2019 IEEE World Haptics Conference (WHC)
Tokyo, Japan
9-12 July 2019

HaptiGlow: Helping Users Position their Hands for Better Mid-Air Gestures and Ultrasound Haptic Feedback

Euan Freeman[1], Dong-Bach Vo[1] and Stephen Brewster[1]

***Abstract*— We present HaptiGlow, a technique that combines ultrasound haptics with peripheral visual feedback to help users find where to place their hand for improved mid-air interaction. Hand position is important. If a user's hand is poorly placed, input sensors may have difficulty recognising their gestures. Mid-air haptic feedback is also hard to perceive when the hand is in a poor position. Our novel feedback addresses this important usability problem. Our results show the combination of ultrasound haptics and peripheral visuals is effective, with the strengths of each leading to accurate (23mm) and fast (4.6s) guidance in a 3D targeting task. Our technique improves mid-air interaction by easily helping users find a good hand position.**

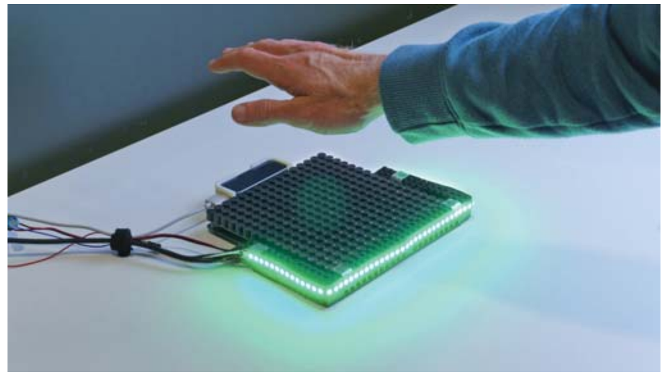

Fig. 1. HaptiGlow combines ultrasound haptics with peripheral visual cues from lights, to give feedback and help users find where to gesture.

I. INTRODUCTION

Users need to find where to gesture before they even begin interacting with a mid-air user interface. Hand position is important because it affects the quality of the input sensing. Users might not know where the sensor is located or what it can see, making positioning difficult. If hands are too close, or too far from the sensor, then it may have difficulty tracking them accurately and gestures may not be recognised. For example, if a hand is at the limit of the field of view, then some gestures may occur outside the range of tracking and will not be recognised. The space in which gestures can be sensed is invisible and often ambiguous to users, especially when different sensing technologies are used. However, good feedback can help users understand the capabilities and limitations of the sensor, helping them find where to position their hand for successful mid-air input [1].

Hand position is also important for mid-air haptic feedback. Several technologies have been developed to allow users to experience haptics in mid-air without direct contact: for example, focused ultrasound [2], [3], air vortex [4], [5], electrical arcs [6], and lasers [7], [8]. The quality of the haptic feedback depends on the hand position. For example, ultrasound haptic feedback needs sufficient distance for the ultrasound waves to focus, but weakens if the hand is too far from the device. Different haptic technologies also cover a broad range (mm [6], cm [2], [3], or m [4], [9]), requiring different hand positions to feel strong feedback.

We present HaptiGlow, feedback that combines ultrasound haptics with lights positioned around a haptic display, to help users find where to position their hands for optimal interaction (Fig. 1). Both modalities give information about hand position, helping users find the location where sensing is more robust and haptic feedback feels stronger. This helps users *address* the system [10] when they initiate interaction, a necessary first step that precedes task-oriented gestures (e.g., manipulating control widgets or issuing a command) and will improve usability, the input quality, and haptic perception. HaptiGlow is important because we cannot take for granted that users will understand the importance of hand position and that a good position will be easy to find.

In this paper, we present a study that found the HaptiGlow feedback effective for guiding hand movements. Ultrasound haptic and peripheral light feedback both performed well on their own, but their combination was especially effective. We found that the strengths of each modality complemented the weaknesses of the other, leading to better hand positions above the device. Our results suggest that our technique is an effective way of helping users place their hands in the right place when they begin using a mid-air user interface.

II. RELATED WORK

A. Finding where to interact with a mid-air system

Feedback is necessary to help users overcome challenges when interacting with sensing systems [10]. A usability issue specific to gesture sensing systems is finding where to position the hand or body, so that input can be reliably and robustly sensed. Hand position is important because gestures in a poor location (e.g., too far from the sensor or partly out of sight) may be misrecognised or not recognised at all. This significantly reduces the usability of such systems and can cause much frustration. When mid-air haptic feedback is used, this is doubly important, as users also need to be in a position where they can perceive the feedback as well.

