ViBracelet: Investigating the Viability of a Dual-Bracelet Wearable for Interpreting a Vibrotactile Alphabet

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Fig. 1. Left: ViBracelet ,top down view. Right: ViBracelet during user evaluation study

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1 ABSTRACT

One prevalent method for enhancing the museum experience is through the use of audio descriptions, which provide detailed accounts and narratives to supplement visual displays [12]. However, these audio descriptions use headsets that block out noise from the surroundings and discourage conversations, which can inadvertently detach visitors from their physical environment and the social interactions within it [23]. Recent advancements in wearable technologies can enable people to absorb information without the need for audio or visual channels through using sequences and patterns of haptic feedback worn on the arms [7, 15, 18, 21, 27]; however, there is limited exploration of the transmission of a haptic alphabet using bracelets with off-the-shelf vibration motors. In this paper, we propose a dual-bracelet form factor that encodes vibrotactile patterns inspired by Braille to deliver exhibit information discreetly and directly to its wearer. Our overall average character recognition rate was 85.7%, with the average recognition rate for our expert users reaching 98.33%. From our qualitative study, we received feedback to take the device beyond the museum; this technology could be used by a wearer to discreetly interpret information in contexts

where the audio and visual channels are restricted or unfavoured. For example, users could receive notifications and perceive their content through touch alone, without needing to use their eyes or ears.

2 INTRODUCTION

In the age of interactive digital media, museum experiences have largely retained traditional approaches, predominantly featuring static displays accompanied by informational plaques. While this method has stood the test of time, it requires visitors' visual attention and can often detract from the overall experience by limiting the ways in which visitors engage with content. Modern museum visitors often seek richer interactions that go beyond mere observation [3]. As an attempt to increase interactivity, many museums have adopted complementary audio guides that supplement visual displays and provide an additional layer of context and information without requiring visitors to read from a plaque [13]. These audio guides also offer tours in multiple languages, expanding accessibility beyond what is possible with traditional plaques. Furthermore, research has found that audio descriptions can enhance memorability and emotional connection with museum exhibits [12].

However, this reliance on audio channels often leads to visitors feeling isolated, which decreases their capacity for social interaction within the museum [17]. This isolation can foster negative feelings towards audio guides as it disrupts communication with peers; an essential part of the learning process [4].

While existing research explores alternative modalities of conveying information, such as augmented reality (AR) and virtual reality (VR), no studies at the time of writing have investigated less obtrusive methods like wearable devices in a museum setting. Research using vibrating wearable devices primarily exists outside of the museum context and offers promising results on the capabilities of interpreting vibrotactile alphabets delivered to various locations on the body such as the arms [6], and the fingers [15, 18]. Our research further explores this domain by investigating the viability of a dual-bracelet design consisting of six affordable, off-the-shelf vibration motors which aim to discreetly deliver information to the wearer through Braille-inspired vibrotactile patterns.

This paper assesses the feasibility of using this vibrotactile alphabet modality through a user study (n=14) and an expert study (n=4). Participants are given three minutes to familiarise themselves with the bracelet's operation before being tested on their ability to identify letters transmitted to their bracelets from five multiple-choice options. This process is repeated three times to analyse the speed and accuracy of participants' learning, with a mean correct identification rate of 85.7%. We also analyse the ease of using such a device through content analysis and NASA TLX surveys, revealing that our dual-bracelet approach is easy to use, does not require much physical demand and induces low levels of frustration.

Beyond the museum context, there is the possibility for this non-intrusive hardware to be applied in numerous scenarios. With extended learning, users can begin to comprehend strings of text transmitted to the device in vibrotactile form. This capability means users could receive text information discreetly without relying on audio-visual channels, enabling, for example, notifications to be understood through touch alone, without the need to look at a phone or hear an audio alert.

3 RELATED WORK

There has been various research exploring the field of vibrotactile feedback, in particular, as a method of relaying information. This can range from information cues about motor functions [2], to spacial warning systems for drivers [28]. The majority of research in vibrotactile information processing has focused on sensitive regions of the body, such as the fingertips [10]. Numerous work has also explored to localise vibrotactile feedback over a larger area of the body as it provides a larger distance between haptic actuators [5, 25, 30, 32]. Work for transferring information via the wrist is relatively unexplored and could provide a more discreet form of communication.

3.1 Implementation of vibrotactile feedback

As a method of communication, there have been multiple experiments trying to emulate Braille using vibrotactile feedback. The papers we have explored have had varying degrees of success with certain letters being much easier to recognise compared to others.

3.1.1 Motors laid out on the fingers in one hand. Kanno et. al [15] proposed a Braille input/output device allowing communication. They used one hand to lay out their motors in a configuration shown in Figure 2. The downside to having such motors in close range to each other meant that smaller stimuli would be easier to perceive as compared to a stronger signal, which overall reduced the accuracy of many people who participated in the experiment. There was also the case that when the signal was sent to two motors in the same finger the accuracy was further diminished. The average recognition rate for such a design seemed to be 84%. However, with more use of the device the people participating improved their accuracy at recognising characters, suggesting a long term model for training would be suitable.

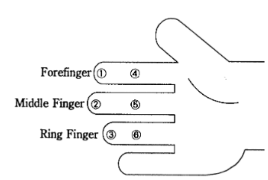

Fig. 2. Kanno et al. Proposed layout of vibration motors

3.1.2 Haptic feedback laid out on the fingers across two hands. Nicolau et. al [18] proposed a device for private and inconspicuous interaction. They propose a vibrotactile reading device to read textual information. They laid out their design as shown in Figure 3. This design had better results with an accuracy rate of 92.86%. However, certain words were much harder to recognise than others. The letters 'A' and 'F' were always recognised whereas the letter 'Y' had a recognition rate of 45%. In particular, the letters N, O, V, Y, and Z had a very low recognition rate due to them having similar Braille patterns to other letters as most of the errors seemed to stem from characters that were missed by one finger.

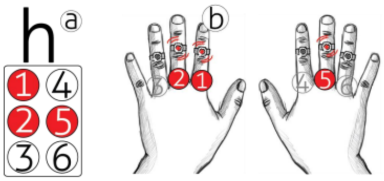

Fig. 3. Nicolau et al. Proposed layout of vibration motors

3.1.3 Feasibility of using forearm to sense feedback. As seen with the examples above, there have been experiments aimed at providing vibrotactile feedback using fingers, however, there seems to be a limited number of studies that use forearm based vibrotactile feedback. This brings into question the feasibility of using forearms as a method to provide feedback. Piateski and Jones [22] suggest that the accuracy of using forearm based feedback ranges from 80% to 97%, which suggests that accuracy for forearm based feedback can be compared to finger based feedback. Furthermore, it is also mentioned that the signals across the forearm are more accurate than signals going along the forearm. Cholewiak and Collins [6] also suggests that frequency and amplitude have no real effect on detection of vibrotactile feedback therefore allowing us to build a relatively inexpensive device to be used in multiple museums and for various scenarios. The localisation across the forearm is further supported by Oakley et al. [20], wherein they suggest that using landmarks such as the sides of the arm to distinguish different signals can improve localisation late by over 30%. They also further suggest using a unidirectional array instead of a 2 dimensional array for the motor layout.

