Augmenting Automotive Gesture Infotainment Interfaces through Mid-Air Haptic Icon Design

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1. Abstract

A growing body of work is demonstrating the potential benefits of haptic interfaces for the automotive domain, including the use of ultrasound haptic interfaces. In this chapter, we present our work into the development of an in-vehicle mid-air gesture interface for drivers, utilising ultrasound haptic feedback. Our interface uses carefully designed “ultrahapticons” to give feedback and present information to users. We discuss the design and evaluation of our ultrahapticons, giving insight into the design of ultrasound haptic feedback for a gesture interface and contributing a set of effective haptic patterns that can be applied in new application areas.

2. Introduction

Haptic interfaces offer clear potential in the automotive domain given their lack of dependence on the traditional, and already potentially overloaded, visual and auditory channels of the human sensorium, and have been shown to alleviate visual and cognitive load while driving (Gaffary and Lécuyer, 2018). As discussed in Chapter 4,they also have the potential to encourage a sense of responsibility, which is critical in this context. Indeed, interfaces delivering active haptic feedback have already been successfully employed in various locations within cars, such as the steering wheel, seat and foot pedals, where they can provide driver assistance, alerts and warnings (see: Riener et al., 2017).

The emergence of mid-air ultrasound haptics as a novel method of human-computer interaction (Iwamoto et al., 2008; Carter et al., 2013; Large et al., 2019) provides further scope in this context, as the need for contact with a physical surface is no longer required. This means, for example, that driver assistance and warnings may be delivered to any part of the body and at any time (for instance, see: Gil et al., 2018). Moreover, binding mid-air haptics to gesture interfaces can provide agency to contactless interaction, thereby enhancing the utility and usability of gesture interfaces within the automotive domain and providing scope to enrich the affective in-vehicle experience (e.g., as discussed in Chapter 2 and Chapter 4). This makes mid-air gesture (MAG) interaction a particularly attractive user interface solution in contemporary, manually driven vehicles, where issues of driver distraction and workload still persist, but it also offers huge potential across all levels of vehicle automation (Society of Automotive Engineers, 2016). Indeed, novel, MAG interfaces could also be uniquely employed to keep the driver in (or “on”) the loop of control (Merat et al., 2019) during lower and intermediate levels of automation or may be harnessed to provide novel and engaging user experiences in higher levels of automation where vehicle occupants are no longer required to drive. Nevertheless, issues such as haptic discrimination, task compatibility, resilience and learning still exist and can hinder the success and adoption of haptic automotive user interfaces and vehicular applications, especially if haptic sensations and gestures are indiscriminate, articulatorily vague or lack feature specificity (Brown et al., 2019).

In this chapter, we present an overview of, and key findings from, our pioneering human-centred approach to the design of an in-vehicle, MAG interface. This approach, which is framed and grounded within established human cognitive processes, was used to design and validate exemplar ultrasound, mid-air haptic icons ("ultrahapticons") attuned to the automotive domain. Nevertheless, the method and approach are equally applicable in many other domains and readers may find benefit in adopting this. We outline the approach taken, so this may be employed by other researchers and practitioners in the field, and provide full details of all sixteen ultrahapticons, including their metaphorical inspiration and haptic implementation, enabling designers to replicate, develop, and adapt these for their own applications. Further details of the empirical studies upon which the approach is based can be found in Brown et al. (2020; 2022).

3. Formative Studies

Previous, formative investigations into mid-air haptic interfaces in the automotive domain have produced encouraging results (Harrington et al., 2018; Large et al., 2019; Shakeri et al., 2018; Young et al., 2020). For example, Harrington et al. (2018) and Large et al. (2019) created a mid-air haptic interface comprising virtual buttons and a slider-bar arranged as they might be on a traditional, two-dimensional touchscreen interface. The authors reported significant reductions in eyes-off-road-time (EORT) as well as a subjective preference for mid-air haptics and gestures, compared to a traditional touchscreen interface and the same MAG interface provided without haptics, also evaluated during the study. Shakeri et al. (2018) revealed benefits to EORT by pairing mid-air haptics with visual, auditory and peripheral lighting effects, and comparing these to visual-only feedback. However, both of these formative studies revealed shortcomings in participants' ability to consistently detect and distinguish different mid-air haptic sensations; moreover, Shakeri et al. (2018) postulated that in some situations, the cognitive effort required to do so may have outweighed any perceived benefits. In addition, Young et al. (2020) concluded that subtle differences may not be perceived when used concurrently with driving.

Needless to say, mid-air haptic technology is continually evolving. Indeed, Shakeri et al. (2018) utilised Amplitude Modulation (AM) (Iwamoto et al., 2008), which is generally perceptively weaker than contemporary rendering approaches like Spatiotemporal Modulation (STM) (Frier et al., 2018) and limits the design of haptic patterns (e.g., as Chapter 3 reveals). Although Young et al. (2020) employed STM, they were unable to take advantage of the contemporary "Dynamic Tactile Pointer" method of rendering sensations (Hajas et al., 2020). Therefore, although the aforementioned, formative studies show clear potential, ongoing improvements in haptic resolution afford exciting new opportunities for researchers and practitioners to re-imagine and optimise mid-air haptic sensations, for example, by employing the approach outlined in this chapter. Furthermore, we remind readers that although this work is situated in the automotive domain, the design and evaluation approach we use can be used equally well to inform the design of haptic icons to deliver practical benefits across a wide range of other application areas, such as those explored elsewhere in this book.

4. Stimulus Creation: Ideation and Prototyping

The aim of our work was to design and evaluate distinct and salient **Mid-Air Haptic Icons** (**MAHIs** or "**ultrahapticons**") that could be symbiotically paired with hand poses in an exemplar MAG In-Vehicle Infotainment System (IVIS). Grounded in human factors engineering and human cognitive processes, the approach was inspired by related work in semantic information transfer using conventional vibrotactile haptics and gesture elicitation studies (e.g. Brunet et al., 2013; Enriquez et al., 2006; MacLean, 2008; Seifi, 2019). The ultimate goal was to develop unique haptic icons that were: **distinguishable**, **learnable**, **salient** and **recognisable** – key factors in tactile information design known to improve stimulus clarity and reduce overall cognitive effort (MacLean, 2008). The entire process (from stimulus elicitation to validation) is shown as a flowchart in Figure 1.

Method: The first stage involved a participatory design exercise, aiming to capture participants' metaphorical associations with different infotainment features, and to elicit a possible mid-air haptic embodiment of these. Seven common in-vehicle infotainment features/interactions were selected: Fan Speed, Cabin Temperature, Seat Temperature, Navigation, Phone Calls, Audio, and Home Screen. In our study, seventeen study participants were recruited for one-to-one design sessions. In line with the top-down semiotic approach (Danesi, 2007), the first step was to understand the participants' expectations and schemas. Thus, they were asked to verbalise the mental model they associated with each infotainment feature, focussing on tactile, visual and auditory elements (i.e., physical sensations, mental images or objects, and sounds). Participants were then asked to sketch their visual, auditory and tactual associations. To eliminate any effects of participants' differing artistic capabilities, they were encouraged to follow a "think-aloud" protocol as they sketched; this enabled the investigator to understand participants' thought processes if the sketch was insufficiently communicative on its own.

Participants were then informed of twelve adjustable, mid-air haptic parameters that could be manipulated to create different sensations, for example, planar shapes, spatial travel direction, diameter, temporal rhythm etc. Where possible, exemplar sensations conforming with each parameter were demonstrated to participants using the Ultraleap STRATOS explore array. Based on this information, participants were then asked to highlight elements of their designs that they thought most embodied their chosen metaphor, and to suggest how they might use the aforementioned mid-air haptic sensations with a nominal open palm gesture or hand pose to encapsulate these characteristics. Finally, participants were asked to consider how each feature might be adjusted, considering factors such as along which axis the hand pose should move (e.g. up/down, right/left etc.).

Results: This elicited 119 possible designs (an example is shown in Figure 2). Sketched designs were subsequently analysed for their semiotic composition to determine the most intuitive design or designs for each feature (or, "referent"). To achieve this, participants' designs were classified into distinct prevailing styles (or "proposals"). Where participants had proposed multiple styles for a single referent, these were analysed for "maximum consensus" (i.e., the percentage of participants eliciting the most popular proposal) and "consensus-distinct ratio" (i.e., the spread of participants displaying the most popular proposal), in line with Enriquez et al. (2006). Singular incidences of proposals were eliminated, resulting in a shortlist of twenty-three ultrahapticons for the seven infotainment features.