[1]Glasgow Interactive Systems Section, University of Glasgow, Glasgow, UK {first.last}@glasgow.ac.uk

This work is funded by the European Union Horizon 2020 research and innovation programme (#737087: Levitate).

Recent work investigated novel ways of helping users find a better hand or body position for input. Vermeulen *et al.* [11] used lights on the floor to guide users when interacting with wall displays. Their focus was on body position within the room and the floor display was successful at helping users position themselves as they entered the room. Alt *et al.* [12] distorted visual content to guide users to 'sweet spots' in front of large screens; these were positions where content was best perceived or where input was most reliably sensed. They modified the visual appearance of the display content in order to encourage users to move to a better position.

Others have focused on smaller scale gestures, guiding the hand over a sensor rather than the whole body within a room. Freeman *et al.* [1] used LEDs to give visual feedback in the space around a mobile phone. The LEDs got brighter as the hand approached the 'sweet spot' of the sensor. They also used audio feedback and haptic feedback from an actuator worn on the skin, telling them how close they were.

The works discussed here have focused on guiding users to a position for better input sensing, but position also affects the quality of mid-air haptic output. Whilst only anecdotal, in our years of experience with ultrasound haptic feedback, users tend to place their hands directly above the ultrasound array, where feedback quality is poor. Our aim with this work is to change users' behaviour with good feedback that lets them know they have found a good hand position.

B. Ultrasound haptic feedback

Mid-air haptic devices allow users to receive feedback in the space in which they perform gestures, without the need to wear or hold anything. This haptic feedback can help compensate for the loss of tactile cues when using mid-air gestures [13]. A common method for mid-air haptic feedback uses focused ultrasound to create acoustic radiation pressure against the skin [2], [3], which feels like gentle vibration. This feedback is continuous, has high spatial resolution ($\lambda \approx 8.6\,\mathrm{mm}$), and can be felt over a moderate range (10 to $70\,\mathrm{cm}$). These properties make it ideal for gesture feedback, as it can stimulate the hand whilst following its movements.

Ultrasound haptic feedback is created by focused acoustic pressure from an array of ultrasound transducers [2], [3]. The focal point amplitude may not be strong enough to be perceived, so perception can be improved by modulating the amplitude of the focal point in the range of tactile sensitivity (approx. $250\,\mathrm{Hz}$). Alternative methods include moving the point continuously, instead [14], [15]. Many focal points can be perceived simultaneously [2], but a single point can be used to create feelings of movement or shapes [16].

Alternative mid-air haptic methods include stimulation by air pressure, electrical arcs, and lasers. Air vortices have been used to create moving regions of air pressure that collide with the hand [4], [5], creating low-resolution ($85\,\mathrm{mm}$) haptic sensations over a greater range (up to $3\,\mathrm{m}$). Electrical arcs have been used to create tactile feedback on the fingers [6], over a short range (up to $1\,\mathrm{cm}$) with varied tactile and thermal properties (e.g., rougher and warmer). Lasers can also be used for non-contact tactile output [7], [8].

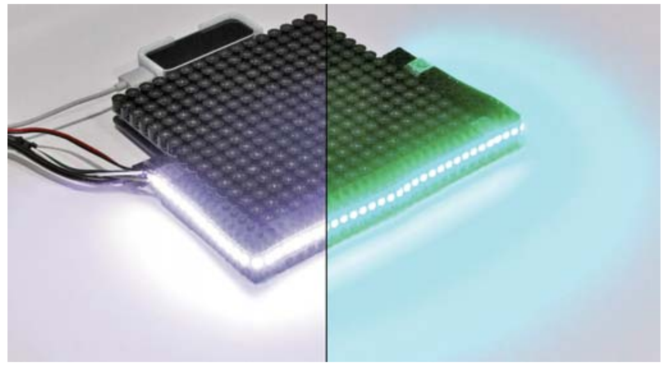

Fig. 2. *HaptiGlow* consists of LEDs wrapped around the user-facing half of an Ultrahaptics mid-air haptic display. This image shows the two colours our visual feedback interpolates between: white and green.