3.2 Wearable Design Research

3.2.1 Multimodal Vibrotactile Wristband. Pezent et al. (2022) developed Tasbi, a multi-modal haptic wristband that can provide haptic feedback at six discrete locations around the wrist, as well as a tension cord that can provide a squeezing effect [21]. Pezent et al. offers detailed insights into design and implementation of wearable haptic devices. Their design presented a wristband that to their knowledge has the smallest and lightest footprint of any previously developed multi-modal haptic wristband which can be seen in Figure 4. Their user study evaluated the accuracy of participants recognising the distinct vibration locations around the wrist, at different levels of squeezing effect. They found individual motor activations around the forearm were identified with a mean accuracy rate of 67.8%.

3.2.2 Vibrotac. Schätzle et al. (2017) present a single bracelet with 6 vibration tactors that transmits a vibrotactile alphabet by mapping Braille letters to a vibrotactile display [27]. They explored the following approaches for transmitting vibrotactile letters: sequential (activating one motor at a time); semi-sequential (activating 2 full columns of 3 motors sequentially); and parallel (activating all 6 motors simultaneously), with each method presenting a trade-off between duration and distinguishability. Participants tasked with

Fig. 4. Pezent et al. Tasbi, a compact multimodal hpatic wristband.

identifying vibrotactile representations of letters sent to Vibrotac achieved accuracy rates between 88%-98% depending on the complexity of letters and the vibration transmission method. The design implementation used tactors to provide highly precise haptic feedback and adjustable frequencies, however, these are less affordable and less readily available than off-the-shelf eccentric rotating mass vibration motors.

3.3 Research Within the Museum Context

3.3.1 Auditory-Vibrotactile Museum Experience. This research presents a multi-sensory experience including visual-auditory and vibrotactile stimuli within a dinosaur museum exhibit. The experiment involved 113 visitors who experienced differing sensory stimuli chosen to enhance immersion in the exhibit, for example by representing a dinosaur's roar. It was concluded that visitors who experienced vibrotactile feedback considered the exhibit more realistic and memorable [14]. Whilst this study effectively used vibrotacile feedback, it didn't explore a mobile vibrotactile museum intervention that could generalise to a variety of exhibits.

3.3.2 Haptic mobile museum guides. Ghiani et al. suggested the combination of haptic channels to mobile museum guides [9]. The study aimed to support the user's movement and orientation, obstacle avoidance and access to information and description of display items. The study concludes vibrotactile information is useful for providing an unobtrusive indication of dynamic information within a museum.

3.4 Applications of vibrotactile displays

Vibrotactile displays have found diverse applications in multiple areas like vehicle navigation, spatial disorientation and gaming environments. For example, in aviation, torso-based vibrotactile feedback has been used for pilots in conjunction with the airplanes' instruments to mitigate the risk of spatial disorientation[25]. For navigation, a 3x3 vibrotactile matrix has been integrated into a chair to give directional cues [31]. Direction cues were achieved by activating vibration motors sequentially in the desired direction. In the world of gaming, vibrotactile feedback was first introduced in the Nintendo 64. Recent advancements include feedback to the fingers using a glove device for a virtual bubble popping game and navigating a car interior using a wearable vibrotactile sleeve[1]. There has also been research done in terms of information delivery inside a vehicle where they demonstrated a high potential for vibrotactile messages for the communication of system information[26].

Overall, current research into vibrotactile feedback shows that it is effective when implemented for niche use cases and therefore explores a variety of form factors. However, there is a gap in the literature on the form factor design to optimise learnability and ease of use discreet in public. ViBracelet aims to fill this gap by design iterations of multiple bracelet form factors using off-the-shelf vibration motors to assess how users distinguish between vibrotactile patterns representing different letters.

4 USER DATA GATHERING

Through a preliminary survey, we gathered vital data to guide the initial designs of our wearable device.

4.1 Participants

Our survey reached 20 respondents, with an age range of 18 to 54. To ensure a diverse perspective of responses, participants were sought from outside the individual team members' immediate circles.

4.2 Questionnaire Design

We chose to use an online questionnaire as the primary data collection method because it was easy to distribute, enabling us to gather a diverse set of valuable insights into user experiences and preferences. The Questionnaire was designed to help focus on the following factors:

4.2.1 Design preference. This question asked participants how willing they would be to wear different forms of vibrational devices for a short museum activity. The question allowed respondents to express their willingness on a Likert scale ranging from "Not at all willing to try" to "Strongly willing to try".

4.2.2 Comfort and Convenience. For the following 2 questions, our wording was carefully selected to distinguish the physical and social factors contributing to a participants' willingness to engage with different forms of wearables in the long term. This question aimed to understand whether each design option was considered physically comfortable and convenient to wear, with a scale from "Not physically comfortable and convenient" to "Extremely comfortable and convenient". This invited participants to consider its usage over a long period and think about the practicality of usage in everyday life.

4.2.3 Social Acceptability. For social factors, a similar Likert scale was used to understand to what extent people found each design choice socially acceptable for use in an everyday context. We provided examples of wearing a device to school, or in the workplace for longer periods. The social acceptability scale ranged from "Not at all acceptable" to "Extremely acceptable"

4.3 Questionnaire Results

4.3.1 Design preference. Figure 5 showed that respondents generally preferred a bracelet compared to the alternative options with a majority saying they would be strongly willing to try it and not a single respondent being neutral or not willing to try it to some degree. Some also preferred a sleeve design to roll over their arm and a glove for their hand. A headband and belt had more varied responses and data ranged mainly from the somewhat willing to down to not at all willing to try it. Figure 5 highlighted that the bracelet was a clear winner and the best form factor for implementation.

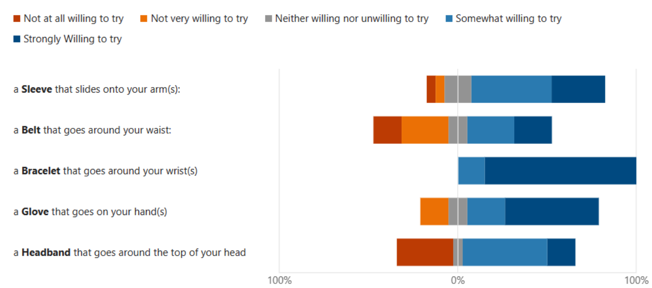

Fig. 5. Results from the slider question about design preference

4.3.2 Comfort preference. Referring to Figure 6 the data highlights how the bracelet choice was seen by the majority as a physically comfortable and convenient device to wear. Whilst for the belt, glove and headband people's views leaned towards being uncomfortable and an inconvenience to wear.

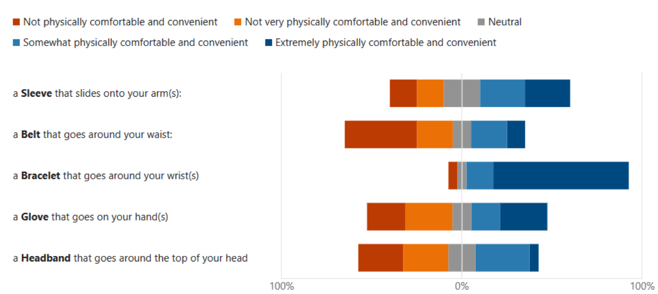

Fig. 6. Results from the slider question about comfort

4.3.3 Socially acceptable. When asked about this, Figure 7 showed that the majority of participants found the bracelet design to be the most socially acceptable to wear. No participants had a neutral stance or thought it would not be socially unacceptable. This highlighted further that a bracelet would be the best design choice to pursue. The headband design saw a majority of respondents finding it socially unacceptable and the rest had a range of input across the spectrum with a slight tendency towards social acceptability.

