usability) like "easy and quick to use", and hedonic (experiential) goals like "immersive" or "surprising". As we've already covered in this chapter, mid-air haptic feedback can help improve utility (e.g., with reduced eye-off-the-road in automotive applications [26, 27]), usability (e.g., with tasks like shape recognition [55] or widget localization [92, 73]), experience (e.g., with movies [52]), and engagement (e.g., with digital signage displays [37]). However, designers may often consider additional or alternative design goals. For example, Kim and Schneider recently tried to formalize a specific construct of "haptic experience (HX)" [137]. Their HX model is intended to guide UX goals across different haptic devices and capabilities. While it is not yet evaluated with mid-air ultrasound haptics, a study of over 260 participants experiencing vibrotactile feedback provides initial evidence that the HX model's 5-factors form different, but coherent, goals when rated [138]. These goals may be suitable in your next haptics project.

In summary, two key tasks when establishing design requirements for a haptic experience are to:

1. Find ways to effectively communicate about haptics with stakeholders, e.g., using modifiable demonstrators; and
2. Define goals and application requirements, both pragmatic and hedonic.

4.3 Design Alternatives

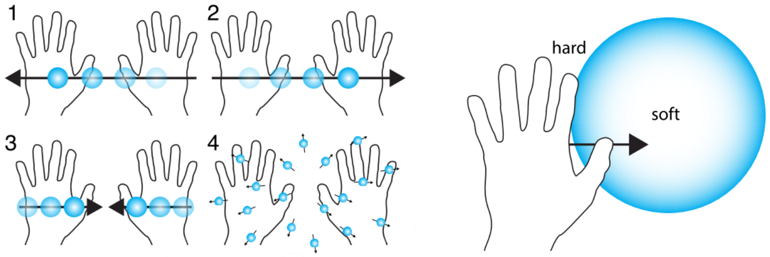
Once goals have been identified, many designers instinctively launch into building a prototype. However, pausing to deliberately think through what you might design will help create the most effective designs and mitigate hidden risks. There are two ways to deliberately think about your designs: 1) conceptually (top-down), and 2) through device exploration (bottom-up).

4.3.1 Top-down: employ a conceptual model

It can be valuable to step away from the device you are using and think about the concepts that might be used in your design. This is known as conceptual design or conceptual modelling [139, 140]. Novices to haptic design, especially those with an engineering-focused background, are often unaware of conceptual design, leading to a common misstep in haptic design [141].

A conceptual model is a "high-level description of how a system is organized and operates" involving major metaphors and analogies (e.g., the desktop interaction metaphor with files and folders), task-domain concepts (e.g., a computer file has a date created, last modified, file size), and relationships between concepts (e.g., folders contain 0 or more folders and files) [139]. A conceptual model can take several forms, from diagrams to a defined lexicon, and can inform application vocabulary and documentation, whilst initiating and focusing the implementation, thus saving time and money by reducing development time [140]. In haptic design, conceptual models include decisions like how haptics fits in with other sensory feedback (is it primary or secondary? synchronized or complementary to other senses? cf. with some of the guidelines presented in Section 3) and how the user is represented (are they an idealized invisible observer or linked to a object with an impact in the environment?). For more ideas, MacLean et al. [142] offer a selection of frameworks for multisensory haptic interactions, while Seifi et al. [141] document an in-depth set of design decisions and consequences for novices with force-feedback design.

Once you have established the conceptual design, you can then start to map concepts to how they are represented in the *concrete design.* Concrete design is what most people think about when they think about design, for example, the colours, fonts, materials, and layouts used in a visual interface. In haptics, this involves making careful choices about when to deploy haptics, and how to set the technical parameters that result in the intended experience. Many practical examples about mid-air haptics were given in the previous section of this chapter. While your specific conceptual model will inform the right concrete design, you may be able to leverage existing research to determine the right mapping. For example, Obrist et al. [136] document a vocabulary used to describe different frequencies and amplitudes for mid-air feedback; if you need to represent a “strong” or “weak” sensation, you might have natural concrete design decisions to represent those variations.



