Validating the Salience of Haptic Icons for Automotive Mid-Air Haptic Gesture Interfaces

Eddie Brown[1,2], David R. Large[1], Hannah Limerick[2], William Frier[2], Gary Burnett[1]

[1]Human Factors Research Group, University of Nottingham, [2]Experience Design & Research, Ultraleap

ABSTRACT

Mid-air haptic technology has enabled a new research arena in spatial interaction to emerge. Various efforts have attempted to pair mid-air haptics with gestural input for In-Vehicle Infotainment Systems but have not explored the higher reaches of semiotic information transfer during these interactions. Building on a participatory design study in which participants' metaphors for seven infotainment features were "haptified", twenty-five participants were recruited to evaluate the perceptual efficacy of the sixteen resulting mid-air haptic icons. Four perception metrics (Instant Identification, Recognition Rate, Instant Articulatory Directness and Distinguishability) were collected through stimulus matching and descriptive tasks. The haptic icons which offered the best saliency (i.e. received the highest cumulative scores for all four metrics) were subsequently selected to represent their respective features in a prototype Mid-Air Haptic Gesture Interface, which will be evaluated in further, ongoing work. The study highlights an important stage in the development and deployment of semiotic mid-air haptics for gestural interfaces.

KEYWORDS

Mid-air haptics, Haptic icons, Gesture interface, In-vehicle infotainment system

Introduction

Mid-Air Gesture (MAG) interaction offers a novel automotive interface solution with the potential to overcome problems with existing interfaces, such as visual distraction caused by touchscreens (Large et al., 2019), and the lack of continuous precision in adjustment associated with voice interfaces (Pfleging et al., 2012). Initially introduced by BMW in 2015, several automotive companies (for example, VW, JLR, Mercedes) have included gesture functionality to actuate features in the car. Nevertheless, MAG interfaces have their own disadvantages, notably a steep learning curve for the gesture set and gesture execution (Garber, 2013), cultural nuance (Van Laack, 2014), and a lack of feedback which causes detriment to the driver's sense of agency in their interaction (Martinez, 2017). The emergence of commercially available mid-air ultrasound haptics has stimulated a resurgence in addressing these fundamental barriers to gesture interaction. Ultraleap (formerly "Ultrahaptics") technology uses focused ultrasound that is modulated at a specific frequency and actuated onto the user's bare hand. The displacement causes a vibrotactile response in the Pacinian corpuscles which allow complex spatio-temporal haptic sensations to be perceived (Carter et al, 2013). Existing research efforts into exploiting this technology for automotive interfaces have shown genuine benefits over gestures without feedback and led to significant reductions in Eyes-Off-The-Road-Times (EORT) as well as subjective preference for this interaction type when compared to a touchscreen (Large et al., 2019; Shakeri et al., 2018). Nevertheless, Large et al. (2019) and Shakeri et al. (2018) focused on non-goal-oriented tasks during their lab-based studies to avoid confounding effects of semantics. In other words, the gestures and haptics used during the studies were function-associated (i.e. increasing/decreasing, on/off etc.) but in a real context, the user will also need information on which feature they are interacting with. The user would then not only be confident their input has been recognised but also that the correct feature has been activated thereby, theoretically, optimising their sense of agency.

The current programme of work therefore aims to explore the efficacy by which unique feature-associated semantic information may be conveyed through the haptic channel. Indeed, previous, related work (conducted in other contexts) has shown that mid-air haptics can convey shape information (Long et al., 2014), facilitate emotional communication (Obrist et al., 2015) as well as embody semantic features of artwork (Azh, 2016). Optimising the apparent benefits of mid-air haptics requires careful study of human perception and information transfer within the intended context to avoid stimuli discrimination issues encountered. The authors therefore set out to design distinct and salient Mid-Air Haptic Icons (MAHIs) that can be paired with hand poses in a MAG In-Vehicle Infotainment System (IVIS).