4.3.4 Insights. The results from the survey showed the bracelet design had the most promise. In all, of the survey's factors of design preference, comfort and social acceptance; the bracelet form factor came on top. This led to our design process to create and prototype our device in the bracelet form factor.

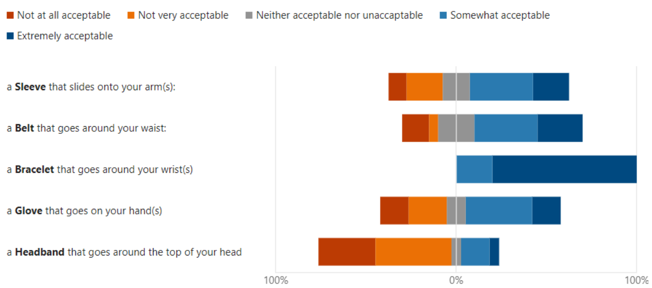

Fig. 7. Results from the slider question about social acceptability

Fig. 9. Final design showing the reverse of the wristband showcasing the vibration motors adhered to the fabric

5 FINAL DESIGN

5.1 Hardware

ViBracelet's final design consists of two bracelets made from a soft, elastic fabric comprised of 70% nylon and 30% spandex. This material composition ensures the bracelets can be easily stretched to be put on and removed by the user without the need to adjust the size of the bracelet through using for example a buckle. Each bracelet has three Adafruit Eccentric Rotating Mass (ERM) motors adhered equidistantly around the bracelet. Using a single fabric for the bracelet allows the motors to stretch and compress an equal distance no matter the size of the users' wrists. Although alternatives like linear resonant actuators or piezoelectric actuators could offer more refined control and precise haptic feedback, the selected vibration motors strike an optimal balance between cost, ease of use, and functionality, facilitating the production of more prototypes with multiple iterations. The final design can be seen in Figure 8

Fig. 8. Final design showing 2 elastic wristbands with vibration motors adhered to the inside

We adhered the ERM motors to the inside of the bracelet using hot glue. A dedicated channel along the top of the bracelet conceals the motor cables, with the fabric folded over ensuring a clean unobtrusive finish, this can be seen in Figure 9. The bracelets are connected to a 5V Arduino Micro that controls the vibrations that are activated using a single Ethernet cable that is soldered to each motor. Each motor is connected to a pulse width modulation (PWM) pin on the Arduino allowing us to calibrate the intensities of the vibrations and account for any differences in the manufacture vibration intensities.

5.2 Software

5.2.1 Vibration patterns. To encode a vibrotactile alphabet, we took inspiration from Braille, a tactile alphabet that represents letters and symbols as distinct patterns of raised dots arranged in a 3x2 Grid [16]. This 6-bit encoding allows for up to 64 distinct permutations. In our vibrotactile alphabet, the left braille column is mapped around the wearer's left arm, and the right braille column is around the right arm. When transmitting a vibrotactile mapping of a braille symbol, each of its raised dots are instead represented by activating

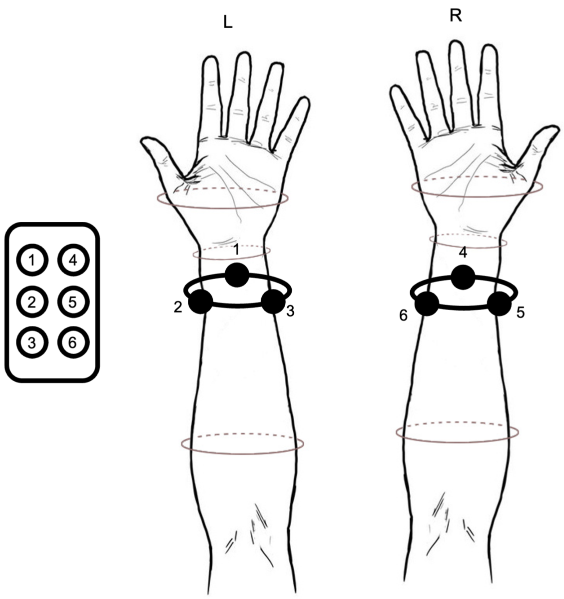

Fig. 10. Palms facing up view of the dual-bracelet setup

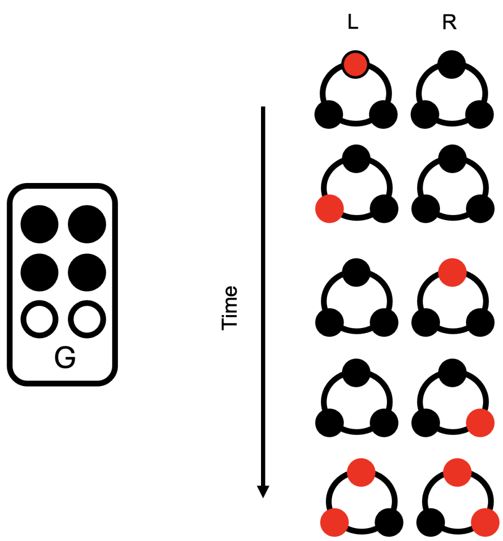

Fig. 11. Sequential view of the letter 'G' being played

the corresponding vibration motor on the bracelets as shown in Figure 10.

Our device delivers the vibrotactile patterns in a staggered approach that combines the *Sequential* and *Parallel* approaches explored by Schätzle et al. with their *Vibrotac* wearable [27]. To communicate a letter our device activated corresponding motors one-by-one. To do this, each motor representing a raised dot is quickly activated and deactivated in sequence, skipping any dots that aren't raised. Finally, the motors for all raised dots are activated simultaneously to signify the end of a character. For example, a wearer delivered the pattern for 'G' would feel the activation of motor 1 in isolation, motor 2 in isolation, motor 4 in isolation, motor 5 in isolation, and finally motors 2, 3, 4, and 5 at the same time, Figure 11. Our device didn't implement Vibrotac's most accurate transmission method, *Sequential Raised/Unraised*, which represented unraised dots with a reduced intensity tactor activation. This is because we found that many of the ERM motors we sourced often varied dramatically in intensity, which presented challenges when trying to represent a reduced-intensity vibration that was adequately distinct for every motor; a transmission approach limited to a binary encoding of activated or deactivated motors was most appropriate for the materials available to us.

5.2.2 Web interface. We built a graphical user interface (GUI) using the Web Serial API to facilitate the delivery of vibrotactile patterns to the Arduino-controlled bracelets. Patterns are represented digitally by setting 6 array elements to binary values corresponding to the desired motor activations (e.g. G = [1,1,0,1,1,0]). This array is then packed into a single character, sent to the Arduino Micro via serial and converted into analog or digital outputs for the relevant vibration motors. To send different vibrotactile patterns to bracelets, the GUI supports the entry of characters and words via keyboard input, as well as the activation of any arbitrary pattern by using a mouse to specify which motors should be activated. The user can also design their own set of custom vibrotactile patterns and assign them their own meaning. These collection of custom patterns can be downloaded to a text file and reuploaded for future use.

To support the learning process of our vibrotactile alphabet, our GUI features a *Quiz* mode which lets users select the specific letters they are interested in learning. These letters are included in a multiple choice quiz where the user learns to distinguish between letters by sending vibrotactile patterns to their bracelet and identifying which option of letter it corresponds to. In *Quiz* mode, the user can send the pattern to their bracelets an unlimited number of times before making a selection and receiving an indication of their correctness.

To support our device evaluation, our GUI includes an *Evaluation* mode that tests a user on identifying letters sampled from the entire alphabet in a multiple choice format. Here the user answers a fixed number of questions and is restricted in the number of times they can replay each letter before selecting an option. After completing an evaluation, metrics on the participant's performance are made available for download in a JSON file.