In this work, we develop feedback for guiding users to a good hand position. Our motivation is twofold: to guide users to a position where their gestures can be reliably sensed, which is also the position where the haptics is at its strongest. We investigate visual feedback from simple lights placed around the haptics device, as this is a low-cost modification and LED feedback was successful for guiding hand/body movements in the work discussed before [1], [11]. We use ultrasound haptics too, as the quality of the haptics will naturally improve as users find a better hand position.

Other sensors with different input ranges are likely to be paired with appropriate haptic devices (e.g., Kinect and air vortex haptics [4], [5], or infrared proximity sensors with electrical arcs [6]) and may, therefore, use different haptic feedback designs. Our LED feedback designs, however, are independent of the haptic device and could be easily applied to these other haptic devices and interactive systems.

III. HAPTIGLOW: DEVICE & FEEDBACK DESIGN

HaptiGlow (Fig. 2) combines ultrasound haptic output with peripheral visual feedback from lights, for multimodal feedback about mid-air gestures. Our aim is for this feedback to guide users to a better hand position, prior to interaction, so that input sensing and haptic quality are improved. Once in a better position, input should seamlessly transition towards intended use (e.g., to grasp a virtual object or manipulate a virtual control). We do not focus on this transition in this work, but envisage the feedback in the periphery of attention gradually disappearing as users turn their focus to task-oriented interactions.

We created the HaptiGlow device by attaching a strip of LEDs[1] to the user-facing edge of an Ultrahaptics UHEV1 device[2]. This allows the LEDs to illuminate the table surface around the front of the haptics device, facing the user. We did not completely surround the device with LEDs because the rear edge is less visible to users and because of cable positions for the haptics device. The UHEV1 device has 256 $40\,\mathrm{kHz}$ ultrasound transducers ($\varnothing 1\,\mathrm{cm}$) in a 16x16 square, and it uses a Leap Motion sensor for tracking users' hands.

[1]NeoPixel LEDs: `http://www.adafruit.com/product/1506`
[2]Ultrahaptics: `http://www.ultrahaptics.com`

A. Feedback Design

HaptiGlow gives users feedback to help them find the 'sweet spot' for gesture input. The sweet spot is a position where the sensor can robustly track the hand and where haptic feedback is at its strongest. For optical sensors like Leap Motion, this is a position where the full hand is visible and sufficient detail can be captured about the fingers, often centred in the field of view. For ultrasound haptic devices, this is a position far enough for the sound waves to focus but not so far that the feedback gets weaker. In this case, the optimal input and output ranges coincide, around $20\,\mathrm{cm}$ to $30\,\mathrm{cm}$ over the haptic device. Note that the sweet spot is not a precise position, but a general area where input and output quality is highest. Our implementation uses a precise position to define the sweet spot, but we do not intend users to find this precisely (e.g., with mm precision).

Others have used feedback that only tells users how close they are to the interaction sweet spot, rather than giving explicit guidance [1], [12]. The motivation for this is that users would have to explore the input space and form their own understanding about how the change in feedback relates to their movements. This also means our feedback can be used by other devices with simpler display capabilities: e.g., a thermostat or voice-activated home assistant with a simple colour-changing display or status light. We use the sweet spot concept in our feedback designs: HaptiGlow uses visual and haptic stimuli to tell users how close they are to the sweet spot, encouraging exploration to improve their hand position.

For the peripheral visual feedback, we use colour transition from white to green to show the proximity to the sweet spot (green means close). We chose this design because: (1) the white lights confirm tracking even when in a poor position, thus no light means the hand cannot be seen; (2) the positive connotations of green reinforce the 'goodness' of gesturing in a good position; and (3) the transition between the white and green light was found to be effective in pilot testing. We tested other transitions (e.g., from red to green) but the intermediate states were often ambiguous (pilot testers found it difficult to judge the relative position between two colours). Fig. 2 shows the white and green used in the final visual feedback design. In other work using LEDs to guide hands [1], the transition was between 0% and 100% brightness of white light. We improve on that design by reducing ambiguity: *c.f.*, (1) above.

