2bit-TactileHand: Evaluating Tactons for On-Body Vibrotactile Displays on the Hand and Wrist

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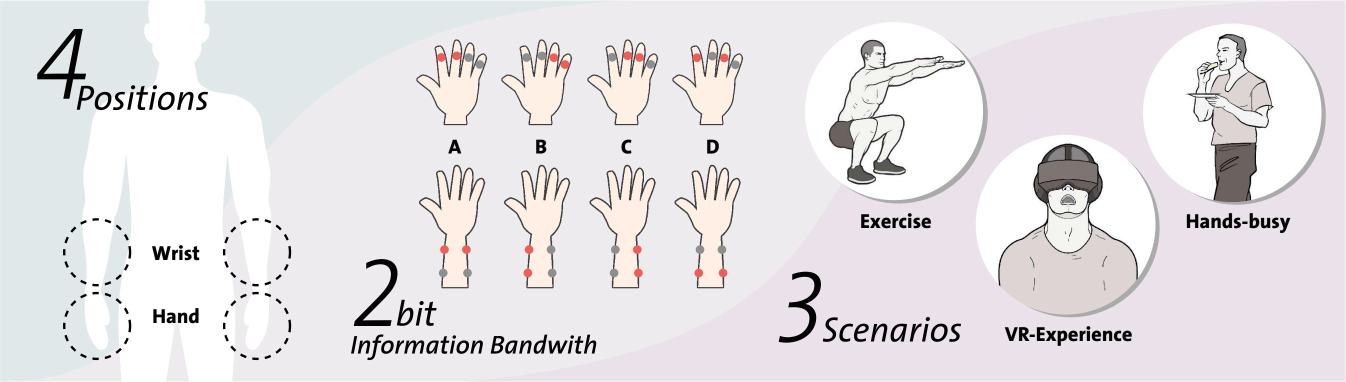

Figure 1: For our investigation, we selected four body positions, which are the left hand, right hand, left wrist, and right wrist. On two gloves and on two sleeves, we mounted four vibration motors at a certain distance (5cm in wrist configuration), considering the two-point discrimination known in literature. Subsequently, we provided the user with different tactons, not exceeding a 2bit bandwidth (4 states: A, B, C, D), to investigate the perceptual abilities. Finally, we demonstrate three different multitasking scenarios in which 2bit- TactileHand could be beneficial.

ABSTRACT

Visual interfaces can provide a great density of information. However, the required focused visual attention results in a high cognitive effort. This cognitive load significantly increases when multiple tasks are performed that also require visual attention. In this paper, we evaluate the perceptual abilities of 2bit tactons on the wrist and the hand as a type of complementary feedback. Based on our evaluation, 2bit tactons are reasonably high perceivable (≈ 92%) at the hand distributed among several fingers. Additionally, the data concluded that vibrotactile feedback on hand is significantly more accurate than the wrist, which coincides with the subjects' preference. TactileHand's feasibility was demonstrated in three pilot studies, encoding ambient, explicit and implicit information into 2bit tactons in different scenarios.

CCS CONCEPTS

- **Human-centered computing → Haptic devices**; *Ubiquitous computing*;

KEYWORDS

Tactons; On-body Feedback; Vibrotactile Display; Low-density Information; Information Presentation Interface

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1 INTRODUCTION

Vibrotactile stimuli as a feedback modality has been widely explored in different application scenarios, particularly to convey information when the visual and auditory channels are overloaded [17] or impaired [58]. Also, it has been used in multimodal feedback systems to provide redundant or additional information on the system's or environment's state [2]. Other applications are related to teleoperation or remote controlling [27] where haptic interfaces are used to imitate the feeling of touch. While most vibrotactile displays are designed for specific applications, some research such as

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Ambient Touch [47], T-mobile [61], semFeel [62], and OmniVib [3] have explored the potential of a more generalized vibrotactile displays for mobile devices. Tactile Brush [28], an on-body tactile grid display, has been developed to produce two dimensional moving strokes on the skin utilizing apparent tactile motion and creating phantom sensation.

Building on these researches and drawing inspiration from Brewester [8], we present 2bit-TactileHand, a vibrotactile display to replace low-resolution or complement complex graphical and auditory user interfaces. An information density of 2bits was chosen, being the maximum limit of information a user can process, while engaged in a quick Reflexive Interaction [37]. This perception limit is supported by Azadi et al. [6] findings, who in particular focused on evaluating the information capacity for finger tips and at the forearm.

This research focuses on evaluating the perceptual abilities of 2bit tacton encoded single characters and messages formed by multiple characters on the hand and the wrist. We found that 2bit tactons for the hand are significantly more perceivable than the wrist, which coincides with the users' preferences. We implemented a proof of concept application scenario and received initial user reactions. Our contributions are twofold:

- Design and development of a wearable 2bit tacton-based vibrotactile low-resolution display, which was proven to be slightly better perceivable on the hand than on the arm.
- Envisioned use cases in which we encode ambient, explicit, and implicit information into 2bit tactons that potentially support Reflexive Interaction [37].