6 DESIGN ITERATION

6.1 Prototype V1

Our initial prototype was developed to evaluate the ergonomics and distinguishability of motors positioned at four distinct locations on one wrist. This design was inspired by Jonggi Et al., which suggests that vibration distinguishability improves when associated with physical landmarks, such as the cardinal directions on a wrist [11]. Accordingly, we arranged the motors in a North, East, South, West configuration (i.e. top, right, bottom, and left of the arm). This low-fidelity prototype consisted of four ERM motors held in place using adhesive and tucked under a Grounding band attached tightly to the user. The motor activations were managed using a 5V Arduino Micro. We supplemented the hardware with a Python interface that facilitated the activation of each combination of motors which enabled us to test the distinguishability of different letters.

Through internal experimentation with the V1 prototype, we discovered that the four motors were individually distinguishable with ease, however simultaneous activation of multiple motors required a learning curve for the user to deem distinguishable. A key ergonomic challenge we encountered while testing the V1 prototype was that distinguishability was affected by the position of the motors around the circumference of the wrist. For some members, the bracelet was suitable for their wrist circumference, with the individual motors spaced equidistant from each other. However other members found that the bracelet was too loose or tight for their wrist, and tightening or loosening the strap introduced an element of asymmetrical spacing between the motors which ultimately reduced the distinguishability.

This prototype not only shed light on the fundamental challenges of designing an Arduino-enabled vibrotactile bracelet but also helped us anticipate the resources and design modifications required for producing more refined, robust iterations that were ergonomic for a variety of users.

6.2 Prototype V2

The second prototype was designed to assess the distinguishability of six vibration motors around a single wrist, see Figure 12. This number was selected because encoding the Latin-derived alphabet and digits (0-10) is 64 which can be achieved with a minimum of six distinct vibration motors.

The bracelet was fabricated by 3D printing six motor housings for the individual motors using Polylactic Acid (PLA). These housings securely encapsulated the motors, minimising damage during use and enhancing durability. Additionally, the individual motor casings helped mitigate vibration propagation compared to the previous version's singular material design, although this improvement was somewhat offset by the increased surface area in contact with the user's wrist, which inadvertently enhanced vibration spread. The individual motor housings were fastened together using equally sized elastic strips.

During further internal testing, we found that increasing from four motors to six greatly inhibited our abilities to distinguish between distinct motor activations, likely due to the average distance between each adjacent motor being reduced by a third.

To connect the vibration motors to the Arduino we opted for a 0.2mm diameter insulated copper wire, which provided more reliable solder joints when connecting it to the thin wires of the vibration motors compared to the thicker wires used in the previous prototype. However, this cable proved too thin and not durable enough to withstand the rigorous nature of a bracelet, frequently breaking at multiple points.

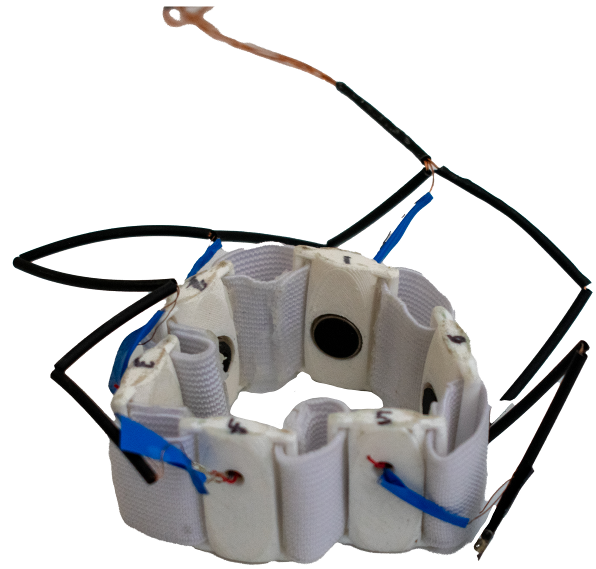

Fig. 12. V2 prototype showing 6 vibration motors held in cases attached with elastic strips

6.3 Prototype V3

Our third prototype transitioned to a dual-bracelet design, each equipped with three vibration motors, as illustrated in Figure 13. The design maintained the motor housings used in the V2 prototype and continued to be fastened using equally sized elastic strips. However, to address the issues encountered with the wiring in the V2 prototype we opted for a thicker, but stranded gauge wire, enhancing durability while maintaining reliable solder joints between the wires and the vibration motors. These iterations resulted in a prototype robust enough to endure the stresses of repeated stretching during wear.

This new form factor of three vibration motors distributed across each wrist was tested internally and proved an effective approach for delivering vibrotactile sequences. Each motor was distanced sufficiently apart to allow the user to distinguish it with relative ease, following a brief calibration period.

To improve the design of this prototype we explored methods to increase the comfort of the bracelet and a design that was more sleek and inconspicuous, this led to the decision to use the solid construction of the fabric seen in the final design 8.

7 DEVICE EVALUATION

We conducted 3 studies to investigate the distinguishability of characters from our vibrotactile alphabet. The first was a pilot study (n=7) that helped us design a more nuanced user evaluation study (n=14) assessing a participant's ability to identify which vibrotactile

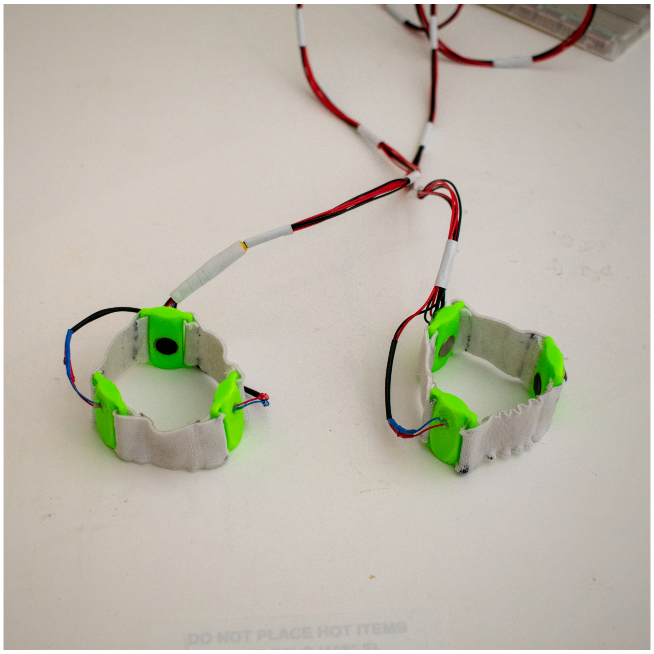

Fig. 13. V3 Prototype showing 2 bracelets, each with 3 vibration motors encased and attached using strips of elastic

patterns were sent to their bracelets over short bursts of learning time. This was then followed by an expert user study (n=4) to investigate whether long-term usage impacts accuracy and other performance metrics such as the time and number of replays needed to help identify a character.