For the haptic feedback, we wanted to create the sensation of feedback becoming stronger as the user approached the sweet spot, whilst also using the position of the feedback to give spatial cues about where to move the hand. We designed the feedback to be presented to the palm, rather than the fingers, because of its larger contiguous surface area. The direct spatial relationship between the input (hand position) and output (feedback) means that the position of the haptic feedback could hint towards the best interaction area. We did this by creating an ultrasound haptic cone, whose base was centred in the sweet spot (Fig. 3). The orientation of the cone was changed so that it was always perpendicular to the palm of the hand. This preserved the spatial relationship between hand position and the feedback, whilst ensuring it could be perceived regardless of hand orientation (Fig. 4). The conical shape of the feedback meant that users perceived its circular cross-section on their hand, increasing in diameter as they approached the sweet spot, as in Fig. 3. The increasing area of feedback should feel stronger due to spatial summation of tactile stimuli on the hand: as the area of multiple stimuli is increased, they are perceived as a whole and there is a greater probability of stimulating tactile receptors. This is more appropriate than adjusting the amplitude of the ultrasound to create the perception of weaker/stronger haptics. Since the feedback itself is already quite weak, reducing it further would make it more difficult to detect.

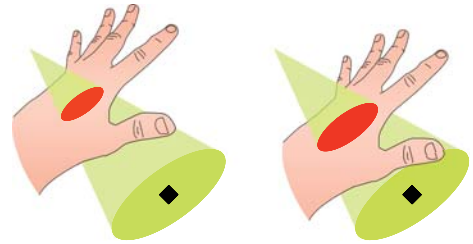

Fig. 3. Users feel the circular cross-section of the haptic cone as their hand intersects it. As the hand approaches the base at the sweet spot (⧫), the wider cross-section creates the feeling of stronger feedback.

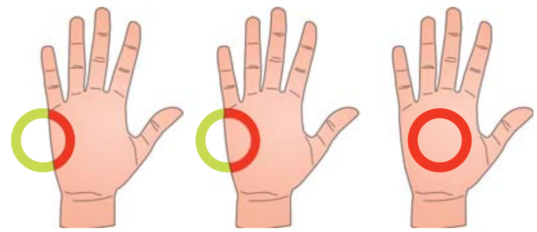

Fig. 4. Users can feel where the feedback is in relation to their hand position, giving spatial hints about where to move. The red shaded area shows the region of the circle outline that would be felt at each position.

B. Implementation

Our interaction is based on the distance between hand position and sweet spot. We define the sweet spot as an arbitrary 3D point within the input sensor range. This is varied for the purpose of our user study, but it would normally be the position where the sensor can capture optimal data about the hand. We calculate the Euclidean distance d between the centre of the palm (from the Leap Motion sensor) and the sweet spot. Distance d is then divided by $100\,\mathrm{mm}$ to give proximity p, from 0.0 to 1.0, where 0 is the closest proximity to the sweet spot. This means the feedback varies over a $\varnothing 200\,\mathrm{mm}$ sphere; this size was chosen during prototyping because it allowed a noticeable variance of feedback within the space above the Ultrahaptics device. This 3D distance is then used for both visual and haptic feedback.

The peripheral visual feedback was created by interpolating between green (RGB: 0 255 0) and white (RGB: 50 50 50) hues, as p increased to 100%. These RGB values were chosen to compensate for the disproportionate luminance of stronger white light (e.g., RGB: 255 255 255), meaning the two colours appeared to have a similar intensity, even though our 'white' light would be dark on an LCD screen.

The haptic feedback was created by rendering the outline of the circular cross-section of the cone in mid-air, perpendicular to the palm (determined using the Leap Motion hand tracking data). The maximum diameter of the circular cross-section was $40\,\text{mm}$ and the actual diameter was $\{(1–p)$ x $40\}$mm. For example, if the hand is $60\,\text{mm}$ from sweet spot (p = 0.6), the circle diameter would be $16\,\text{mm}$. The haptic circle was rendered using lateral modulation [14], [15]: one ultrasound haptic focal point traversed the circumference of the circle at $75\,\text{Hz}$. We found that $75\,\text{Hz}$ offered the strongest sensation for this shape and size range. We used the maximum sample rate of the UHEV1 device ($16\,\text{kHz}$).

IV. User Study: Evaluating HaptiGlow

We ran a study to investigate if the HaptiGlow feedback was effective for guiding hand movements in mid-air. This study also looked at the effectiveness of each type of feedback on its own, to better understand how peripheral visuals and mid-air haptics might be used together.

We used a within-subjects design with three feedback types: (1) Lights, (2) Haptics, and (3) Haptics+Lights. We recruited 20 participants (9 female, 1 left-handed), whose mean age was 26.9 years (sd 5.3 years). All were paid £6 for participation. Ethical approval was provided by our institution's ethics committee.