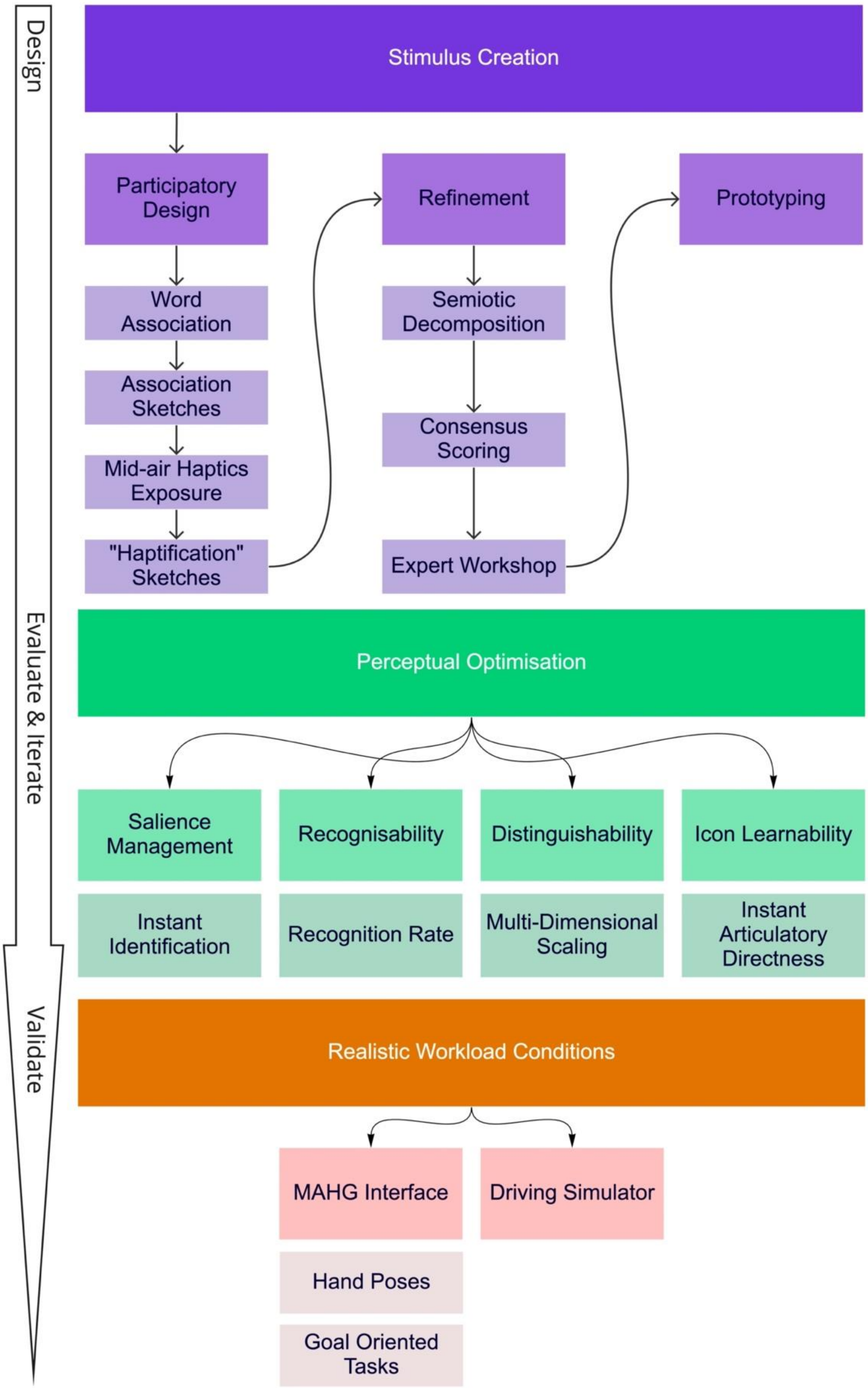


Figure 1: A flow chart depicting the methodology for developing and testing mid-air haptic icons for an In-Vehicle Infotainment System (IVIS).

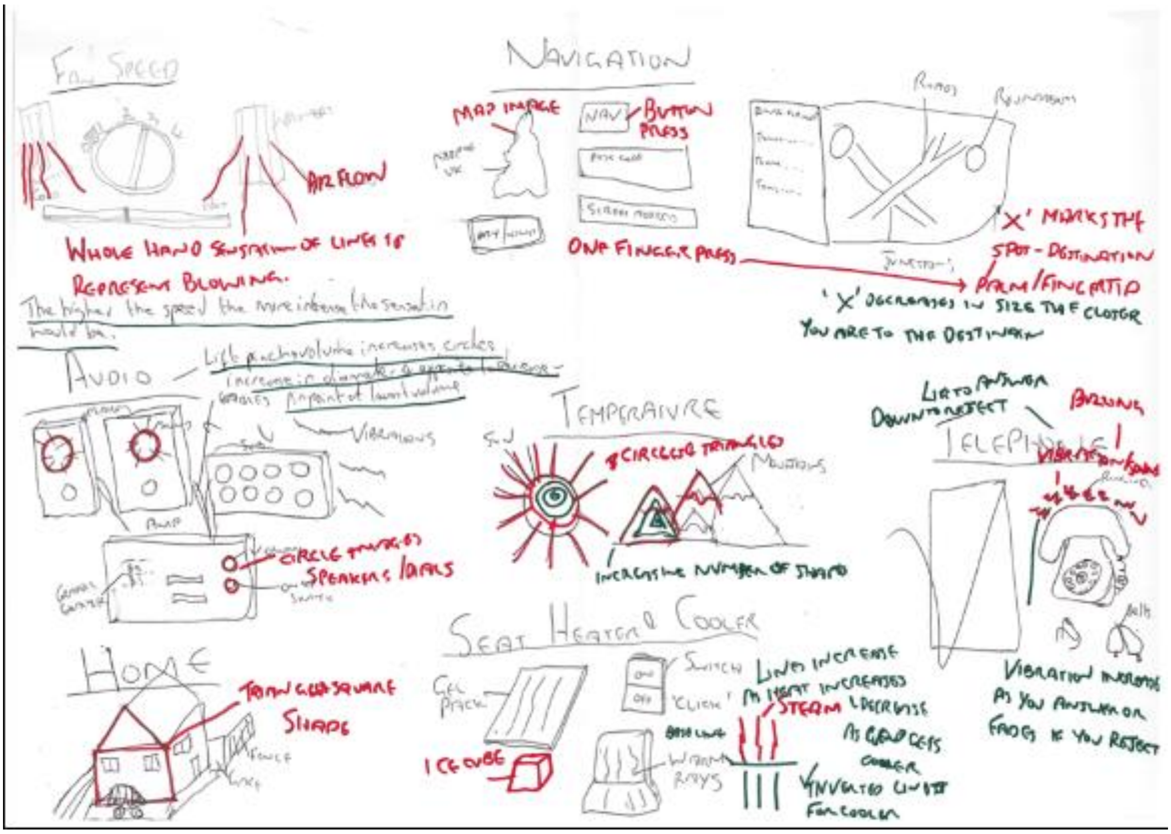


Figure 2: Example sketch of a participant's metaphorical associations with IVIS features.

Analysis: Proposed ultrahapticons were broken down into exemplar level semiotic components, i.e., the feature "constructs" and "intents" (Seifi, 2019). *Constructs* are defined as physical characteristics of a feature that, collectively, comprise the holistic mental model (e.g., the rails of a rocking chair), whereas an *intent* is defined as a symbolic construct that is used to express meaning or behaviour (e.g., blurred lines indicating movement of the rocking chair). This revealed eighty-eight distinct semiotic features, which were analysed further for consensus, resulting in sixty-five commonly occurring components. These components were subsequently decomposed into their value level elements to understand participants' expectation of the real-time interactional feedback. This included understanding any consensus regarding construct rendering, i.e., which spatial, temporal and spatiotemporal parameters were used to signify feature intents, location of the sensations on the hand, axial direction of the adjust gesture, and the dynamic adaptation of the sensation to reflect the feature adjustment.

This process resulted in thirty user-centred MAHIs. To evaluate and refine these further, a remote workshop was conducted with four mid-air haptic experts, who were asked to rate each concept on a five-point Likert scale pertaining to feature appropriateness, expected salience, naturalism, instant recognisability, perspicuity, and technical feasibility. The experts then provided suggestions on how to adapt the designs to maximise the aforementioned aspects. The data from the workshop was used to fine-tune the concepts and the result was a shortlist of sixteen MAHIs for the seven aforementioned infotainment features.

The sixteen sensations were subsequently prototyped using an Ultraleap STRATOS Explore haptics array. The MAHIs were refined using iterative design, aiming to match the user-centred concepts as closely as possible (Brown et al. 2020; Hajas et al., 2020; Rutten et al., 2020). As part of this process, each sensation was designed for two second presentation, aligned with the "glancing" convention in literature for haptic stimuli and controlling the exposure between stimuli (Brown et al., 2006; Enriquez et al., 2006; Enriquez and MacLean, 2008; MacLean and Enriquez, 2003; Tang et al., 2005; Ternes and MacLean, 2008). Full details of this first stage of the development process can be found in Brown et al. (2020).