2 RELATED WORK

Vibrotactile Displays (VtD) for Sensory Substitution

For sensory substitution, vibrotactile displays have been widely used with many applications, such as learning and producing music for deaf users [30, 41, 45, 46], word and sound identification for deaf users [21, 39, 42], object and visual context awareness for blind users [15, 58, 63], and prosthetic limb augmentations [34]. These displays are application specific and designed for certain body locations. For instance, in some music sensory substitutions systems, such as MussBits [46], the feedback is provided by a wrist-worn interface. Other works also include the torso of the body.

VtD as an Additional/Secondary Feedback Modality

In many applications, vibrotactile feedback has been used as an additional or secondary feedback modality to improve task performance. For example, Raj et al. [19] and van Erp and van Veen [56] discovered that presenting tactile and visual information, as opposed to solely using visual information, improves driving performance. Akamatsu et al. [2] also discovered that the pointing accuracy can increase, such as when positioning a pointer while providing additional tactile feedback to the user. Also, Lehtinen et al. [33] investigated the effects of a vibrotactile glove which supports visual search tasks while pointing. In other domains, such as rehabilitation, vibrotactile feedback proved to have a positive effect on improving the patients' recovery process [14, 29, 49].

VtD for Easing the Visual & Auditory Overload

Previous studies demonstrate that vibrotactile feedback is generally beneficial when the visual and/or auditory channels are overloaded or weakened [48, 50, 55]. Such a system was designed by U.S. Naval Aerospace medical research laboratory for military pilots [17]. A vest filled with 32 tactons and worn on the torso enabled a pilot to increase orientation awareness in relation to the ground. Other applications include pedestrian navigation, in which vibrotactile information is used to ease visual overload, such as by using gloves [54], wristband [44, 59], and shoes [38]. Creating awareness of orientation and guidance in VR using a vibrotactile glove has been demonstrated recently [24]. In sports, such as football, vibrotactile feedback displays were found to be useful in providing on filed coaching instructions without overloading the players' visual or auditory channels [51, 52]. Generally, most vibrotactile displays being proposed in literature are application-specific.

Tactons

As Brewester and Brown defined, Tactons are structured abstract messages that can communicate complex information to users non-visually or non-auditory [8]. Brown et al, [9] evaluated 9 tactons designed by using 3 amplitude levels and 3 rhythm levels. The results emphasized that tactons could successfully communicate information in user interfaces. A similar study was conducted to evaluate tactons, encoded by using frequency, amplitude and waveform as parameters [26]. Another study conducted by Azadi and Johnes discovered that the identification accuracy significantly lowers when there are no spatial cues or parameters in tactons [5]. In a subsequent study, they found that the mean Information transfer capacity for fingertips and forearms is 2.23 and 2.58bits [6]. The parameters used to encode these tactons were frequency, waveform, and duration.

3 THE 2BIT-TACTILEHAND

Placement of Actuators

The design of our wearable vibrotactile display is based on the two-point discrimination (TPD), which defines the minimum distance required for two spatial stimuli to be discriminated [31, 32]. This also determines the number of actuators that can be used.If insufficiently separated, the perception of two separate points during a simultaneous vibration may not be distinguishable. Previous work suggests that the hand and the arm are optimum locations to offer high spatial accuracy in perceiving vibrotactile tactons [10].

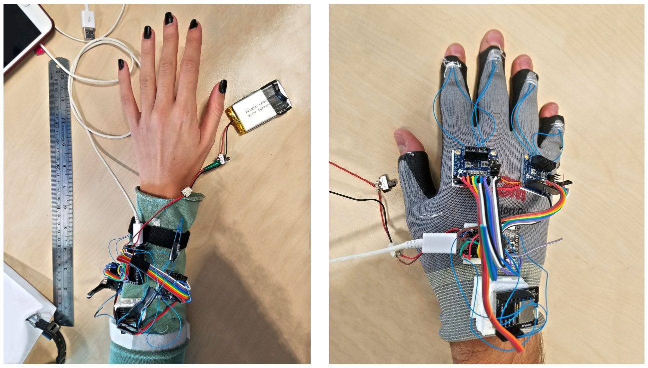

Figure 2: Wrist prototype (left) and glove prototype (right).

Hand Configuration. Following literature, fingertips have a high resolution of mechanoreceptors [10]. However, it is desirable to prevent obstructing the fingertips to maintain the availability of typical finger interactions for primary tasks. Therefore, we positioned actuators on the intermediate phalanges (*see Figure 1*). Also, actuators were not attached to the thumb, as it is the most essential finger used to grasp objects. To make fingertips open, we used partially fingerless glove as shown in Figure 2.