Method

Aims and Approach

The design methodology outlined in this paper has been inspired by research into semantic information transfer through conventional vibrotactile haptics (see: Enriquez et al, 2006; Seifi, 2017; Brunet et al., 2013; MacLean, 2008). The approach is predicated on satisfying the properties of a "usable" icon according to MacLean (2008). These are: icon distinguishability, icon learnability, salience management and recognisability. The MAHIs under evaluation were elicited using a participatory design process in which participants' "top-down" expectations (Azh et al., 2016) for the mid-air haptic embodiment of their own metaphorical associations with seven infotainment features were identified (these features were: Fan Speed, Cabin Temperature, Seat Temperature, Navigation, Phone Calls, Audio, Home Screen). Please refer to Brown et al. (2020) for a full report on the participatory design study. A shortlist of sixteen MAHIs for the seven infotainment features was generated. These were subsequently prototyped using the Ultraleap STRATOS Explore (SDK8, Firmware version 2.0.0). The core aim is to measure how recognisable the MAHIs are once they have been learned, and how distinguishable the icons are from one another (Maclean, 2008). Additional aims of this study were to understand the icons' fidelity to the original design intent as well as their "Instant Articulatory Directness" – the immediate obviousness of the icons in their ability to signify their root metaphor without a cue. Previous haptic perception studies look to paired comparison methodologies to establish the dissimilarity between stimuli. However, the icon set explored in this research was too large and a paired comparison methodology would likely result in participant fatigue (Bonebright, 2005). Instead, a perceptual Multi-Dimensional Scaling process was followed. This process was successfully employed by Rocchesso et al. (2019) in their mid-air haptic icons study involving two-dimensional rendered shapes.

Participants

Twenty-five participants took part in the study: 13 males and 12 females, with ages ranging from 25 to 55 (mean, 34). Due to COVID-19 restrictions, there was limited scope for external participant recruitment. As a result, all participants were Ultraleap employees, though largely from non-technical roles. Indeed, two participants had never experienced mid-air haptics; nine participants reported having used a mid-air haptics device a few times in the past year; 8 participants, about once a month; two participants once every two weeks and only four participants used MAH devices regularly (i.e. once or twice a week). As an incentive, the participant with the highest overall "score" in the tasks was given a £40 shopping voucher. The remaining participants were entered into a draw where four participants were chosen randomly, each receiving a £40 shopping voucher. None of the participants disclosed any impairment in the sense of touch in their left hand, which was used to correspond with the expected UK automotive context and configuration.

Experimental Setup and Procedure

The Ultraleap STRATOS Explore array was used to present the MAHI stimuli onto the participants' hand. To ensure that the MAHIs were actuated onto each participant's hand in a controlled way, a custom-made hand/arm rest was constructed (Figure 1). This ensured participants placed their hand exactly 20 cm above the array (the optimum interaction region). Threads of acoustically permeable speaker material spanned the aperture of the box which enabled the participant to keep their hand spread open while minimising fatigue. A video camera was poised overlooking the experimental setup and the participant to capture qualitative data. Noise-Cancelling Bluetooth headphones with disposable ear-piece covers were worn by the participant throughout the experiment in order to block out any spurious noises generated from the array; this also facilitated communication with the researcher. PPE was worn by both the participant and the researcher at all times (due to COVID-19) and all equipment was sterilized with alcohol-based wipes between participants.

Figure 1: Experimental setup showing participant with left hand resting on wooden arm rest

Instant Identification

As a precautionary measure, participants were provided with information sheets and were required to sign an electronic consent form and complete demographics questionnaires prior to attending the study. When seated in the study room, they were taken through an initial exposure stage. The purpose of this part of the study was both to familiarise the participants with the stimuli involved but also to obtain qualitative data on *Instant Identification* (IID). IID is a raw "bottom-up" processing metric to describe how well the prototype icons matched the design intent and thus gives an indication of perspicuity. By knowing how the participants initially perceived the icons, the researchers could then understand if there was loss of haptic information (constructs and intents). This qualitative data could be used to inform adaptations to improve the similarity to the original designs. With no prior knowledge of what the sixteen MAHIs were, participants had each sensation played (in an order dictated by a balanced-Latin square) onto their left hand – three times for discrete sensations or for six seconds for continuous sensations. They were then asked to describe what they had felt. They were then shown a graphical representation of the icon design and asked to verbalise if/how the diagram matched what they had perceived.