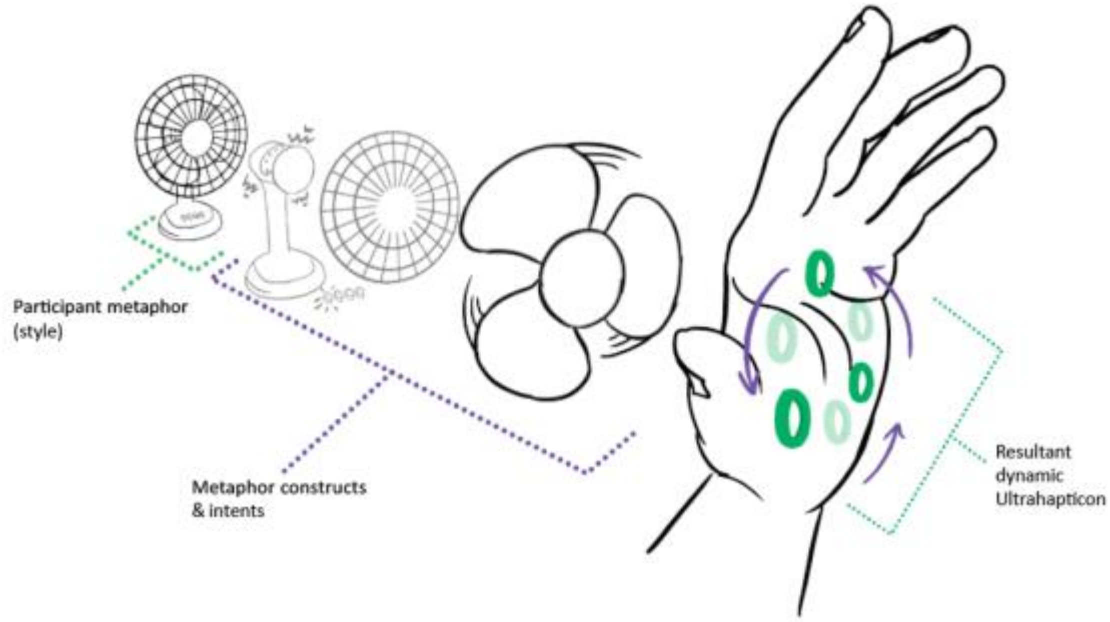


Figure 3: A pictorial representation of the semiotic decomposition process to achieve a mid-air haptic icon from a participant metaphor.

5. Perceptual Optimisation

The next stage of developing semiotic mid-air haptics for gestural interfaces was to perceptually optimise the sixteen MAHIs (see: MacLean, 2008). This involves employing a different cohort of users to determine how recognisable the derived haptic icons are and to evaluate how distinguishable they are from one another. A further aim of this activity is to quantify each icon's fidelity to the design intent and to determine their "instant articulatory directness" – in other words, the ability of each icon to signify their root metaphor without a further cue (recall from Chapter 4 that ambiguity may occur in the absence of more reliable sensory signals). Combined, these data provide an indication of how easily each MAHI could be learned and reveal if and how certain characteristics of the sensations might conflict with each other. Haptic perception studies commonly employ paired comparisons to establish dissimilarity between stimuli. However, this can become too cumbersome for large numbers of stimuli (Bonebright et al., 2005) and an alternative, employed here, is to use perceptual multi-dimensional scaling (see: Rocchesso et al., 2019).

Method: Utilising an Ultraleap STRATOS Explore array, the MAHIs were presented to twenty-five participants, with the aim of providing a compromise between comfort and optimal acoustic pressure, i.e. participants were seated at a desk with their left hand located 20cm above the ultrasound array; this configuration is also in keeping with the expected in-car location. In addition, threads of acoustically permeable speaker material allowed participants to rest their open hand, thereby minimising fatigue. This also ensured that MAHIs were actuated onto every participant's hand in a controlled and consistent manner. Noise-cancelling Bluetooth headphones connected to video conferencing software were worn by participants throughout the experiment in order to inhibit any spurious noises generated from the ultrasound array while still allowing researcher-participant communication. Before taking part, participants had no prior knowledge of what the MAHIs were. Full details of this second stage of the development process can be found in Brown et al. (2022).

4.1 Instant Identification

In a control scenario, it is important that the user is able to instantly identify the semantic meaning of the control system taxonomy. Instant identification (IID) is a metric to determine how well each icon matched the design intent (conveying the mid-air gestural user interface). In order to quantify IID, we captured participants' opinions of how well-matched the haptic sensation and a visual representation of the haptic icon design were.

Method: In our study, participants began by having each of the sixteen sensations played (in an order dictated by a balanced-Latin square) onto their left hand. Discrete sensations were played three times each, whereas continuous sensations played out for six seconds. Participants were then asked to describe what they had felt. After this, they were shown a visual representation of the haptic icon design and asked to describe how well the diagram matched the sensation they had felt. To quantify IID, and to minimise any confounding effects or demand characteristics, and enable direct comparison, three haptics experts independently assessed participants' descriptions by subjectively evaluating how closely these matched the exemplar definitions. Exemplar definitions had previously been curated around the core semiotic features and locations on the hand and were based on the rationale that object recognition processing is influenced by its "anatomical substrate" (Kaneshiro et al., 2015). For example, the sensation associated with propeller fan was expertly described as, "continuous anti-clockwise rotation of three haptic circles on the centre of the palm". Participants' descriptions were subsequently allocated two points for an exact match, one point for a minor error, or no points in situations when the participant's description was incorrect. A mean value of the median arbitrated scores for each participant was calculated as a percentage of the maximum possible score. Resulting IIDs ranged from 82% for "Thermometer" to 18% for "Propeller fan", with a mean IID (for all haptic icons) of 47%.

The IID metric is useful at understanding the quality of the haptic icon designs and it can also give an indication of how easily the features of the icons will be able to convey the meaning when presented as a taxonomy. However, limitations exist with quantising the accuracy of the participants descriptions for the sensations. Moreover, any prior knowledge of mid-air haptics may influence users' ability to accurately articulate the icons. For example, users with no prior knowledge of mid-air haptics may be able to generally articulate the location in which a sensation is actuated but those possessing lexical knowledge or expertise in mid-air haptics may be able to interpret micro-geometry of the sensations (e.g., haptic rings versus haptic points).

4.2 Recognisability and Distinguishability

Recognisability relates to a user's ability to identify a stimulus once it had been learned and is important in the initial adoption and continued use of the haptic icons. In order to quantify recognisability, users can be provided with visualisations of the haptic icons and asked to select which of the visualisations most closely matches the haptic icon they have just experienced.

Method: In our study, participants were exposed to each MAHI three times or for six seconds, as before, and in an order dictated by a balanced-Latin square. After each haptic stimulus had been delivered, the researcher displayed visual representations of all the icons side-by-side on a display monitor (Figure 4). Adopting a forced-choice approach, participants were required to select which of the visualisations they thought they had just felt, and to give a Likert rating between one and ten to represent how confident they felt in their selection (where one indicated "not at all confident", and ten, "very confident"). Responses were then entered into a 16 × 16 confusion matrix, that presented (as a percentage) the number of times participants correctly matched a MAHI to its visual representation (Table 1).

Results: The most recognisable MAHI was "Ice" which comprised a pulsating haptic bar on the thumb and was correctly recognised by all participants 100% of the time (denoted by [j] in Figure 4). In contrast, "Sofa cushion", embodied by a circular sensation that expanded and contracted from the centre of the palm, was only recognised 28% (0.28) of the time (denoted by [L] in Figure 4). Mean recognition rate (RR) was 0.66 (or 66%), and all the icons achieved an RR above the chance level of 6% (1/16 = 0.06). These results are similar to those reported in Rocchesso et al. (2019), who found a mean recognition rate of 0.57 (or 57%) for sixteen variants of planar shape-based icons (cross, circle, square).