A. Study Procedure and Measurements

Participants sat at a table with the HaptiGlow device in front of them. They were instructed to use the feedback to help them position their hand above the device. Rather than guide users to the same position for each task, we varied the target position. Target positions were randomly placed within a volume from $(-40,\ -40,\ 140)\,\text{mm}$ to $(40,\ 40,\ 200)\,\text{mm}$, relative to the centre of the Ultrahaptics device (note: z-axis is the vertical axis). This was chosen to keep the hand within the central region of the Ultrahaptics output range, because the mid-air haptic feedback is weaker towards the extremities of the device. Feedback was given about the location of the centre of the palm of the hand, relative to the target point. The middle of the palm was chosen as the reference point so that when directly at the target point, the mid-air haptic feedback would be centred on the palm.

Tasks started when users moved their dominant hand over the device. For each task, participants had to use the feedback to locate the target point "as quickly and as accurately" as possible. We used this wording because a focus on accuracy may have led to long task times unrepresentative of our intended use of quickly finding where to place the hand when beginning to use a gesture system. Tasks ended when participants pressed a large button in front of them, using their other hand; this meant the final palm position could be accurately recorded. Participants were asked to place both hands on the desk after each task, so that all tasks started with the hand reaching over the sensor. For each condition, participants completed two blocks of 20 tasks (six blocks and 120 tasks total) and were allowed to rest between tasks. The order of blocks was balanced using a Latin square.

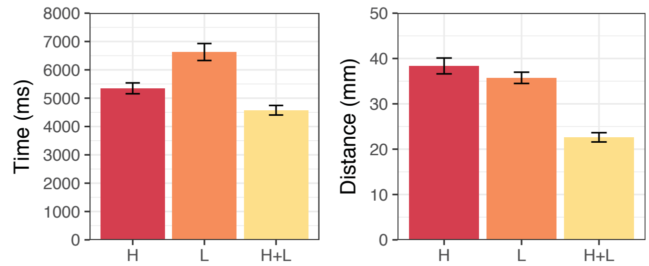

Fig. 5. Mean *Time* (left) and *Distance* (right). Error bars show 95% CIs.

At the beginning of each experimental session, we gave a short tutorial about the interaction, giving participants a chance to try the tasks and experience the feedback. The tutorial was also used to encourage participants to 'feel' for the ultrasound using the palm of their hand, rather than their fingers, since our feedback was intended to be centred on the palm. We encouraged this by placing a small sticker in the middle of palm as a reminder.

We measured the *Time* of each task, from when the hand was first detected by the Leap Motion sensor, to when the other hand pressed the button to end the task. We also measured the *Distance* between the target point and the final palm position ($\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$, the distance from sweet spot described earlier). Final hand position was also recorded. We presented a short survey at the end of the experiment, which asked participants about the feedback and asked them to rank them in order of preference. Raw performance data from this study is available online [17].

B. Results

The mean *Time* across all conditions was $5477\,\text{ms}$ (sd $3149\,\text{ms}$), see Fig. 5. An ANOVA found a significant main effect for feedback on *Time*: F(2, 38) = 17.8, $p < 0.001$. *Post hoc* t-test comparisons found:

- *Time* was higher for Lights than Haptics: $6629\,\text{ms}$ vs $5347\,\text{ms}$, t(38) = 3.39, p = 0.005
- *Time* was higher for Lights than Haptics+Lights: $6629\,\text{ms}$ vs $4574\,\text{ms}$, t(38) = 5.96, $p < 0.001$
- *Time* was higher for Haptics than Haptics+Lights: $5347\,\text{ms}$ vs $4574\,\text{ms}$, t(38) = 2.57, p = 0.04

The mean *Distance*, D, across all conditions was $31.9\,\text{mm}$ (sd $17.7\,\text{mm}$), see Fig. 5. An ANOVA found a significant main effect for feedback on D: F(2, 38) = 37.54, $p < 0.001$. *Post hoc* t-test comparisons found:

- D was higher for Lights than Haptics+Lights: $35.7\,\text{mm}$ vs $22.6\,\text{mm}$, t(38) = 13.3, $p < 0.001$
- D was higher for Haptics than Haptics+Lights: $38.4\,\text{mm}$ vs $22.6\,\text{mm}$, t(38) = 16.8, $p < 0.001$
- The difference in D between Lights and Haptics was not significant: t(38) = 3.47, p = 0.22