(a) A particle collision effect, where the user’s two hands passively feel dynamic particles moving, then colliding and exploding.

(b) A cell nucleus effect, where the user’s one hand actively moves to feel the structure of the nucleus.

Fig. 15: Two examples of mid-air haptic experiences for science outreach [143]. These two designs employ very different conceptual models and interaction modalities, both intentionally designed before implementation. Reproduced with permission from [143].

An excellent example of conceptual design for mid-air haptics is that by Hajas et al. [143], which includes six designs of scientific concepts that were brought to science educators. One design demonstrated a dynamic experience, specifically, a particle collision. The user puts two hands over the device, holding them steady, then feels three effects in sequence: 1) a particle moving left across both hands, 2) a second particle moving right across both hands, then 3) two particles moving towards the middle, followed by a ‘sparkly explosion’. In this example, the user passively feels the experience with both hands, the device needs to render a particle that moves, and an explosion effect. This was then rendered as a concrete design using two Ultraleap devices, one for each hand. Impulses were sent with 200 ms delay to evoke movement, with the particles rendered at 200 Hz using amplitude modulation (AM). The ‘explosion’ was rendered by randomly moving points of 30 Hz using spatiotemporal modulation (STM). A second design was intended to represent the structure of a cell nucleus - in this demonstration, the cell nucleus was statically rendered, and the user could use a single hand to explore its haptic representation, which had a ‘hard’ exterior and a ‘soft’ interior. The concrete design was a disc pattern rendered at 80 Hz frequency for the cell exterior, and a pattern at 10 Hz frequency in the middle to represent the ‘soft’ interior. These two exemplar designs use the same haptics device and are from the same domain (i.e., science communication), but the interaction modality and conceptual models are quite different and are bespoke for the intended application goals.

4.3.2 Bottom-up: use examples

One of the best ways to explore what is possible with mid-air haptic design is to look at existing examples and demonstrators. In more mature fields like graphic design, example viewing at specific times (early and repeated) has been linked to more novel and common elements [144], and dedicated support with example browsing tools has the potential to improve outcomes [145]. In other fields of haptics, such as vibrotactile design, examples have been linked to several benefits in design. Schneider and MacLean [146] presented several interfaces with different ways of incorporating examples into a wearable vibrotactile design, with several key insights of how to effectively use examples. First, when provided with examples, designers tend to inspect all provided examples, find the closest to their intended design, and then use it as a starting point. Second, providing incorporable, visible examples (examples that are "open source" and can be changed and inspected) not only helps designers get started (e.g., by copying then modifying the closest design sample), but also helps them learn how to work with the tactile modality by observing existing patterns.

With mid-air haptics, you can draw inspiration from existing libraries of effects. At the time of writing, several examples include those found in the Ultraleap Sensation editor (Figure 16) or Unity examples[1] and tutorials[2].

In summary, the main advice for exploring design possibilities is to:

1. Engage with conceptual design by deliberately thinking about the conceptual elements of the intended design and how they relate to each other (top-down design).
2. Gather examples of designs, devices, and materials to provide potential starting points, build your repertoire of ideas, and identify compelling candidate designs that are possible with the available haptics hardware (bottom-up design).

4.4 Prototype

Prototyping is the process of taking your designs from initial conception to (near-)final execution. To create effective and successful prototypes, you will need to generate many different prototypes of different scope, searching the design space to come up with a suitable final implementation that satisfies the initial design goals and experience requirements.

To arrive at a suitable design, you must juggle two competing goals: exploring as wide a range of possible solutions as possible, and developing those