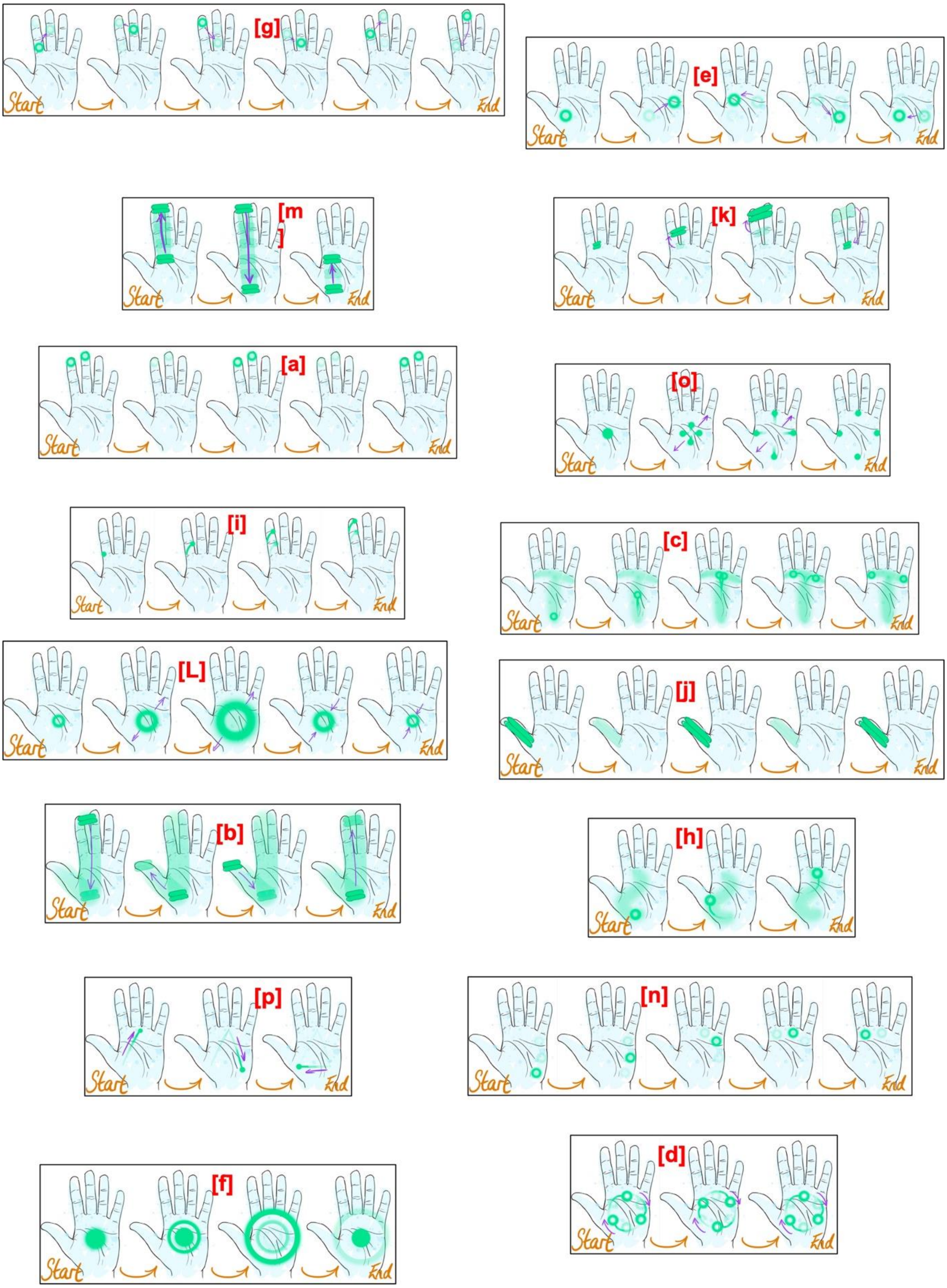


Figure 4: Sketched depictions of all mid-air haptic icon stimuli used in the perceptual optimisation study. (Note: further details of all ultrahapticons are provided in Section 5).

Icon Label [transpose]	[a]	[b]	[c]	[d]	[e]	[f]	[g]	[h]	[i]	[j]	[k]	[l]	[m]	[n]	[o]	[p]
Bass Speaker [a]	0.80	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.04	0.00	0.04	0.00	0.00	0.00
Seat Profile View [b]	0.00	0.76	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
T-Junction [c]	0.00	0.00	0.68	0.04	0.04	0.04	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.12	0.00	0.00
Propeller Fan [d]	0.00	0.00	0.00	0.56	0.08	0.20	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.04	0.08	0.00
Bouncing Telephone Handset [e]	0.00	0.00	0.00	0.08	0.64	0.04	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00
Waypoint Blip [f]	0.00	0.00	0.04	0.04	0.04	0.44	0.00	0.00	0.00	0.00	0.04	0.24	0.00	0.04	0.12	0.00
Flames [g]	0.00	0.04	0.00	0.04	0.00	0.00	0.52	0.00	0.00	0.00	0.32	0.00	0.04	0.00	0.04	0.00
Heating Elements [h]	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.64	0.00	0.00	0.00	0.00	0.12	0.00	0.04	0.12
Coiled Telephone Wire [i]	0.12	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ice [j]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Sound Waves [k]	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.84	0.00	0.04	0.00	0.00	0.00
Sofa Cushion [l]	0.00	0.00	0.16	0.16	0.04	0.16	0.00	0.08	0.00	0.00	0.00	0.28	0.00	0.04	0.08	0.00
Thermometer [m]	0.00	0.08	0.00	0.00	0.00	0.04	0.04	0.00	0.00	0.00	0.08	0.00	0.76	0.00	0.00	0.00
Telephone Rotary Dial [n]	0.00	0.04	0.04	0.08	0.04	0.00	0.00	0.04	0.08	0.00	0.00	0.04	0.00	0.64	0.00	0.00
Compass [o]	0.00	0.00	0.04	0.00	0.00	0.08	0.00	0.16	0.04	0.00	0.00	0.12	0.08	0.04	0.40	0.04
House Roof [p]	0.00	0.00	0.00	0.08	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.04	0.04	0.00	0.76

Table 1: Confusion matrix, where rows (CMx) designate the metaphor label condition while columns (CMy) denote predicted responses given; diagonal values indicate where a correct selection was made (CMxy).

Distinguishability describes whether the icon's features (i.e. its constructs and intents (Jovicic, 2009) are unique enough to be distinguished from others in the set. It is important in enabling a user to be certain that they have selected the correct feature amongst those available. In order to quantify distinguishability, users can be asked to explain which aspect of the sensation informed their previous selection.

Method: In our study, participants' explanations were used in conjunction with their subjective confidence rating to interpret why certain MAHIs may be similar, noting that a low confidence rating may indicate that a participant had previously guessed rather than inaccurately recognised the icon. Incorrect recognition data from the confusion matrix were used to visualise the representational similarity between different haptic icons. In other words, situations in which one haptic icon had been confused with another suggested that an element of similarity existed between these. This process converts similarity metrics into distances in Euclidian space that can be visualised through multi-dimensional scaling (Figure 5). In essence, icons that are close together are deemed to be more similar to one another or possess similar elements.

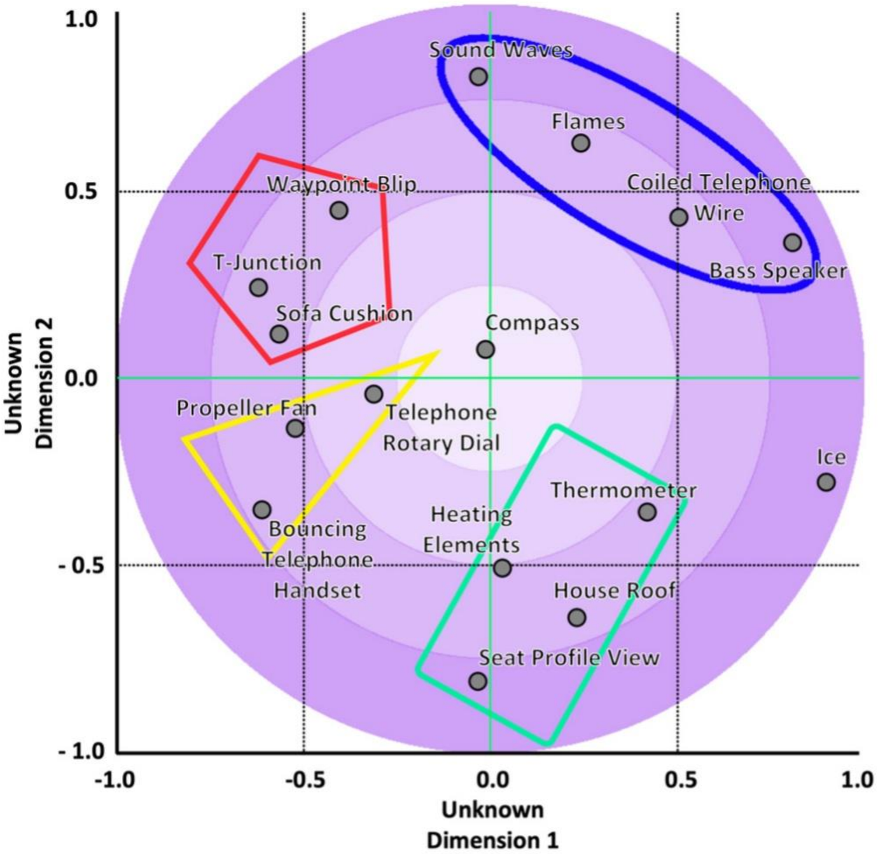


Figure 5: Haptic icon similarity data visualized through Multi-Dimensional Scaling

Results: "Compass" (four focal points emerging from a central position on the hand to represent north, south, east and west denoted by [o] in Figure 4) was most commonly confused with other haptic icons (i.e., least frequently recognised) and is therefore positioned closest to the origin, where no discernible differentiating dimensions exist. In contrast, "Ice" was never confused with another icon (recall, recognition rate was 100%) which is illustrated by its location – furthest from both the origin and any other data points (denoted by [j] in Figure 4). It is also evident that there are a number of clusters of data points. These have been enclosed by different coloured planar shapes for clarity, although these shapes bear no resemblance to icon design. The shapes delineate shared commonality among MAHIs. In other words, haptic icons that exist within the same cluster have common elements, although it is not possible to infer what the similarity dimensions are from the visualisation alone. However, participants had already verbalised their decision-making process when making classifications, and therefore it is possible to overlay these qualitative data to help understand which elements were similar between these icons (or, in other words, why certain icons may have been confused). For example, for icons situated within the blue ellipse (the loosest cluster), many participants identified that the sensations were actuated onto the index and middle fingers, suggesting that the location on the fingers was the core confusing attribute. For icons in the green rectangle, several participants mentioned that sensations travelled up and down the palm in some manner; this suggests that the location on the palm and the fact the sensations were rendered dynamically along a pre-defined path may have contributed to confusion. The yellow triangle cluster contains icons that were confused seemingly for their apparent circular path of staccato-like focal points around the palm. The icons within the tightest cluster (red pentagon) all exhibit divergent behaviour (i.e., focal points splitting in opposite directions, or circles expanding and contracting). Indeed, many participants reported feeling the sensations “growing and shrinking”.