7.1 Pilot Study

We conducted a preliminary study (n=7) to inform our future investigations into the learnability of our vibrotactile alphabet. In our first test, participants were given 7 minutes to experiment with the bracelet and interpret different vibrotactile patterns from our alphabet before completing a multiple choice test. For each question, the user's bracelet was transmitted a vibrotactile pattern corresponding to one letter from the alphabet and was tasked with correctly identifying it from 5 options randomly pooled from 26 letters. In this particular format, participants identified characters with high accuracy, but this was likely attributed to the random nature of the multiple choice options. When presented with five completely random options, an effective strategy was to eliminate options based on which wrist(s) did or didn't feel vibrations, and counting how many distinct motors were activated in sequence. For example, when we presented a participant with five options such as 'B', 'L', 'M', 'R' and 'V', as seen in Figure 14, they could employ this process-of-elimination strategy to narrow down their options to B and L based on experiencing vibrations in the left wrist only, and finally decide between the two options by counting how many motors had been activated. This strategy was effective when distinguishing between certain combinations of letters but wasn't generalisable to distinguishing between letters with similar total numbers of activations

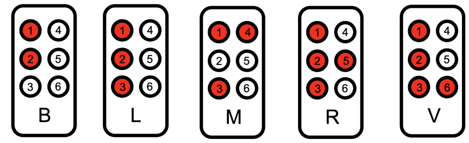

Fig. 14. Braille patterns for 'B', 'L', 'M', 'R' and 'V'

which led us to design a more intentional sequence of questions that measured how distinguishable sets of similar patterns are.

7.2 Learnability Study

We designed our user study to investigate if learning time affects the accuracy of participants' identification of characters transmitted through vibrotactile patterns.

7.2.1 Participants. We conducted our study on a sample of fourteen individuals. All our participants comprised of university students using convenience sampling. Three of our participants had seen the device in action, however had not used it, the rest of the participants were entirely unfamiliar with the device.

7.2.2 Procedure. Our study was conducted throughout a single day, in a busy location on campus. This was to maximise the number of participants, but also allowed us to note if noise impacted the ability of the participants to sense vibrotactile feedback. This was to simulate real use cases of such a device, which may include such a busy environment.

Due to the nature of our study, only one participant could use the device at a time. Firstly, we introduced our concept to the participant as well as the procedure they would be going through. We aided each participant in the process of correctly orienting the bracelet so the motors align with the correct mappings as designed. We then validated if the motors were calibrated by asking the participant if they could feel the vibrations from each motor. Additionally, this provided some self-calibration for the participant to create a mental encoding of how the device maps letters. This was then followed by three sets of three minutes of using and learning the device, followed by ten multiple-choice questions. During each set of the informal learning period, we asked the participant some open-ended questions about the device. Finally, after the final set was over, we followed up with a NASA TLX survey [19].

7.2.3 Informal Interview. This was conducted before each set of multiple choice questions then a final interview during the TLX survey. We asked questions relating to the fit, adaptability, strategy for the MCQ, suggestions and open-ended questions to get as much qualitative data as possible. We aimed to use this data to conduct content analysis following instructions from Erlingsson et. al[8].

7.2.4 Multiple Choice Questions. This was our primary method for obtaining quantitative data on whether the participant improved. Each question involved sending a vibrotactile pattern to the participant and getting them to match it to one of the five options presented.

The participants could replay the pattern an additional three times. We chose five answers as Rodriguez et. al [24] noted, while three may be optimal for random MCQ, five gave us the additional needed difficulty. Throughout the thirty questions we calibrated each question using our previous study; wherein we grouped letters that were being confused together in our pilot study, as well as observing similar patterns and grouping them to form a question. This eliminates some of the irrelevant answers that may crop up during the test, making the result more precise. This also allowed us to conduct a more accurate study as each participant answered the same calibrated questions. We scored each question depending on how many answers the participants got incorrect, with 1 being fully correct, 0.6 for one wrong, 0.4 for two, 0.2 for three and 0 for all wrong. We also recorded the number of replays of vibrations remaining, the time it took to answer the question, and any incorrectly chosen letters.

7.2.5 NASA TLX survey. After participants completed the MCQ they were presented with a NASA TLX survey to asses the mental load of using the device.

7.3 Results

7.3.1 Multiple Choice Results. For each participant, we had 3 JSON files containing all the results which we formatted in tables as shown in Figure 15.

Overall, we noted that for each of our independent variables, time taken had a negative correlation with points earned and replays remaining, whereas points earned and replays remaining had a positive correlation. This can be visualised in Figure 16, figure17, Figure 18.

This suggested that increased time to answer the question had no significant advantage to the number of points earned and rather indicated adaptability to the device as the quicker the participant answered the question, the more points they had. This was a similar case to the replays remaining, therefore suggesting all three variables could be used as a metric to judge how well a participant did during the MCQ.

Throughout the MCQ the participant had an average accuracy rate (correct answer/total answer) of 85.7%. For round one, the participants had an average accuracy of 83.6%, 87.9% for round two and 85.7% for round three.

With regards to letters, participants always correctly identified the letters ‘A’, ‘B’, ‘E’ and ‘L’. The letters ‘X’ and ‘J’ were the second least identifiable with an average point of 0.84. The least identifiable letter was the letter ‘J’ with an average point of 0.81. Figure 19 shows the average points attained for each letter.

The letter ‘L’ had the highest number of replays remaining with an average of 2.79 out of 3. The letter ‘A’ being not far behind having an average number of replays remaining at 2.64. The worst performing letters for this metric were the letters ‘N’, ‘X’ and ‘J’ with an average number of replays remaining at 1.71, 1.64 and 1.42 respectively. Figure 20 shows the respective distribution for each letter.

The letter ‘F’ had significantly higher time taken than the rest of the letters with 26116ms. The next closest letter being ‘U’ with 20542ms. The letters to take the least amount of time, were ‘A’ and ‘L’ with 5509ms and 4821ms respectively. The total distribution of time taken to choose each letter is shown in Figure 21.

We then took the average ranking of each letter based on how well they did for each variable, then normalised the result to match the 1-26 ranking scale for each letter and got the distribution of overall difficulty ranking for each letter as shown in Figure 22.

Overall, the letters ‘L’, ‘A’, ‘B’ and ‘V’, in order were the easiest to recognise and choose for the MCQ, whereas the letters ‘U’, ‘N’, ‘X’ and ‘J’, in order were the most difficult, illustrated in Figure 23

In terms of letter confusion, if the participant got the letter incorrect, ‘G’ was commonly confused with the letter ‘N’. ‘O’ was commonly confused with ‘M’. ‘U’ was commonly confused with ‘R’. Again, ‘J’ seemed to be the most difficult letter always being confused with the letters ‘N’, ‘U’ and ‘O’ before getting the answer correct.

The difference in variables across rounds denoted in Table 1. Generally, there does seem to be a difference between round 1 and 2 with no statistically significant difference between round 2 and 3 for the variables. This can also be visualised in Figure 24, Figure 25 and Figure 26 where there is a substantial enough visual difference between round 1 and 2 with round 3 mostly having similar values to round 2.

	Round 1	**Round 2**	**Round 3**
avg total replays remaining after 10 questions	20.71	22.29	20.21
stddiv replays remaining	1.42	5.08	4.758
avg total points attained after 10 questions	9.06	9.46	9.33
stddiv points attained	1.42	0.63	0.66
avg total time taken to answer 10 questions(ms)	153811	100782	99036
stddiv time taken	87309	30968	39651

Table 1. Table denoting the average replays remaining, points and time taken overall over each round

7.3.2 Interview Results. As mentioned previously (see 7.2.3), we followed instructions from Erlingsson et. al [8]. This included reading through all the answers, to then convert to a list of short sentences. We then formed sets of codes to assign each sentence. These are shown in Table 2. These codes were initially grouped into six themes as shown in Table 3. However, ‘Strategy for quiz’ and ‘Learning styles’ were merged into ‘Strategy for evaluation quiz’ and ‘Improvements’ and ‘Challenges’ were merged into ‘Limitations and Improvements’ theme as shown in Table 4 giving a total of four themes.