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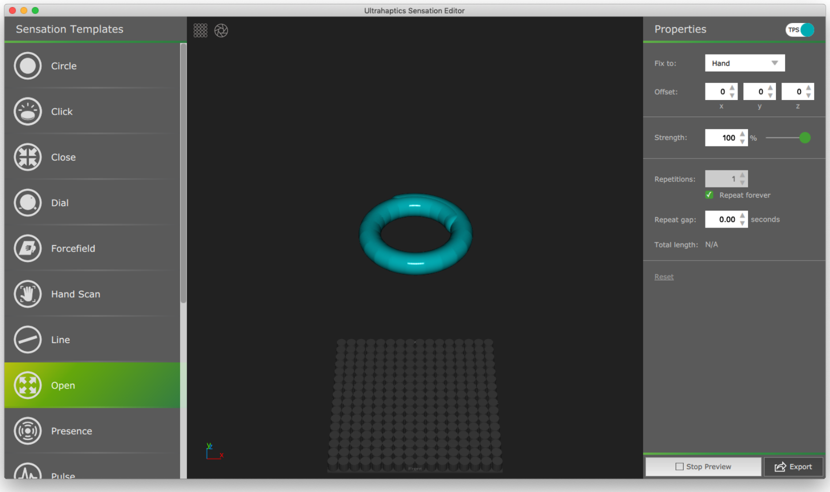
[1] `https://github.com/ultraleap/UnityExamples`

[2] `https://developer.ultrahaptics.com/kb/unity`



Fix to: Hand
Offset: 0 0 0 (x y z)
Strength: 100 %
Repetitions: 1
☑ Repeat forever
Repeat gap: 0.00 seconds
Total length: N/A

Fig. 16: The Ultraleap Sensation Editor demonstrating existing examples for mid-air haptic designs. These are incorporable into designs because they can be edited. Incorporable examples provide a direct starting point for anyone creating a new sensation, and an indirect way to learn how to design new effects by observing patterns used by others [146].

solutions into final proposals. The way to achieve this is through iterative *elaboration* and *reduction*.

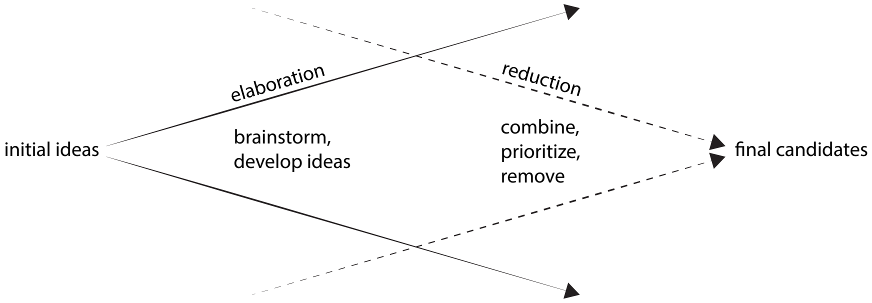


Fig. 17: Laseau's Funnel, adapted from Buxton [147]. When moving from early designs to prototypes, you begin with your conceptual design, examples, or other starting point, then rapidly generate new ideas to explore as wide a space as possible. Once you have a variety of prototypes, you then reduce them by combining, prioritizing, or removing ineffective designs. This is then repeated with your reduced set until you have a final candidate prototype.

Laseau's funnel (Figure 17) visualizes this process as a 'funnel' that widens/closes as ideas are explored and evaluated [147]. An *elaboration* phase is used to explore different ideas and implementations from a starting point, through brainstorming and variation – i.e., widening the design funnel. Its aim is to go for *quantity*, not quality. Once you have several ideas, you then *reduce* the design space; prioritize, compare, and combine ideas into a smaller set of top candidates – i.e., reducing the design funnel. This process can iterate until you have reached promising final designs, guided by prototyping.

To accomplish this in a manageable time period, prototypes need to be generated quickly and only need to be sufficient for testing the design ideas (rather than being of final production quality). Lim, Stolterman, and Tenenberg [148] propose principles to help guide prototyping activities. The first is the fundamental prototyping principle: prototypes filter the qualities in which designers are interested without distorting the whole. This means that your prototypes can view different aspects of your design - perhaps, different frequencies and sizes of a mid-air button to choose those parameters, then different dynamic properties on how it reacts when pressed. Both prototypes are simpler than a fully implemented design, but arrive at a final solution. The second principle is the economic principle of prototyping: the best prototype is the simplest and most efficient while also achieving its goals and requirements. There is great value in low-fidelity prototypes as they enable to get initial ideas extremely cheaply and rapidly, then exerting more time and effort only when there is more confidence in an outcome.