4.3 Instant Articulatory Directness

The final factor to consider is *instant articulatory directness* (IAD). IAD provides a measure of how intuitive the connection between the metaphor and the icon is, and thus provides an indication of how easily it may be learned. Blattner et al. (1989) provide a useful taxonomy that describes the stimulus-meaning relationship in iconography as a continuum that ranges from *representational* at one end to *abstract* at the other. A representational relationship is one where the form directly depicts that of the metaphor or accurately reconstructs the sensory experience (for example, Propeller fan: “The three circles represent each fan blade, and the rotational movement represents the fan blades spinning to generate air flow”). With abstract icons, the representation of semantics is arbitrary meaning that the association is not intrinsic and therefore must be learned or conveyed by other means (for example, Sofa cushion: “The expanding soft circle represents the compression of a sofa cushion as you sit on it”). Between these extremes, relationships are deemed to be *semi-abstract*; in other words, these icons possess elements or features that imply the whole. For the purpose of classification in the current project, Blattner et al.’s (1989) continuum was interpreted as a rating scale from one to five, where one indicated “fully abstract” and five, “fully representational” and each MAHI was assigned a rating indicating its relationship with the root metaphor.

Method: In our study, participants were asked to select the text-based metaphor label to which they believed the sensation was semiotically tethered; they had no prior knowledge of the metaphor and no visualisation was provided. Participants were also asked to articulate why they believed the sensation mapped onto their chosen metaphor. Responses were processed in the same manner as the recognisability data – in a confusion matrix that was normalised to give the frequency of classifications as a proportion of total responses.

Results: The mean percentage of correctly identified metaphors was 35%. Values ranged from 68% for "Seat profile view", to only 8% for "Sofa cushion". In general, results suggest that, although some of the metaphors were well conveyed for some people, others will likely need further explanation or clarification. IAD results were then compared to the abstract/representational ratings. This revealed a strong, significant, positive Spearman's Rank correlation (rs = .786, *p*=.001). As might be expected, the data show a trend towards more representational icons having higher scores for IAD.

A further observation is that representational icons which convey the physical characteristics of a metaphor were more easily discernible than those which convey the non-physical properties (such as the sensory experience) of the metaphor (for example, motion and rhythm in "Waypoint blip" and "Bass speaker"). This is likely to be because users' expectations are built on visual encoding – in other words, we make judgements on how something is going to feel based on how it looks. This aspect was intentionally removed during this stage of the process (i.e., participants had no visual stimuli on which to build their expectations). Nevertheless, the results appear to suggest that visual encoding may well also apply to mid-air haptics (Breitschaft et al., 2019). In other words, IAD was higher when the metaphor contained familiar physical attributes that the user could readily visualise (as opposed to sensations, for example).

IAD also seemed to be directly affected by the ambiguity of the metaphor label. Labels like "T-Junction" or "Seat Profile View" are very specific and leave little open for interpretation, which may have allowed the participants to build a clearer visualisation and/or expectation. In contrast, labels such as "Sofa Cushion" and "Ice" are arguably more ambiguous. For these reasons, participants' expectations will likely need to be established prior to use by providing bespoke learning, for example, through the provision of visual animations that exhibit the "haptification" of the metaphor.

4.4 Deriving the Exemplar Haptic Icons

Whereas traditional multidimensional scaling studies have focused on stimulus differentiation for the thresholds of base parameters in tactile signals (frequency, amplitude etc.) (MacLean and Enriquez, 2003), our approach aims to uncover distinctions based on spatiotemporal behaviour and metaphorical design. This enables any perceptual anomalies to be identified and the prototypes to be adjusted to better reflect the design intent. The set of exemplar haptic icons thus derived reflect those that achieved the highest consensus in the original participatory design study, and subsequently received the highest aggregated scores for instant identification, instant articulatory directness, recognisability and distinguishability for the associated function (future work will explore how these metrics could be weighted). All sixteen MAHIs and their salience scores are shown in Table 2. From those presented, we selected seven for our exemplar icon set to be taken foreword for implementation in the concept in-vehicle, MAG interface (these are shaded in Table 2), although a case can be made for selecting alternatives.

MAHI label	IVIS Feature	Instant Identification	Recognition Rate	Instant Articulatory Directness	Totals
Seat Profile View	Seat Temperature	0.64	0.76	0.64	2.04
Thermometer	Cabin Temperature	0.82	0.76	0.28	1.86
T-Junction	Navigation	0.41	0.68	0.68	1.77
Telephone Rotary Dial	Telephone Calls	0.52	0.64	0.6	1.76
Ice	Cabin Temperature	0.66	1	0.08	1.74
Bass Speaker	Audio	0.73	0.8	0.13	1.66
House Roof	Home Screen	0.45	0.68	0.52	1.65
Sound Waves	Audio	0.55	0.84	0.2	1.59
Coiled Telephone Wire	Telephone Calls	0.34	0.76	0.36	1.46
Flames	Cabin Temperature	0.57	0.52	0.32	1.41
Bouncing Telephone Handset	Telephone Calls	0.50	0.64	0.24	1.38
Heating Elements	Seat Temperature	0.32	0.64	0.2	1.16
Propeller Fan	Fan Speed	0.18	0.56	0.36	1.10
Compass	Navigation	0.20	0.4	0.4	1.00
Waypoint Blip	Navigation	0.25	0.44	0.28	0.97
Sofa Cushion	Home Screen	0.34	0.28	0.08	0.70

Table 2. Cumulative perceptual scores for all icons. Shaded rows indicate exemplar icons for a concept IVIS

Indeed, the intended application or hardware implementation may also influence icon selection. For example, "Bass speaker" was commonly reported by participants in our study as a sensation on their wrist, despite the design comprising two repeating focal points at the ends of the middle and index fingers. This is an example of "grating lobes" – a phenomenon which occurs as a result of the rectilinear arrangement of the ultrasonic transducers (Price and Long, 2018) and would also likely have occurred in the Shakeri et al. (2018) study given that they used a similar haptics array and sensation for their two-finger hand pose interaction. In this situation, the design of the ultrasound array can help – a "sunflower" arrangement of transducers, such as those now employed in the Ultraleap STRATOS Inspire array, is known to mitigate this issue. If using a rectilinear transducer array, "Bass speaker" could be replaced by

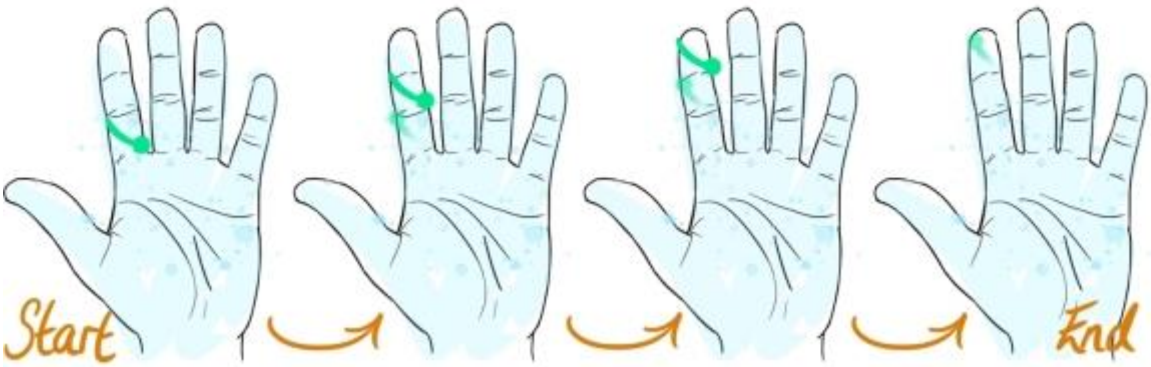
"Sound waves" to avoid the issue of grating lobes; this performed only marginally worse than "Bass speaker" in our study. It is also possible that further refinement or alternatives are required for some icons. For example, although "Propeller fan" achieved very high consensus in the original participatory design study, it did not perform particularly well during the perceptual optimisation study, yet no suitable alternative was identified.

6. Mid-Air Haptic Icon Designs

The following section presents all sixteen of the haptic icons with comprehensive descriptions of their behaviour. Although the haptic icons have been developed for an in-vehicle infotainment system interface, the intention is that other researchers, designers or practitioners may use these or develop them further for their own applications.