Paticipant 1											
	Round1(Thu Apr 25 2024 10:52:59 GMT+0100 (British Summer Time))										
	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	Total
Correct Answer	f	i	d	h	u	n	j	c	x	k	N/A
Participant Correct	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	0.9
Incorrect Answer(s)						y					y
Replays Remaning	3	3	2	1	3	1	2	3	1	2	21
Points	1	1	1	1	1	0.6	1	1	1	1	9.6
Time Taken	4127	3104	9620	12111	11856	14418	12862	3719	8232	6418	86467
	Round2(Thu Apr 25 2024 11:10:49 GMT+0100 (British Summer Time))										
	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	Total
Correct Answer	o	z	v	l	s	p	a	g	t	q	N/A
Participant Correct	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	0.9
Incorrect Answer(s)								y			y
Replays Remaning	2	2	3	3	2	3	3	2	2	3	25
Points	1	1	1	1	1	1	1	0.6	1	1	9.6
Time Taken	7417	6508	4857	3511	5257	4085	4085	2748	9391	7037	54896
	Round3(Thu Apr 25 2024 11:08:46 GMT+0100 (British Summer Time))										
	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	Total
Correct Answer	b	r	y	w	m	e	g	x	q	g	N/A
Participant Correct	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	0.9
Incorrect Answer(s)					x						x
Replays Remaning	2	1	3	3	1	3	2	1	2	3	21
Points	1	1	1	1	0.6	1	1	1	1	1	9.6
Time Taken	6865	7026	4613	4416	11610	3965	5717	11508	6546	4846	67112

Fig. 15. A sample of the results of one of the participants after the MCQ

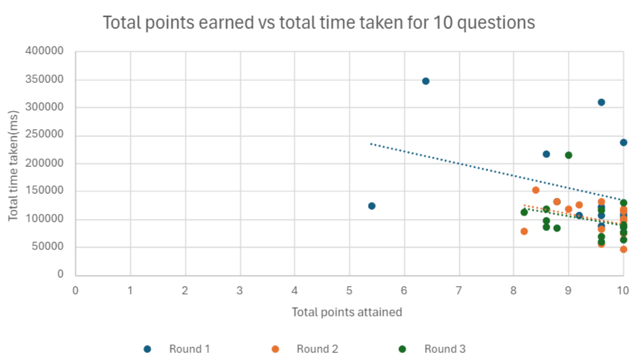

Fig. 16. The number of points earned vs the amount of time taken

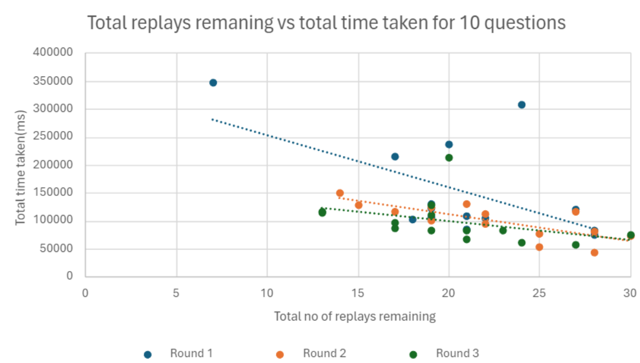

Fig. 17. The number of replays left vs the amount of time taken

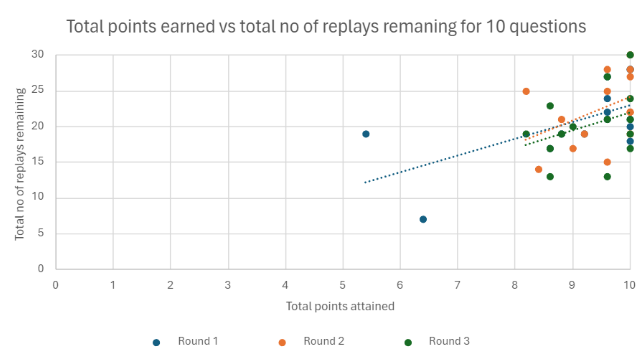

Fig. 18. The number of replays left vs the number of points earned

Physical Serviceability. Most people found the band comfortable, with not a single participant complaining about the initial fit of the band. However, one person found the band irritating after prolonged use. Overall, the comfort of the band did not change over time, with people mentioning tighter or looser fit according to personal preference. There were several mentions of mental fatigue. It was a similar case with the vibration motors with most people finding them comfortable except for one participant who had vibrations ringing in their head.

Strategy for Evaluation Quiz. A lot of people mentioned themselves as visual learners with them aligning to learning from the mapping sheet provided. Most of the people who said they were physical learners moved away from or did not mention the sheet

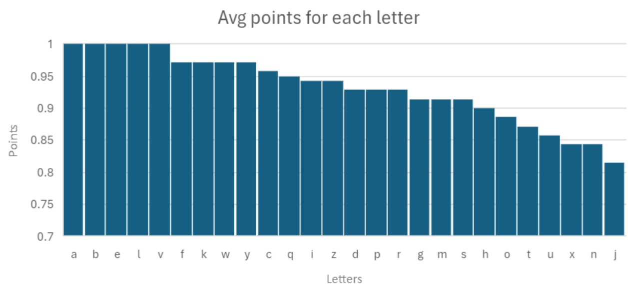

Fig. 19. The average number of points earned for each letter

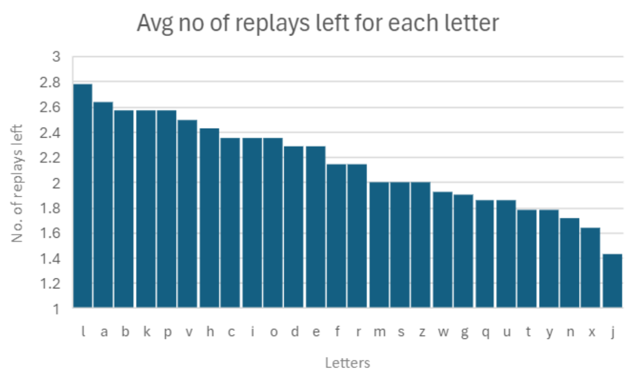

Fig. 20. The average number of replays remaining for each letter

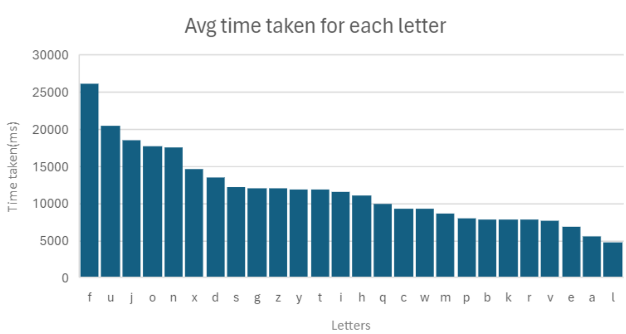

Fig. 21. The average number of time taken for each letter

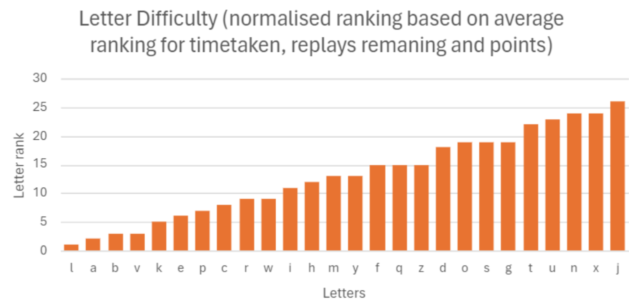

Fig. 22. The average difficulty of each letter sorted via the average rankings for the three independent variables