Recognisability and Distinguishability

The next task aimed to measure *Recognisability*, that is, participants' ability to identify the stimulus once it had been learned. To do this, participants were exposed to each MAHI in turn, with the order again informed by a balanced Latin square. After each haptic stimulus had been presented, the researcher displayed all of the haptic visualisations side-by-side on a computer monitor in front of the participant (Figure 1). The participants were then required to select which of the visualisations (labelled "a" to "p") they believed they had just felt. The participant's selection was then entered into a 16x16 confusion matrix. In the Rocchesso et al. (2019) study, sensations were played indefinitely until a selection was made. Here, sensations were played for a fixed amount of time/number of repetitions (i.e. three times or for six-seconds). The was to ensure that the icons were presented to participants in a manner approximating to how they would be experienced in a genuine, vehicular interface.

Distinguishability describes whether the features (i.e. the constructs and intents) enable the icon to distinguish itself from others in the set. To explore this, participants were asked to explain which aspect of each sensation had informed their choice. This qualitative feedback could then be used to help interpret why certain MAHIs may be similar. Participants had also been asked to give a Likert rating between 1 and 10 to indicate how confident they were in their selection (where 10 = very confident). This could then be used as a subjective indicator to interpret whether participants genuinely recognised the icons, or were merely guessing.

Instant Articulatory Directness

The final task in the study aimed to measure the *Instant Articulatory Directness* (IAD). This is adapted from Hutchens et al. (1985) definition and gives an indication as to how well the icons can be learned. To explore this, the metaphor labels from which the MAHIs were derived were presented to participants (for example, *"bouncing telephone handset"*). The metaphors were described with text only so as not to influence the participants' personal mental models of the metaphor. The participants were then played each sensation again (three times for discrete icons and six seconds for continuous) and asked to select the metaphor label they believed the sensation was semiotically tethered to. Again, their responses were entered into a confusion matrix. The participants were asked to articulate why they felt the sensation mapped onto their chosen metaphor and give a rating (as before) to indicate the confidence in their selection.

Analysis and Results

Instant Identification

Participants had been asked to describe what they had felt without any prior knowledge of the icons. Unfortunately, three participants struggled to clearly describe the icons due to English being their second language, and their data were excluded from this analysis. The remaining data were quantized in order to generate a metric: three reviewers (with expert knowledge of mid-air haptics) were asked to assess the qualitative data and to score the descriptions by determining how closely they matched an exact expert description of the MAHI. The exact expert descriptions were curated around the core semiotic features and locations on the hand on the rationale that object recognition processing is influenced by its "anatomical substrate" (Kaneshiro, 2015) (for example, *"focal ring 'bouncing' between 4 locations on the centre of the palm."*). The language participants used may not have been as technically precise as the expert descriptions, but the reviewers were asked to use their expertise to decide if they alluded to the same meaning. Two points were awarded for an exact match: the participant was able to describe two or more core signifiers (i.e. parameters that construct the identity of the sensations), which might be a path, micro-geometry, or dynamic behaviour. A minor error match received one point: For a minor error, the participant was able to describe at least one core signifier but might miss latent signifiers. This would not be expected to inhibit recognition but might reduce capacity for metaphor representation (i.e. there is ambiguity in their articulation). No points were awarded if the participant was incorrect, i.e. they detected a spurious part of the sensation that would confound the icon identity as a whole or they were unable to identify any signifiers of the sensation. A final, arbitrated score was given as a median average between the three reviewers. The median arbitrated scores for each participant were then summed to give a percentage of the maximum total (22 participants × 2 points (exact match) = 44 points). The average IID score was 47%, with “Thermometer” scoring the highest IID at 82% and “Propeller Fan”, the lowest at 18%.