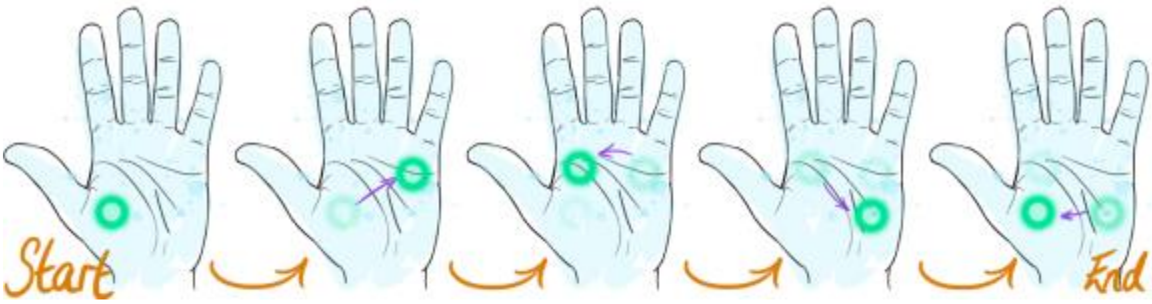
5.1 Telephone Calling Features

"Coiled Telephone Wire"(Representational Class)



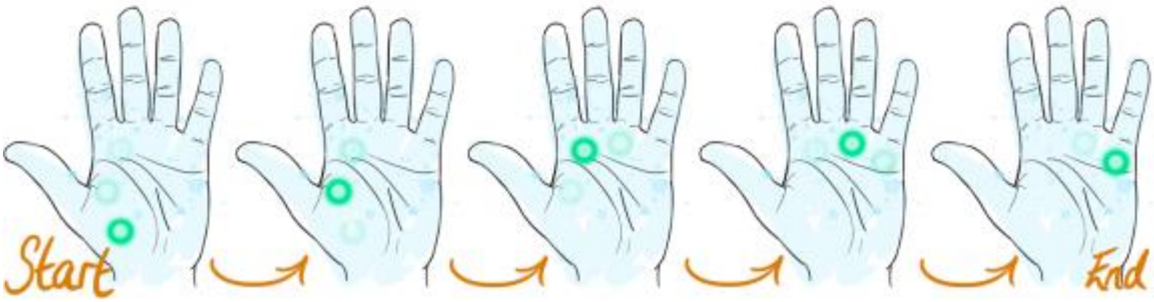
The coiled telephone wire ultrahapticon emulates the metaphor of coiling the wire of a traditional telephone around the finger. The user shall receive a single focal point (green dot) that travels along a path (green lines) rendered at around a 35-degree angle from right to left in three sequential locations going up the index finger towards the tip.

"Bouncing Telephone Handset" (Semi-Abstract Class)



The bouncing telephone handset ultrahapticon emulates the handset of an old telephone, bouncing in its cradle as it rings – the focal rings represent the speaker and microphone sections of the handset. The user shall receive a focal ring “bouncing” between four locations to the temporal rhythm of a retro telephone ringtone. The full sensation consists of a one second loop of six taps over the four locations (with two taps at the final location, i.e. base of thumb). After the first three taps there is a small pause before the next three follow.

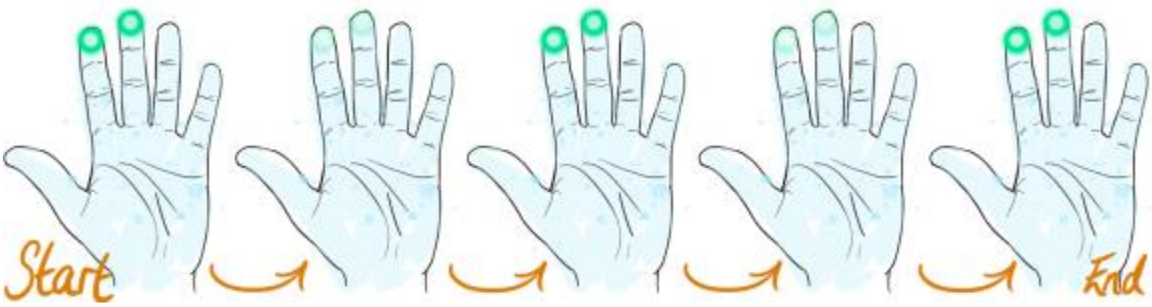
“Telephone Rotary Dial” (Representational Class)



The telephone rotary dial ultrahapticon emulates the finger holes of a rotary dial on an old-fashioned telephone. When accepting an incoming phone call, the user shall receive five sequential, equally spaced haptic circles that are rendered from the bottom left of the palm in a semi-circular path to the base of the little finger knuckle; each haptic circle is sequentially stronger intensity than the last. If the user were rejecting an incoming phone call, they would receive a similar sensation, but it would be mirrored so that the sensation starts at the base of the little finger, follows the medial edge of the palm and ends at the base of the thumb. The sequence of intensity when rejecting an incoming call is also reversed so that each haptic circle is 0.1 less than its previous i.e. from 1 (full intensity) to 0.6 intensity.

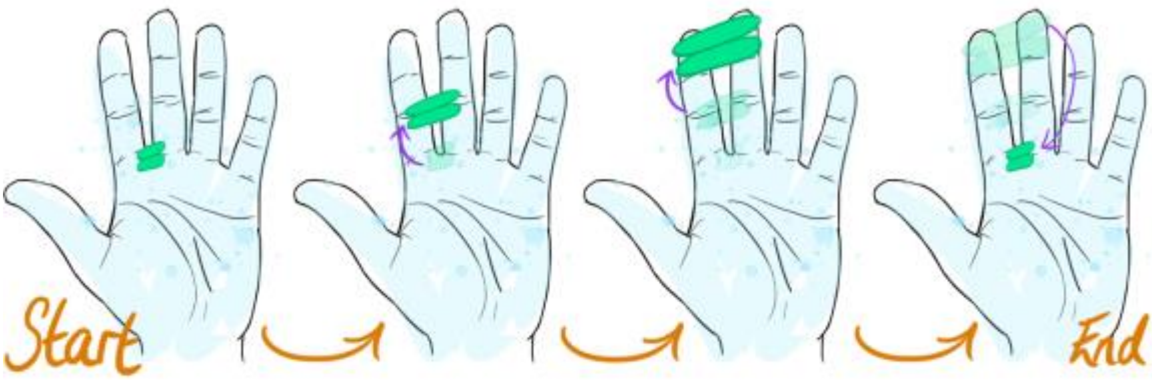
5.2 Audio Features

“Bass Speaker” (Semi-Abstract Class)



For the base speaker ultrahapticon, the driver shall receive a continuous pulsing sensation at the ends of the fingertips that resembles the user’s metaphor of bass sound waves emanating from a speaker.

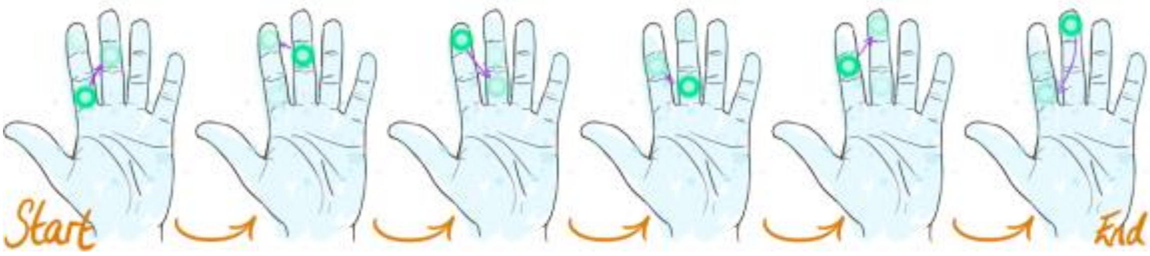
"Sound Waves" (Semi-Abstract Class)



The sound waves ultrahapticon signifies sound waves travelling along the user's fingers. The user shall receive a small two bar sensation that starts in between the middle and index finger knuckle that increases in size as it travels up the fingers.

5.3 Cabin Temperature Features

"Flames" (Abstract Class)

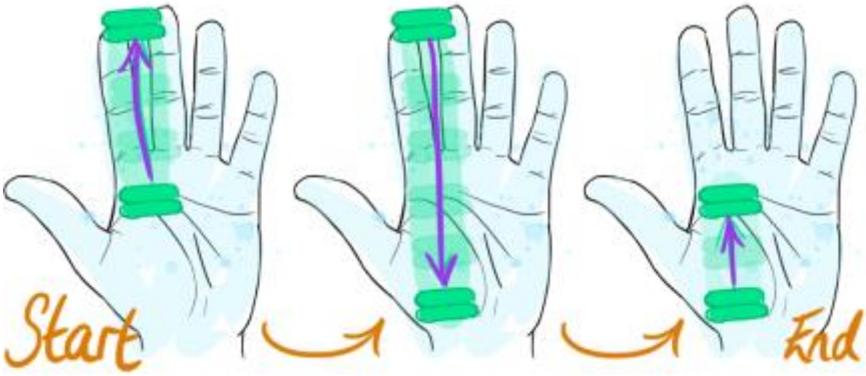


The flames ultrahapticon is associated with heat and comprises a continuous sensation of focal points representing the metaphor of flames licking the index and middle fingers. The focal points jump randomly from one location on one finger to another on the other finger with equal intervals. The locations will be dictated by the three joints on the fingers.

"Ice" (Abstract Class)

The ice ultrahapticon is associated with cold and signifies the cool aspect of temperature. The user shall receive a solid double bar on the thumb representing a block of ice, that actuates at four pulses per second. It is anticipated that the ice ultrahapticon can be used in conjunction with "flames" to create a representation of a temperature scale.