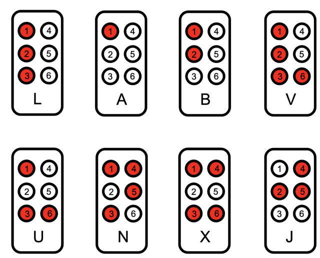

Fig. 23. Braille patterns for 'L', 'A', 'B' and 'V' (easiest letters) and 'U', 'N', 'X' and 'J' (hardest letters)

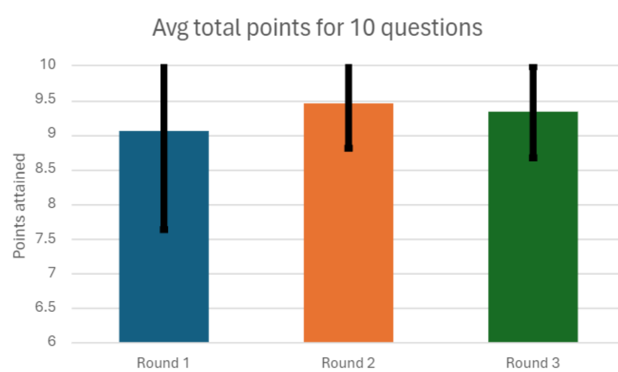

Fig. 24. The average points earned by each participant for each round

provided. After people got used to the device, the participants who considered themselves to be visual learners also moved away from the sheet. The most common method to complete the evaluation quiz was to count the number of vibrations to eliminate other possibilities with 8/14 participants directly mentioning counting the number of vibrations. For most people, they stuck to the strategy they developed with a few moving to mapping from counting. There was also a participant who compared vibrations from one hand then another. For more complex patterns, participants seemed to sometimes ignore some motors and just eliminate options in the evaluation quiz. The participants also mentioned getting used to the device and finding themselves getting better in the second MCQ. However, some participants mentioned the third set of MCQ being significantly more difficult than the first two sets, with most complaining about the higher number of vibration patterns.

Application and Public Use. Every participant mentioned that the device does not stand out and is not that noticeable. The experiment however was done with a wired band and participants mentioned that the device would be better wireless. Participants mentioned the device could be used for surgical robots, danger alerts, processing information whilst running or exercising, means of communicating small code words, haptic feedback, sending information in high

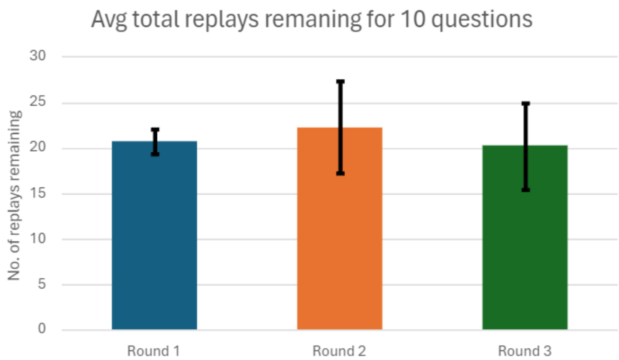

Fig. 25. The average replays remaining of each participant for each round

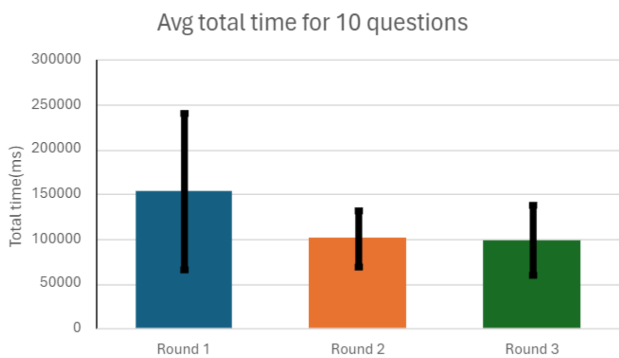

Fig. 26. The time remaining of each participant for each round

Codes
Physical comfort
Mental discomfort
Evaluation Strategy
Strategy changes
Learner type
Adaptability
Public use
Further use
Improvement suggestion
Confusing vibrations

Table 2. Codes generated via Content Analysis

Themes	Codes
Physical Serviceability	Physical comfort Mental discomfort
Strategy for quiz	Evaluation Strategy Strategy changes
Learning Styles	Learner type Adaptability
Application and public use	Public use Further use
Improvements	Improvement suggestion
Challenges	Confusing vibrations

Table 3. Themes generated via Content Analysis(version1)

Themes	Codes
Physical Serviceability	Physical comfort Mental discomfort
Strategy for evaluation quiz	Evaluation Strategy Strategy changes Learner type Adaptability
Application and public use	Public use Further use
Limitations and Improvements	Improvement suggestion Confusing vibrations

Table 4. Themes generated via Content Analysis(final)

stress situations, reading notifications from phones and the potential for navigation.

Limitations and Improvements. Many participants mentioned that they guessed the answer for difficult MCQ options or observed which motors didn't vibrate to help identify complex patterns resulting in the awarding of points when the participant couldn't confidently pair the vibrations they felt to the correct answer. Consequently, a new entirely new format may be beneficial to better determine a participant's capacity to learn how to recall precisely which motors they felt. In terms of suggested improvements, participants mentioned that with our current design, the bottom 2 motors on each wrist were less detectable than the top motors. Some participants also suggested the symmetrical mapping of the middle and bottoms rows across the wrists was unintuitive. And finally, participants who used vibrations for their phone's notifications were at times "thrown off" by the additional vibrations whilst attempting the evaluation quiz, which presents a challenge worth exploring in regards to the our device's integration into the broader context of the wearer's device ecosystem.

7.3.3 TLX survey. As the TLX survey uses ordinal scales, the central tendency is the median. The scale goes from very high to very low which is opinionated, thus standard deviations have no validity [29]. We have therefore used a box plot to analyse our data as shown in Figure 27. For all values except performance, the values range from very low to very high from bottom to top. As for performance, they range from perfect to failure from bottom to top.

Overall, there does not seem to be a significant physical demand with values being very low. This is similar to frustration where mostly all values seem to be near the bottom. Most participants also don't seem to think there is much temporal demand and seem to believe that they performed quite well. Primarily, effort and mental demand seem to be the highest but also have the largest range and IQR.

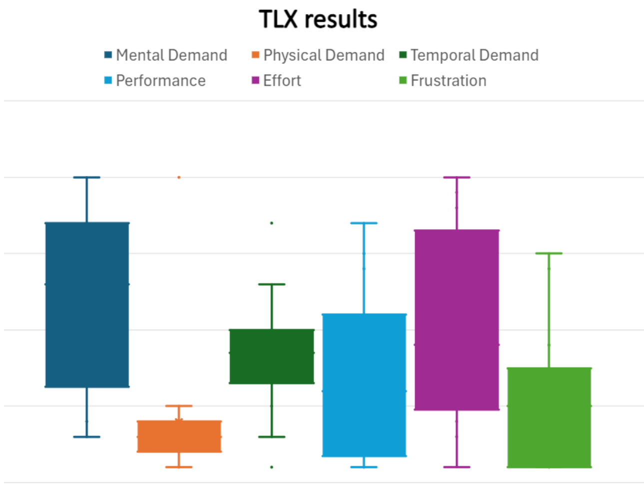

Fig. 27. Box plot of the TLX survey results

7.4 Expert users study

Our results on the learnability study (7.2) did not show a statistically significant improvement of participants. Aside from the time taken to answer each question between round 1 and 2, having a p-value of 0.01, the rest of the comparisons did not have a p-value below 0.05. This motivated us to do a comparison between participants of the learnability study and expert users who have used the device for a longer period of time. The participants consisted of four individuals, two who were involved in the making of the device and a further two individual(s) who had further experience testing the device.