We used the final hand position data to calculate the 'error' between the hand and the target position (i.e., the

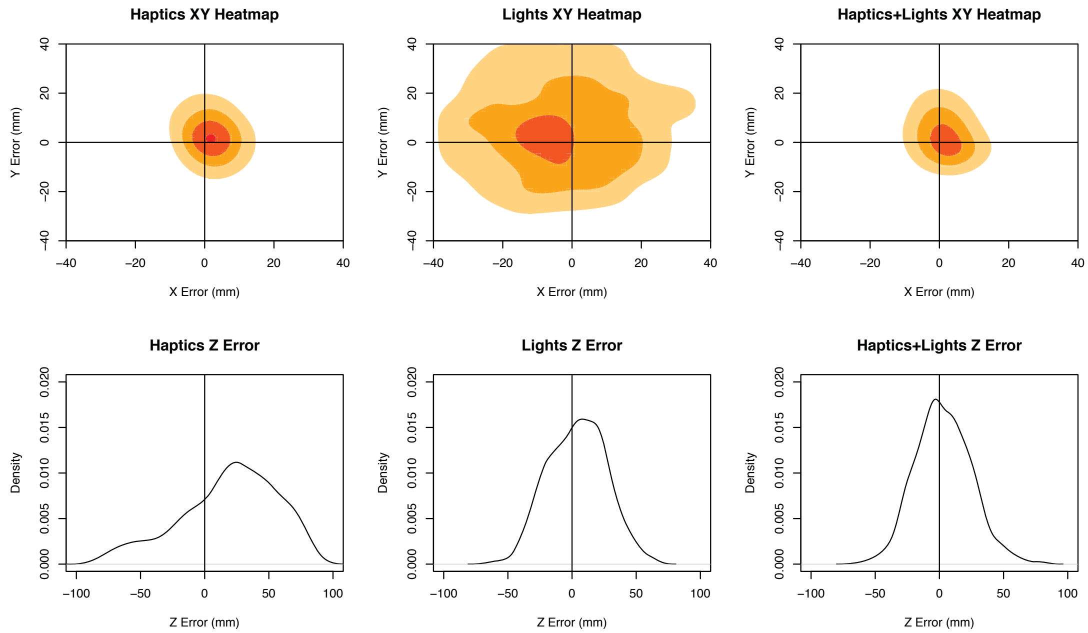

Fig. 6. Top: heatmaps showing the distance between the final hand positions and the target points in the horizontal plane (x and y axes), for each feedback type. Bottom: density plots showing the height difference between final hand positions and the target points (z axis), for each feedback type.

difference in each axis). Fig. 6 visualises this data. The top row shows heatmaps of the error in the horizontal plane, for each type of feedback. These plots visualise where the hand was located relative to the target point in horizontal space over the ultrasound haptics device. Note the wide distribution of errors for the LIGHTS condition, compared with the higher accuracy for the others. The bottom row shows density plots for the error in the vertical plane (i.e., height difference), for each type of feedback. Note the skew for HAPTICS.

Order of feedback preference, from most to least favourite, was: HAPTICS+LIGHTS (median 1^{st}), HAPTICS (median 2^{nd}), LIGHTS (median 3^{rd}). Friedman's test found a significant difference in the ranks: $\chi^2(2) = 20.8$, $p < 0.001$. *Post hoc* Nemenyi's tests found a significant difference between ranks for HAPTICS+LIGHTS and both HAPTICS ($p < 0.001$) and LIGHTS ($p = 0.005$). The difference between HAPTICS and LIGHTS was not significant ($p = 0.42$).

C. Discussion

Our results show that HAPTICS and LIGHTS had unique strengths that, when combined, led to an effective multimodal feedback design. Haptic feedback was good at conveying the position of the target point in the horizontal plane (Fig. 6). This was not surprising, because the haptic feedback gives spatial information directly to the hand; users knew they were in the right area when the feedback was centred on their palm and many of our participants said this in the post-study survey. The haptic feedback also conveyed the proximity to the target point by varying the radius of the feedback area (Fig. 3). Our participants do not appear to have used this aspect of the feedback as much as the position of it, suggested by the lower accuracy in the z-axis (Fig. 6). The skewed density of positive errors in the z-axis shows that participants were generally below the target points for the HAPTICS condition. Anecdotally, users tend to put their hands too close to ultrasound haptic displays and this may also have been the case in this study. Future work should investigate a better way of manipulating the haptic feedback to help users get their hand at an appropriate height over the device, since the relative change in haptic circle size was less successful than change in colour.