Recognisability

Recognisability explains how easily mid-air haptic icons can be identified once the participants had been familiarised with the stimuli. Data were consolidated into a master confusion matrix (CM) (Table 1), indicating the number of times a MAHI was correctly matched to the visual representation by the participants. Rows (CMx) designate the metaphor label condition while columns (CMy) denote predicted responses given; diagonal values indicate where a correct selection was made (CMxy) (Kaneshiro et al., 2015). Each value in the matrix was divided by the sum of its row to generate classifications as a proportion of all responses for that icon. The highest recognition rate (RR) was for the “Ice” icon which exhibited a pulsating haptic bar on the thumb. This was correctly recognised 100% of the time. The icon with the lowest RR (28%) was “Sofa Cushion”. This sensation exhibited a circle that expanded from the centre of the palm and then contracted again. The mean RR for the MAHIs was 66% (Standard Deviation of 18%) and all the icons achieved an RR above the chance level of 6% (1/16 = 0.06). These results are similar to those reported by Rocchesso et al. (2019), who found an average recognition rate of 0.57 (57%) associated with sixteen variants of planar shape icons (cross, circle, square).

Table 1: Confusion matrix. Diagonal values indicate where a correct selection was made.

		CMy															
		[a]	[b]	[c]	[d]	[e]	[f]	[g]	[h]	[i]	[j]	[k]	[l]	[m]	[n]	[o]	[p]
CMx	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
	Profile View of a Seat [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

Distinguishability

Incorrect classification data from the master confusion matrix (Table 1) was used to visualize the representational similarity between the icons. This process converts similarity metrics into distances in Euclidian space that can be visualised through Multi-Dimensional Scaling. In conventional correlation-based confusion matrices, the central intersect (xy) is a null data point. However, for this analysis, the diagonal elements contain correct classifications. The data therefore needed to be normalized so that the diagonal intersects of the confusion matrix became unitary. This was done by dividing every matrix cell by the diagonal of its row (CMxy = CMxy/CMxx). Next it was necessary to symmetrize the matrix by calculating the geometric mean of the cells and their transpose, i.e. GM = √(CM x CMt). The symmetrized Confusion Matrix could then be processed by SPSS Multidimensional Scaling (PROXSCAL) to visualize proximities between data points over two notional dimensions (Figure 2). The normalized raw stress level for the data was 0.781 which suggests a fairly good fit. “Compass” was the icon that was confused most commonly with other icons and is therefore positioned closer to the origin (i.e. where no discernible differentiating dimensions exist with the stimuli). This is a sensation that exhibits four focal points emerging from a central position on the hand to represent the North, South, East & West. “Ice” was never confused with another icon which is signified by its data point being furthest from the origin, as well as furthest from any other data point.

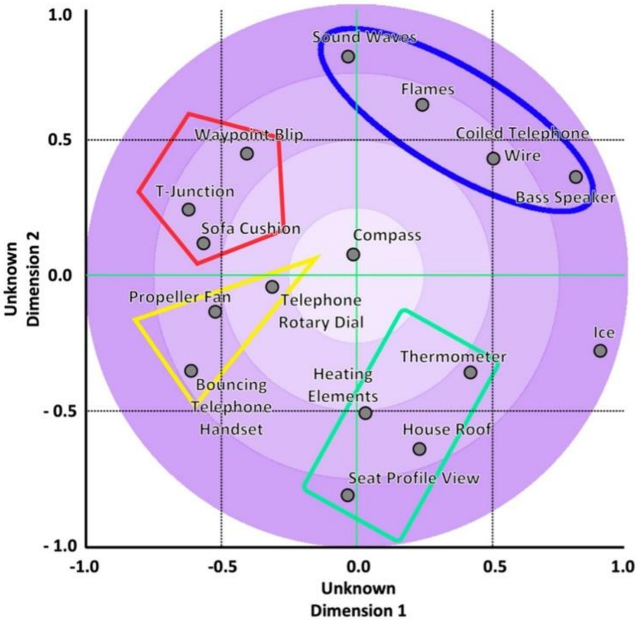

Figure 2: Haptic icon similarity data visualized through multi-dimensional scaling