Haptics tends to be more difficult for prototyping than other technologies. It is heavily reliant on other modalities and the rest of the system, so it is more difficult to apply these principles. However, careful decisions about what you prototype will speed up your design process. You can find inspiration in Simple Haptics [149], which demonstrates the attitudes of sketching expressed in hardware to inform haptic interaction design. In this approach, you move from prototypes implemented in seconds, to those implemented in minutes, hours, and eventually days, starting with household objects and puppetry then moving towards more sophisticated technology. This iterative and progressive prototyping process was used by Young et al. [29] when designing mid-air haptic gesture controlled user interfaces for cars. Their first prototype consisted of visual non-interactive wireframes, slowly and iteratively built up towards a multimodal interactive user interface.

In summary, our main advice for prototyping alternative haptic designs is to:

1. Rapidly produce lots of ideas: widen the design funnel. Explore design candidates through rapid prototyping, then iteratively refine those ideas by comparing, combining, and prioritizing: narrow the design funnel.
2. Carefully consider the format of your sketches and prototypes, including their scope (what parameters are they exploring) and how economical their implementations are. Be intentional here, and only do what you need to in order to learn and inform your next design.

4.5 Evaluate

Evaluation may be the least formally developed activity in haptic experience design. Typically, expert hapticians use qualitative methods such as focus groups and interviews, or simply trusting the judgement of designers and developers who iterate until a haptic experience “just feels right” [129]. However, short of trusting your own intuition, there are some ways to receive feedback in a principled way.

First, evaluations are best framed in terms of the design goals articulated when gathering requirements. These goals can inform suitable questions and metrics for both informal and formal evaluation. For informal evaluation, try bringing your prototypes to colleagues or potential users whenever you can, to evaluate and inform your next iteration. If your prototypes can be rapidly adapted in response to feedback, this will help you achieve a common understanding of what can be done [129]. For formal evaluation, quantitative metrics can complement qualitative feedback. Task completion time and error rate are common metrics for usability, and for example have been used for evaluating and comparing the added benefits of mid-air haptics when interacting with an automotive infotainment system [27]. Usability and UX questionnaires are other common tools for general usability and experiential goals; for example, [130] used the AttrakDiff questionnaire to quantify improvements to aspects of the experience of watching movies with haptics. In industry, custom scales are often used [137]. Other widely used methods include removing the haptic feedback after people experience it to see if they want it back (often users do not notice haptic feedback until it has been removed), and trusting people whose design sense has a track record of results.

In summary, our advice for evaluating haptics is to:

1. Relate evaluations back to the intended experience goals and requirements, established earlier in the design process.
2. Collect rapid feedback through informal evaluation methods.
3. Use formal feedback methods such as UX questionnaires and interaction metrics.

5 Conclusion

This book chapter aspires to equip the reader with an understanding of the many different applications of ultrasonic mid-air haptics studied to date (see Sec. 2), the guidelines and best practices which have been derived from said applications (see Sec. 3), and methods for the design of useful and delightful interactive systems (see Sec. 4). To that end we have presented five key application themes (Automotive, Public displays, Virtual and Mixed Reality, Healthcare, and Neuroscience R&D) that we hope provide useful context when reading the later chapters in this book. We also presented mid-air haptic design guidelines and a general UX design framework, to inspire and inform your own mid-air haptic designs.

Throughout this chapter, we have highlighted compelling challenges and open questions for future research. Importantly, we have identified the need for more advanced, integral and system-level UX studies which look at the interplay of mid-air haptics independently but also in unison together with other technologies and sensors. Moreover, we have stressed the lack of application-specific prototypes and UX studies in the areas of healthcare and VR training. We have also highlighted the need for more fundamental research on touch and the transfer of that knowledge back into applications and enhanced experiences. Finally, we have hinted towards the need for generative UX design tools that leverage our current know-how, and possibly artificial intelligence (AI) predictive capabilities to automatically create multiple creative mid-air haptic options that meet certain application related constraints and requirements thereby making the design process shorter and less uncertain.

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