The visual feedback in the LIGHTS condition led to good accuracy in the z-axis but not in the xy-plane (Fig. 6), opposite to the HAPTICS condition. We expected HAPTICS to perform better because of the spatial information it presents, but we were surprised that the visual feedback was successful at helping users get their hand at the right height above the device. We calculated the colour for the visual feedback using the Euclidean distance between hand and target, which means the feedback changed in the same way, regardless of which axis the hand was moving in. One explanation for good accuracy in the z-axis comes from the 'search strategies' reported by some participants in the post-study survey. We asked participants to justify their top-ranked type of feedback and many explained that they preferred HAPTICS+LIGHTS because they would first use the haptic feedback to get their hand in the right area (i.e., centred over the haptic feedback), then they would use the visual feedback to help adjust the height of their hand. This was one of the strengths of HaptiGlow's feedback: each modality encoded the same information but were used in different ways. Our design shows that users can use such information to improve their hand position, motivating future work into optimising visual and haptic cues towards this goal.

The HAPTICS+LIGHTS condition led to the best accuracy as well as the fastest times. As mentioned, this was the most effective feedback because participants used the strengths of each modality to quickly and accurately find the target points. Each modality was individually effective and our designs could be used successfully by other gesture systems to guide users, but the results show that multimodal feedback is the most effective and we recommend enhancing ultrasound haptic displays with peripheral visual feedback where possible. Our approach was to add a low-cost LED strip to the hardware, which turned the surrounding area into a low fidelity, but effective, display. In cases where the ultrasound haptics device is fully integrated (e.g., a car dashboard), nearby lights or displays could be used to present our simple colour-based feedback, as this can help users position their hand prior to interaction. In this work we focused on mid-air interaction but our designs may have benefits for mixed-reality headsets. For example, the haptic feedback for a virtual object could be extended towards the user's hand, getting larger and moving towards the centre of the palm as the user moves towards it (like our haptic 'cone'). Likewise, visual cues in the headset periphery could raise awareness of proximity to interactive objects or controls.

V. CONCLUSION

In this paper, we presented HaptiGlow, a system that combines ultrasound haptic feedback with peripheral visual feedback from lights to enable users to address mid-air gesture systems effectively. We investigated its ability to guide users to target points in mid-air, to better understand how the feedback could be used to help them find a good hand position before they start to interact. Hand position is an important factor because it affects the quality of input sensing and haptic feedback, so our technique is designed for use *before* the user starts performing other gestures. Users located points with $32\,\mathrm{mm}$ accuracy in $5.5\,\mathrm{s}$, improving to $23\,\mathrm{mm}$ accuracy in $4.6\,\mathrm{s}$ with the multimodal feedback. The combination of lights and mid-air haptics was more effective than the individual modalities. Users used them in different ways, leveraging the strengths of each to minimise time and increase accuracy when positioning their hand. This also shows the benefit of adding low-cost peripheral visuals to ultrasound haptic devices, since our simple visual feedback was sufficient to improve interaction.

REFERENCES

[1] E. Freeman, S. Brewster, and V. Lantz, "Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. ACM Press, 2016, pp. 2319–2331. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2858036.2858308

[2] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, "UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces," in *Proceedings of the 26th Symposium on User Interface Software and Technology - UIST '13*. ACM Press, 2013, pp. 505–514. [Online]. Available: http://dl.acm.org/citation.cfm?id=2502018

[3] T. Iwamoto, M. Tatezono, and H. Shinoda, "Non-contact method for producing tactile sensation using airborne ultrasound," in *Proceedings of EuroHaptics 2008*. Springer, 2008, pp. 504–513. [Online]. Available: http://www.springerlink.com/index/X41J595757401387.pdf

[4] S. Gupta, D. Morris, S. Patel, and D. Tan, "AirWave: Non-Contact Haptic Feedback Using Air Vortex Rings," in *Proceedings of UbiComp '13*. ACM Press, 2013, pp. 419–428. [Online]. Available: http://dl.acm.org/citation.cfm?id=2493463