Clusters of data points have been highlighted with ellipses which denote shared commonality among MAHIs. Nevertheless, it is not possible to infer what the confused dimensions are from the chart alone. Because the participants were asked about their decision-making process when making classifications, we interrogated the qualitative data to understand why these icons may have been confused. For the loosest cluster (in the blue ellipse) many participants attribute their decisions to the fact that the sensations were actuated onto the index and middle fingers in some way, suggesting that the location on the fingers was the core confusing attribute. For the green ellipse cluster, participants tended to mention that these particular sensations go up the palm and back down in some way. This indicates that the location on the palm and the fact they were rendered path sensations contributed to misclassification. The yellow cluster ellipse contains icons that were confused seemingly for their apparent circular path of individual focal points around the palm, according to participants’ responses – even though “Bouncing Telephone Handset” was a randomized actuation of a small haptic ring across four corners of the palm, it was still perceived as circular. The tightest cluster in the red ellipse contain icons that exhibited divergent behaviour i.e., focal points splitting in opposite directions, or circles expanding and contracting. This was corroborated by the qualitative data as many participants reported feeling the sensations growing and shrinking.

Instant Articulatory Directness

Data collected for IAD was processed in the same manner as the recognisability data - in a confusion matrix that was normalized to give the frequency of classifications as a proportion of total responses. Without any accompanying visual or prior knowledge of the metaphor, the mean percentage of correct identifications of a metaphor via haptics was 35% per icon (maximum, 68%, minimum, 8%). This suggests that although the metaphor was well conveyed to some people, for many others the meaning would still need to be explained. Nevertheless, general feedback indicated that once the meaning has been explained, the association is clear to the user. All metaphor classifications achieved above chance level of 6% (1/16 = 0.06).

To help interpret why some of the icons were more easily identified than others, three expert reviewers categorised the icons in line with Blattner et al.'s (1989) definitions. Blattner et al. (1989) described the stimulus-meaning relationship in iconography as a continuum that spans from *representational* at one end to *abstract* at the other. A representational relationship is where the form directly depicts that of the metaphor or accurately reconstructs the sensory experience. With abstract icons, the representation of meaning is arbitrary, in other words, the association is not innate and therefore must be learned. Between these categories lies the semi-abstract icons whereby "features of the icon imply the whole". This theoretical continuum was adapted by the reviewers as a rating scale. They appraised the MAHIs and their association with their root metaphors by assigning a number between 1 and 5 (1 being completely abstract and 5 being completely representational). Since there were only three reviewers, a Cohen's Kappa greater than 0.7 could not be reached. Instead, the reviewers discussed the categorisations until consensus of at least 66% agreement rating was achieved (i.e. at least two out of the three reviewers agreed). The data were then analysed alongside the IAD data demonstrating a strong significant Spearman's Rank correlation ($p = .001$, $r_s = .786$) between Icon type and IAD. As might be predicted, the data show a trend toward more representational icons having higher scores for IAD. Even though the data points are not evenly spread across the categories, a relationship between the variables is apparent.

The identification data was further examined through Multidimensional Scaling to see if the metaphors were bound by similar dimensions (Normalised Raw Stress = 0.061). The visualisation of the data showed no discernible clustering, and the qualitative responses surrounding participants responses allude to uncertainty when making their selections. The MDS does, however, show the metaphors that were confused most often to be centred around the origin. The "Waypoint/Radar Blip" and "Bass Speaker" icons were commonly reverted to when the participants were unsure about their selection. When these were selected, the responses as to why the sensation maps onto this metaphor were consistently different. Sensations further away from the origin, on the other hand, seemed to attract less ambiguity. Common responses such as, "the triangular shape correlates to the roof of houses" for the Icon "House Roof" further support the premise that more representational icons have higher IAD. The data also indicate that icons which convey the physical characteristics of a metaphor are more intuitively discerned than icons that convey the non-physical properties of the metaphor (i.e. motion, rhythm etc.).

Exemplar Icon Set

The scores from the Instant Identification, Instant Articulatory Directness, Recognisability were combined for each icon to give a total salience score. The icons with the highest salience scores were selected and implemented alongside their respective features in a prototype Mid-Air Haptic Gesture Interface, which will be evaluated in further, ongoing work.