	Average total across 10 questions	Stddev across 10 questions
Participant Correct	85.71	16.70
Replays Remaining	21.07	5.03
Points	9.28	0.97
Time Taken	117876	62302

Table 5. Table showing inexperienced users' average total results across four metrics for ten questions

	Average total across 10 questions	Stddev across 10 questions
Participant Correct	98.33	3.89
Replays Remaining	25.08	2.39
Points	9.92	0.20
Time Taken	60447	18336

Table 6. Table showing experienced users' average total results across four metrics for ten questions

Overall there seems to be a minor improvement in all metrics. The standard deviation has narrowed by a large margin. The total accuracy of the participants has improved by 12.62%. On average the number of replays remaining across ten questions has increased by 4.01. There has been no significant improvement on average points earned across ten questions. The time taken to answer each question has had a sizeable decrease of 34%. Figure 28 visualises the difference in time taken across the ten questions for inexperienced and expert users.

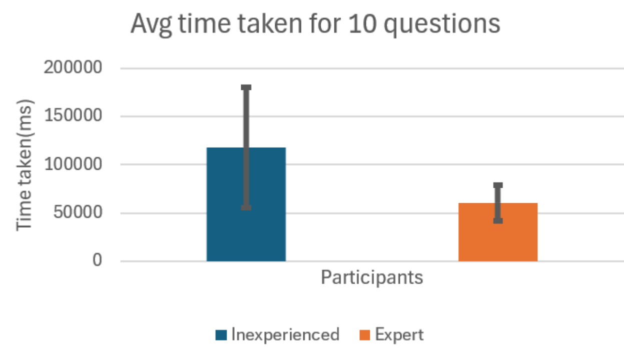

Fig. 28. Average total time difference between inexperienced and expert users across ten questions.

8 DISCUSSION

8.1 Interpretation of results

The ViBracelet study provides a novel exploration into the use of a dual-bracelet to communicate text information through haptic feedback. While our study showed an overall accuracy level of 85.7%, increasing to 98.3% with the expert study, it is crucial to note that our data showed no statistical significance. This limits our ability to generalise our findings to general contexts and applications.

8.2 Potential and positive impacts

Despite the limitations of our quantitative data, the positive reception from participants when using ViBracelet led to insightful qualitative data. Many users found the bracelet comfortable to wear and unobtrusive in design, appreciating its potential for discreet communication in environments when audio-visual channels are impractical. This is supported by the TLX result wherein the physical load was extremely low. This feedback is particularly encouraging for future applications.

8.3 Alternative Design Possibilities

There are many factors left to explore that could improve the viability of our haptic alphabet with minimal modifications to our dual-bracelet hardware. For example, the duration of vibration pulses may present a trade-off between distinguishability and average character duration that's worth exploring. Furthermore, the mixed feedback on the intuitiveness of our symmetrical mapping highlights that our approach of presenting the user with a prescribed mapping is perhaps detrimental to their interaction, and we should instead place more emphasis on providing alternative use patterns through easy customisation workflows. This could be implemented in the future by providing a software interface the wearer can use to alter the vibrotactile mapping, and experiment with different pulse durations and intensities.

8.4 Limitations and Future Research

The lack of statistical significance from our quantitative studies highlights the need for further research, catering to more rigorous experimental controls. Future studies should take into account the shortcomings of our research and aim to have a larger sample size, a longer assessment period, and be in a controlled environment. Incorporating these changes could provide statistically significant data, and concretely proving or disproving the efficacy and feasibility.

In addition to this, while our study showed promise into the distinguishability of individual vibrotactile letters, the comprehension of strings of letters is important for our device to find real-world applicability. At this stage, two of our most advanced users have committed the majority of the vibrotactile letters to memory and can successfully identify them outside of a multiple choice context, leading to progress in the identification of small words which warrants further investigation.

8.5 Implications for HCI Design

The Vibracelet study contributes to the HCI field by highlighting the practical challenges and considerations when designing a personal device for wearable usage. The insights gained from the qualitative aspects of our study emphasises the importance of user-centred design and the importance of personalised devices, especially in the realm of wearable technology, such as adjustable size, vibration intensity, and vibration placement.

8.6 Broader Impact and Ethical Considerations

ViBracelet could potentially be useful in various scenarios where audio-visual channels are non-optimal. However, along with further research, extra consideration should be taken into account to investigate the ethical considerations when using the ViBracelet. Such as, exploring the psychological effects of continued use of haptic feedback over a longer period of time.

It is also imperative to note, that while ViBracelet uses a Braille-inspired encoding, it is by no means an accessibility product. While there may be space for this type of research with minimal adaptations, our research has not been conducted with participants of communities with sensory difficulties or visual impairments. For the scope of this research, the ViBracelet acts as a novel modality for discrete text transmission and makes no claims to being an accessibility aid.

9 CONCLUSION

In conclusion, our ViBracelet study has evaluated the accuracy rate when identifying our vibrotactile alphabet as 85.7%, with limited learning periods, increasing to 98.3% with users who are more familiar with the device. While these averages seem positive, they should be taken with the knowledge that our data did not achieve statistical significance, highlighting the need for future research. Despite this, our qualitative feedback received an overwhelmingly positive reception regarding form factor and comfort, suggesting the viability of the ViBracelet as a method of discreet text information directly to the user. With this foundational research in place, future work may explore the dual-bracelet approach's capabilities in terms of alphabet distinguishability and informational bandwidth with the goal of determining whether ViBracelet could be a viable alternative to information modalities used in museums. As such, further research may look to consider the physiological factors affecting the wearer's ability to distinguish vibrations on the forearm, and the advantages and disadvantages that alternative vibrotactile mapping strategies present to different wearers attempting to comprehend larger strings of vibrotactile text.

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10 APPENDIX

10.1 Teamwork and Diversity

As a team of 5, we aimed to be as collaborative and inclusive as possible, whilst mitigating any contradictions that may arise from the differences in our individual backgrounds and livelihoods.

We worked as an open and welcoming team allowing everyone's opinions and ideas to be expressed fully. This was utilised in our Miro page where we could sketch out our ideas, giving opportunity for constructive criticism and a combination of ideas to further push our creativity.

Although we all pursued this project as part of the same university module, our team spans across 3 different degree programmes which could have introduced scheduling difficulties and conflict when balancing our varying workloads throughout the project. We mitigated this possibility by agreeing on days we would reserve for synchronous meetings (often Monday morning and Tuesday afternoon), and assigning asynchronous work based on our research interests and the skills required. For example, we would allocate work that ensured each member was working on tasks that they felt competent completing and, in many cases, enjoyed.

With 3 team members living in the same accommodation, it made sense to allocate most of the hardware fabrication to those members as they'd have the most opportunity to physically work on the device together. To mitigate the potential information disparity between members who lived together and those who didn't, we committed to sharing regular progress updates and used the weekly workshops to ensure every member was aware of each other's progress and was included in the decision-making process.

10.2 Video Link

https://www.youtube.com/watch?v=Xp-430-36k8