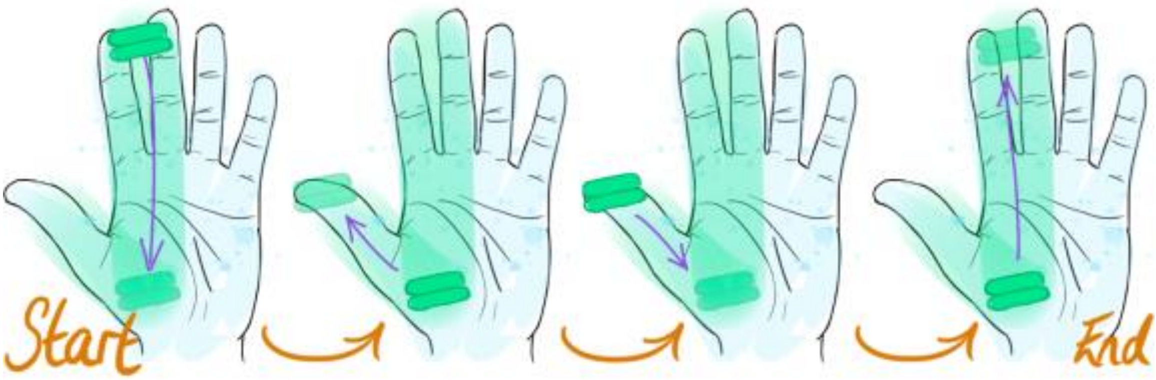
"Thermometer" (Representational Class)



The thermometer ultrahapticon conveys the rising and falling mercury in a thermometer and subsequently represents temperature. The user shall feel a "double bar" haptic sensation initially actuated halfway up the palm. This double bar then accelerates up the index and middle fingers and slows as it reaches the fingertips, where it pauses momentarily. From here, the double bar moves back down the hand, accelerating past the starting point and moving to the bottom of the palm where it pauses momentarily again. Finally, the double bar returns to the starting position.

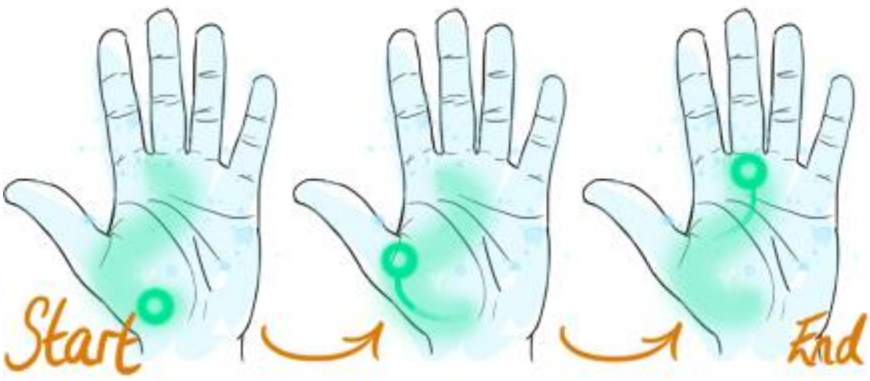
5.4 Seat Temperature (Heater and Cooler) Feature

"Profile View of a Seat" (Representational Class)



The profile view of a seat was identified as a metaphor for seat temperature and the ultrahapticon conveys the shape of the driver's seat. The user shall feel a "double bar" haptic sensation, initially at the tips of the index and middle fingers. The double bar then accelerates down the index and middle fingers, decelerating as it reaches the base of the thumb/bottom of palm where it pauses momentarily. After reaching the base of the thumb, the double bar then accelerates towards the tip of the thumb where it decelerates and pauses momentarily again. After this, it accelerates down to the base of the thumb, pauses momentarily and then accelerates back up the index and middle fingers and culminates with another subtle deceleration/pause.

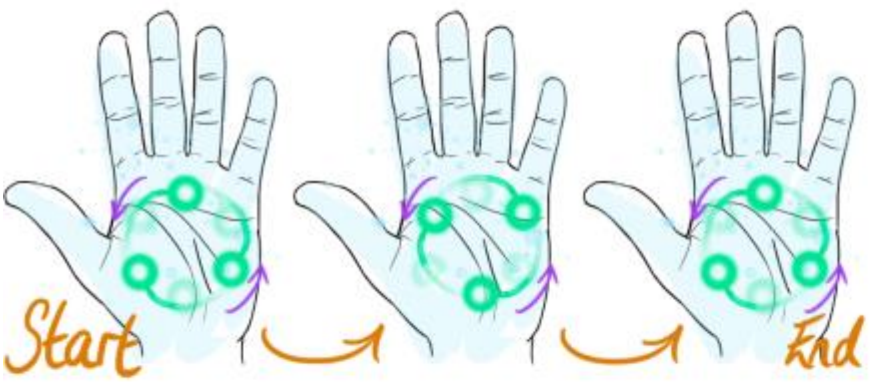
"Heating Elements" (Representational Class)



The heating elements ultrahapticon conveys heating elements embedded in a car seat and is associated with the seat temperature feature. The user shall feel a focal ring at the base of the thumb. This sensation travels in an S-shape path (representing a direct translation of the heating element) up the palm to finish at the base of the middle finger knuckle.

5.5 Fan Speed Feature

"Propeller Fan" (Representational Class)



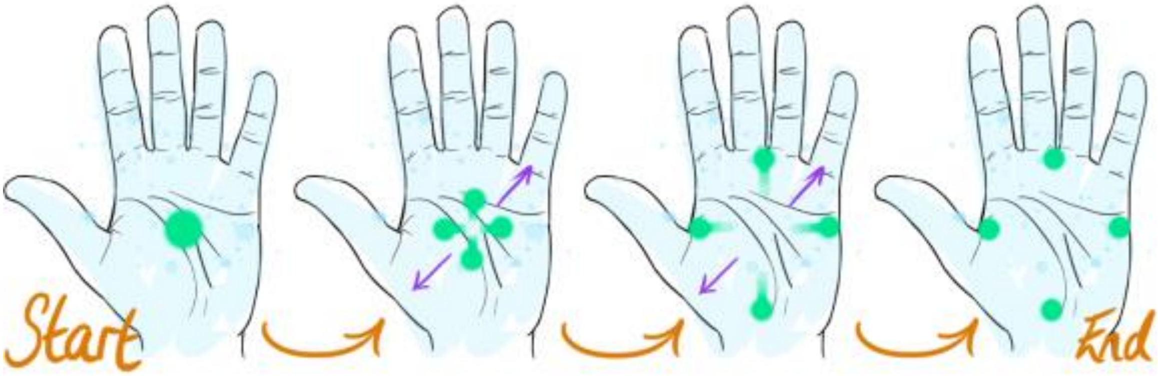
For the propeller fan ultrahapticon, the user shall receive a continuous anti-clockwise rotation of three haptic focal points to represent the users' metaphor of a rotating propeller fan.

5.6 Navigation Features

"T Junction" (Representational Class)

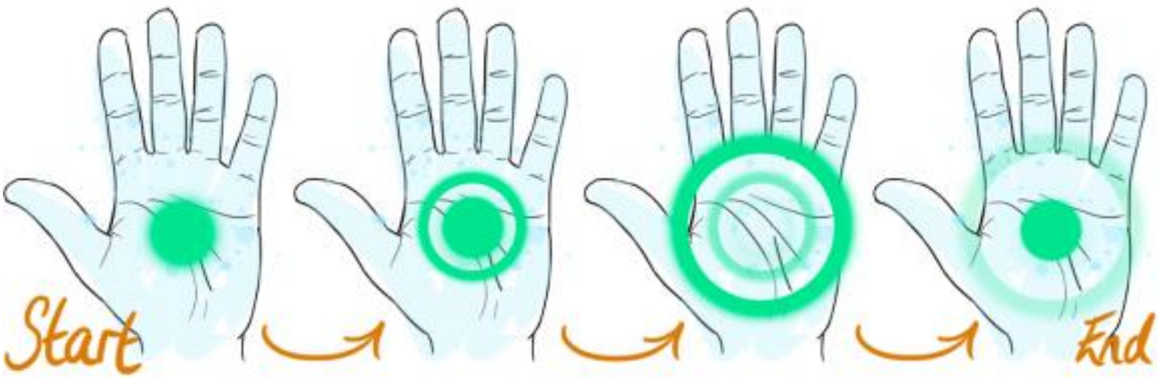
The T-junction ultrahapticon represents the geometry of a junction on a road which was commonly elicited as participants' mental model for navigation. The user receives a dynamic sensation that starts with a single focal point at the middle-bottom of the palm. This then travels up the palm. Once the haptic focal point reaches the centre of the knuckles, it splits into two separate focal points – one travels left across the knuckles and the other follows right along the knuckles, thereby dynamically forming the "T".

"Compass" (Semi-Abstract Class)



The compass ultrahapticon represents three separate metaphors: "the compass", "crossroads" and "X marks the spot". A single focal point starts in the centre of the palm. This splits into four focal points of equal size. The four focal points move in synchrony towards equidistant locations at the distal, proximal, lateral and medial extremes of the palm. To avoid confusion with expanding circle sensations such as the "Waypoint Blip" and "Sofa Cushion" (as seen in our study), it is suggested that the sensation could work in the opposite direction, i.e. the sensation begins with the four focal points at the extremities of the palm and these come together into a single focal point in the centre of the palm.