Discussion

A core aim of this research was to identify if perception data can be used to optimise a set of exemplar MAHIs which could subsequently be used for an in-vehicle MAH interface offering infotainment features. Four metrics were used to inform this decision: Instant Identification, Instant Articulatory Directness, Recognisability and Distinguishability.

The IID metric was useful at understanding the quality of the designs and it also can give an indication of how easily the features of the icons will be able to convey the meaning of the icons. However, limitations exist with quantizing the "closeness" of the participants descriptions for the sensations. Primarily, the participant's knowledge and experience of mid-air haptics may have influenced their ability to describe the icons in detail: participants with no knowledge could generally articulate the location in which a sensation was actuated but those who were more familiar with mid-air haptics were able to interpret micro-geometry (for example, haptic rings versus haptic points). It is also possible that icon design resolution was lost through spurious hardware and software artifacts (bandwidth limits, component fatigue etc.). Future research could utilise acoustic visualization techniques, such as heat maps, to observe if the haptics being emitted truly represent the intended design.

The core premise behind MAHIs is to convey semantic information through the haptic channel. IAD was used as an indication of how intuitive the connection between metaphor and the icon is and therefore how easily it could be learned. Results show that there was a large variation (std dev 19%) in participants' ability to identify the root metaphors through the haptic channel. Consequently, some learning will therefore be required to understand the association between salient features and the root metaphor. Visual encoding often sets the user's expectations on what the haptic stimuli will be and because the way in which the metaphors map onto the haptic icons was not shown prior, participants' expectations were not set. This is an important cognitive process in the identification of physical haptic elements (i.e. buttons and switches) therefore the same principle may well apply to mid-air haptics (Breitschaft et al., 2019). The IAD also seemed to be directly affected by the ambiguity of the metaphor label. Labels like "T Junction" or "profile view of a seat" etc. are very specific and leave little open for interpretation which may have allowed the participants to build a clearer expectation in their heads, whereas "Sofa Cushion" and "Ice" are arguably more ambiguous. For these reasons, participants' expectations will likely need to be set through a learning phase using visual animations that exhibit the "haptification" of the metaphor. Theoretically, and in line with the Multi-Store Model of Memory, this will enable participants to visually encode the information into their short-term memory. The semantics (along with rehearsal) may then allow for long-term memory retention (Malmberg et al., 2019).

Recognisability as a metric is a core indicator for general salience and will reveal the icons that will have the highest probability of identification when integrated into an interface. In order to reduce cognitive demand (i.e. time and effort) in recognising icons, the concepts must be as distinct from each other as possible. The MDS chart (Figure 1) allows us to visualise this distinguishability. The MDS chart and qualitative feedback indicated that convergent/divergent sensations were commonly confused due to similarities in sensations across the underside of the knuckles. This is an area of the hand that seemingly dominated perception of these types of a mid-air haptic sensation. The data indicates that feeling a sensation on this part of the hand was the primary reason that participants made their selections in this cluster, which might suggest the presence of Gestalt processing – the ability to build the whole concept through the experience of constituent parts (Chang and Nesbitt, 2006). This is also part of the rationale behind the mnemonic ability to infer semantic information purely through the existence of semiotic features. An important insight to derive from this is that the first salient feature the participant attends to will likely be the biggest determining factor in their identification.

Conclusion

Traditional MDS studies have focused on stimulus differentiation for the thresholds of base parameters (frequency, amplitude etc.) in tactile signals (e.g. Maclean and Enriquez, 2003). This study, however, aimed to discover the distinctions given to stimuli-based icons on spatiotemporal behaviour and metaphorical design. The metrics employed allowed the researchers to select and perceptually optimize an exemplar set of the seven most salient mid-air haptic icons taken from an initial set of sixteen. Future work will look to incorporate these in a prototype MAHG interface where they will act as semantic confirmation to feature selection alongside specific hand poses. This will subsequently be appraised in a driving simulator study.

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