[5] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr, "AIREAL: Interactive Tactile Experiences in Free Air," *ACM Transactions on Graphics*, vol. 32, no. 4, p. Article 134, 2013. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2461912.2462007

[6] D. Spelmezan, D. R. Sahoo, and S. Subramanian, "Sparkle: Hover Feedback with Touchable Electric Arcs," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '17*. ACM Press, 2017, pp. 3705–3717. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2984751.2985702

[7] H. Cha, H. Lee, J. Park, H.-S. Kim, S.-C. Chung, and S. Choi, "Mid-air Tactile Display Using Indirect Laser Radiation for Contour-Following Stimulation and Assessment of Its Spatial Acuity," in *Proceedings of IEEE World Haptics Conference - WHC '17*. IEEE, 2017, pp. 136–141. [Online]. Available: http://ieeexplore.ieee.org/abstract/document/7989890/

[8] H. Lee, J. S. Kim, S. Choi, J. H. Jun, J. R. Park, A. H. Kim, H. B. Oh, H. S. Kim, and S. C. Chung, "Mid-air tactile stimulation using laser-induced thermoelastic effects: The first study for indirect radiation," in *IEEE World Haptics Conference - WHC '15*. IEEE, 2015, pp. 374–380. [Online]. Available: http://ieeexplore.ieee.org/document/7177741/

[9] R. Sodhi, H. Benko, and A. D. Wilson, "LightGuide: Projected Visualizations for Hand Movement Guidance," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '12*. ACM Press, 2012, pp. 179–188. [Online]. Available: http://dl.acm.org/citation.cfm?id=2207702

[10] V. Bellotti, M. Back, W. K. Edwards, R. E. Grinter, A. Henderson, and C. Lopes, "Making Sense of Sensing Systems: Five Questions for Designers and Researchers," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '02*. ACM Press, 2002, pp. 415–422. [Online]. Available: http://dl.acm.org/citation.cfm?id=503450

[11] J. Vermeulen, K. Luyten, K. Coninx, N. Marquardt, and J. Bird, "Proxemic Flow: Dynamic Peripheral Floor Visualizations for Revealing and Mediating Large Surface Interactions," in *Proceedings of INTERACT '15 in LNCS 9299*, 2015, pp. 264–281. [Online]. Available: http://link.springer.com/10.1007/978-3-319-22723-8{_}22

[12] F. Alt, A. Bulling, G. Gravanis, and D. Buschek, "GravitySpot: Guiding Users in Front of Public Displays Using On-Screen Visual Cues," in *Proceedings of the 28th Symposium on User Interface Software and Technology - UIST '15*. ACM Press, 2015, pp. 47–56. [Online]. Available: https://dl.acm.org/citation.cfm?id=2807490

[13] E. Freeman, S. Brewster, and V. Lantz, "Tactile Feedback for Above-Device Gesture Interfaces: Adding Touch to Touchless Interactions," in *Proceedings of the 16th International Conference on Multimodal Interaction - ICMI '14*. ACM Press, 2014, pp. 419–426. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2663204.2663280

[14] R. Takahashi, K. Hasegawa, and H. Shinoda, "Lateral Modulation of Midair Ultrasound Focus for Intensified Vibrotactile Stimuli," in *Proceedings of EuroHaptics 2018 in LNCS 10894 - EuroHaptics '18*. Springer International Publishing, 2018, pp. 276–288. [Online]. Available: http://link.springer.com/10.1007/978-3-319-93445-7

[15] W. Frier, D. Ablart, J. Chilles, B. Long, M. Giordano, M. Obrist, and S. Subramanian, "Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-air," in *Proceedings of EuroHaptics 2018*. Springer, 2018. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-319-93445-7_24

[16] B. Long, S. A. Seah, T. Carter, and S. Subramanian, "Rendering Volumetric Haptic Shapes in Mid-Air using Ultrasound," *ACM Transactions on Graphics*, vol. 33, no. 6, p. Article 181, 2014. [Online]. Available: http://dl.acm.org/citation.cfm?id=2661257

[17] E. Freeman, D.-B. Vo, and S. Brewster, "User Study Data from "HaptiGlow: Helping Users Position their Hands for Better Mid-Air Gestures and Ultrasound Haptic Feedback"," 2019. [Online]. Available: https://doi.org/10.5281/zenodo.2631398