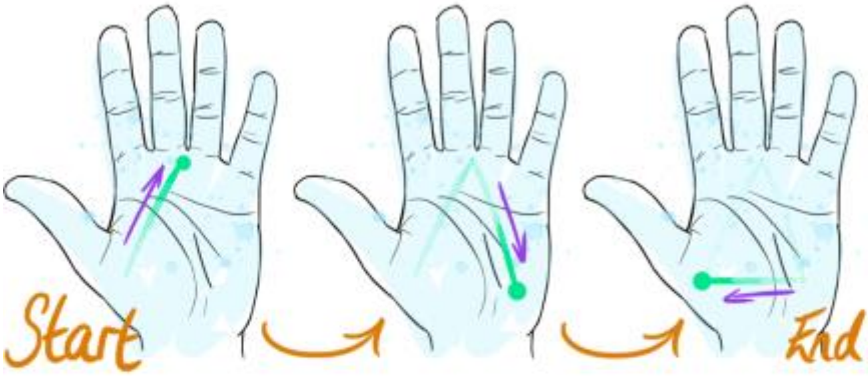
"Waypoint Blip" (Semi-Abstract Class)



The waypoint blip ultrahapticon represents the metaphor of a waypoint visual on a GPS interface and signifies navigation. The sensation begins with a pulse in the centre of the palm and this spreads outwards, increasing in size, and then fades away.

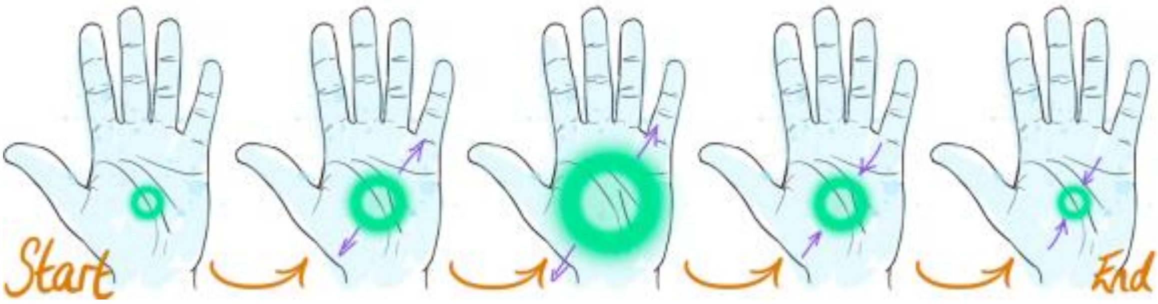
5.7 Home Screen (Landing Page) Feature

"House Roof" (Representational Class)



For the house roof ultrahapticon, a focal point renders an equilateral triangle in the palm of the hand. This represents the roof of a house, which was proposed by participants to indicate the "Home" function. The focal point starts at the base of the thumb and completes three separate strokes to delineate the sides of a triangle. At each vertex of the triangle, there is a momentary pause before the rendering continues.

"Sofa Cushion" (Abstract Class)



For the sofa cushion ultrahapticon, a ring starts in the centre of the palm. It expands in thickness and diameter and then shrinks back to its original dimensions. This ultrahapticon represents the compression of a cushion as one sits on a sofa.

7. Contextual Validation

As a final note in this chapter, it is important to consider the context in which the haptic icons will be employed. In our work, the haptic icons are intended to complement an in-vehicle, MAG interface. Driving is already a highly demanding task (Mehler and Reimer, 2019), and the concern is that this inherent primary task demand will affect the efficacy and usability of our chosen haptic icon designs when used concurrently with driving. Thus, contextual validation is important. Driving simulators provide an ideal setting to conduct driving-related research in a safe and controlled environment (Large and Burnett, 2015). We therefore present a brief overview and preliminary results from our driving simulator study that aimed to evaluate the haptic icons in their intended setting.

Method: In practice, we utilised a simplified interface employing three features to ensure that the study was not unduly onerous for participants. The experimental interface utilised a grab-to-initiate gesture, after which one of three hand poses were required for feature selection – each resulting in the activation of their respective MAHI for audio, fan speed and seat temperature functions (Figure 7). Feature adjustment was made by raising the requisite hand pose up and down, in line with recommendations (see: May et al., 2017; Hessam et al., 2017).

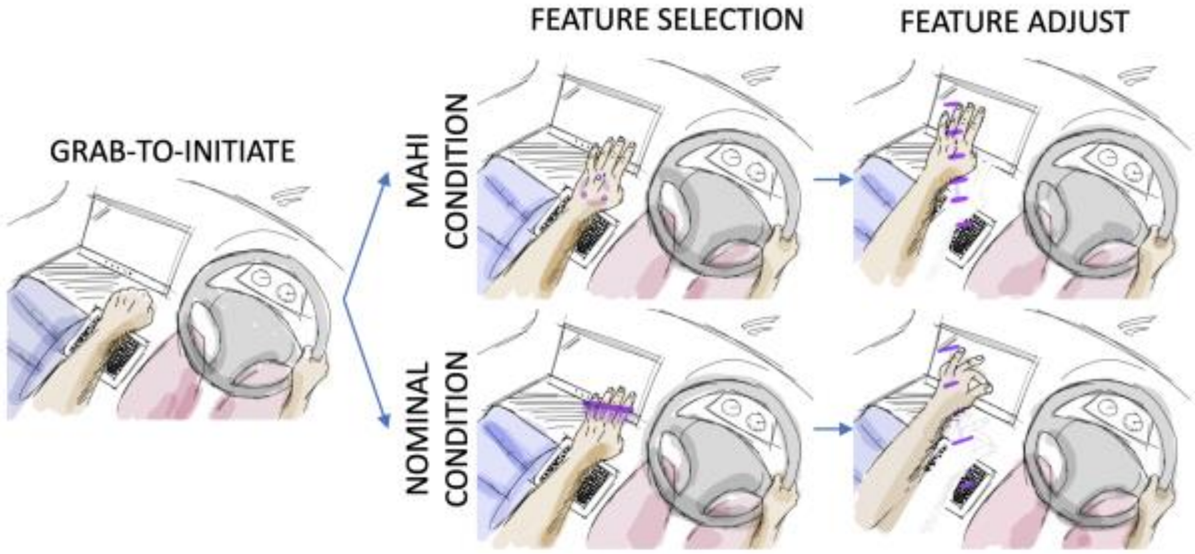


Figure 7: Storyboard of the mid-air haptic gesture interactions evaluated in the study. Purple sketch elements depict haptic sensations actuated onto the underside of the hand.

The study compared the MAG interface with a control condition employing nominal confirmation feedback (i.e. where haptic sensations were the same regardless of feature and a pinch gesture was used to adjust feature settings), and captured traditional driving performance data and relevant metrics. These included eye tracking to measure distraction and cognitive tunnelling, subjective measures (e.g. NASA-TLX (Hart & Staveland, 1988) to measure perceived workload) and simulator control data to understand the effects of the MAHG interface on vehicle control. In addition, UX questionnaires and semi-structured interviews were utilised, and where relevant, these were structured in line with the technology acceptance model (Venkatesh & Davis, 2000).

Results: Preliminary findings indicate that the mid-air haptic icons were preferred by over 60% of drivers, when compared to a control condition employing nominal confirmation feedback (i.e. where haptic sensations were the same regardless of feature). When used for feature selection, the haptic icons enabled participants to complete the interaction without taking their eyes off the road. Participants also commented that the haptic icons supported the recall of the hand poses used for feature selection. However, the study also revealed the importance of other design elements that need to be considered. For example, the onboarding of the interface was a cumbersome and inefficient process, and this needs to be refined so that a user may learn the interface without the need for detailed, and time-consuming guidance (particularly, during "real-world" use). In addition, the manner in which user intent is distinguished from routine hand movements requires further refinement. Contemporaneous methods have employed temporal feedforward mechanisms (i.e. hand pose dwell time). However, this, in combination with the additional time delay caused by relaying haptic feedback, would create unacceptable latency in the context of driving. We therefore selected a user-triggered feedforward mechanism (i.e. the grab gesture to start interacting) which had previously been dismissed in earlier studies as being annoying and distracting (Riener et al, 2013) and adding to cognitive load (Delamare et al, 2015). Nevertheless, the driver gripping the steering wheel could potentially be mistaken for the grab-to-initiate gesture, thereby resulting in the premature initiation of mid-air haptics. This suggests that the MAHI interaction zone needs to be clearly delineated from other active driving hand-zones. Other usability aspects that will be explored in future work include defining a mechanism to guide the user's hand to the interaction zone with haptics, designing to encourage and manage task interleaving behaviour, and defining the limits of the travel envelope in which a driver can move their hand to adjust a feature as well as how feedback on incremental adjustment is best conveyed in the mid-air haptic medium.

8. Conclusion

In this chapter, we have presented an overview of, and key findings from, our pioneering human-centred approach to the design of an in-vehicle, MAG interface. Sixteen haptic icons (ultrahapticons) were created following an icon elicitation exercise. These were perceptually optimised in a subsequent study to ensure they were distinguishable, learnable, salient and recognisable – key factors in tactile information design. From this, an exemplar set of seven ultrahapticons were selected and a sample of these was subsequently evaluated in a driving simulator study. The chapter provides an overview of the methodological approach – allowing other researchers and developers to adopt this in their own work, as well as a comprehensive taxonomy of all sixteen of our ultrahapticons. Although the work is grounded in automotive interface design, it is envisaged that the approach is equally applicable in other domains and application areas (such as those explored elsewhere in this book), and the anticipation is that other researchers, designers and practitioners may use our ultrahapticons directly or develop their own using our approach.

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