Wrist Configuration. Following literature, the forearm's TPD is 4cm [32], which informed our design. Since only four actuators were used in the hand configuration, a four actuator-configuration was also chosen for the wrist prototype. Two actuators were placed on the outer arm and another two on the inner arm, as shown in Figure 1. The distance in between the motors was approximately 5cm. All vibrotactors were fixed within a sleeve, as shown in Figure 2.

Throughput of Vibrotactile Stimuli

We used overlapping spatiotemporal stimulation (OST) [35], which is a special case of spatiotemporal encoding. In OST, the actuators are activated in sequences, while the vibration duration overlaps, as shown in Figure 3. For instance, to convey tacton 'A' (*see Figure 1* - Hand: red dots indicate active vibrations) with OST (*see Figure 3*), we first activate the motor at the middle finger because its sensitivity is lower compared to the index finger. After 10ms, the motor at the index finger starts vibrating. Both motors vibrate together for 20ms and stop vibrating simultaneously. To activate tacton 'B', the pinky will vibrate first followed by ring finger, because the pinky has the lowest sensitivity. Although this yields a higher transmission duration, it has the advantage of providing a higher information throughput.

Perceivability

When Luzhnica et al. [35] initially used OST to encode vibrotactile messages, they used up to three motors and reported OST stimuli is difficult to understand when the number of motors increased. Therefore, we limit the maximum number of active motors to two at a time. To minimize the effect of masking, previous research found that the actuator placed on the finger with decreased sensitivity, requires a longer actuation period [35], as Figure 3 illustrates. For the hand configuration, the finger sensitivities are in increasing order from the pinky, ring, middle, index, and the thumb [25]. For the wrist configuration, the location near the wrist, the radial side is more sensitive [11].

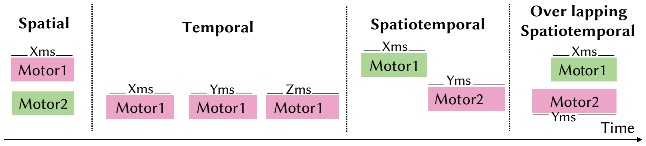

Figure 3: Encoding Techniques: Spatial, Temporal, Spatiotemporal, and Over lapping Spatiotemporal (OST). We used OST, which apparently is different by an overlapping actuation. As depicted, in OST, Motor2 starts actuating first. After (Y-X)ms Motor1 starts to vibrate and both motors vibrate together for Xms. Both motors stop vibrating at the same time. In 2bit tactile hand we use X as 20ms and Y as 30ms. Therefore, Y-X is equal to 10ms.

Designing Tactons and Messages

Our tacton design followed a specific actuation. For instance, in tacton 'A' (*see Figure 1*), the actuator on the middle finger starts before the actuator on the index finger, since the middle finger is less sensitive. Moreover, to reduce the number of basic tactons and ensure continued perceivability, the number of basic tactons involving the pinky finger was further reduced, based on its low sensitivity [25]. Finally, we designated 4 basic tactons. To increase the accuracy in perception, two vibrotactors were consistently actuated at the same time. This reduced the information density to 2bit, which are 4 different states ('A', 'B', 'C', 'D' - *see Figure 1*).

Messages are defined as a sequence of tactons with a time gap of 10ms in between each tacton. The time gap is equal to twice the minimum value (5ms), as suggested in literature [22]. Ideally, for four basic tactons (2bit), we could define a total set of 16 combinations. Considering prior work [35], combinations involving all 4 tactons were not selected due to an increased difficulty in understanding. To investigate more complex information, we created several combinations of tacton-messages ('AB', 'AC', 'BC', 'CD', 'BD', 'ABC').

Implementation

Based on physiological factors, the vibrotactile frequency range of the skin has been found within the range of 10-1000Hz, with a maximum sensitivity of around 250Hz [23]. Therefore, we operated the vibrationmotors at a constant frequency of 250Hz [57]. We used TianCoolKei LRA (Linear Resonant Actuator) bone conduction vibrotactors. These vibration motors were controlled by a Teensy 3.1 microcontroller board. The Arduino tone library was used to generate 250Hz output signals to drive the actuators. To amplify the signal being generated, we used MAX98306 stereo amplifiers with a gain of 18dB.

Table 1: Overall accuracy for tactons based on their confusion matrices.

Tacton >	A	B	C	D
Left Hand	95.5%	96.7%	90.8%	89.6%
Right Hand	100%	93.3%	93.3%	91.7%
Left Wrist	86.7%	81.7%	81.7%	81.7%
Right Wrist	88.3%	83.3%	78.3%	70%

Table 2: Overall accuracy for messages based on their confusion matrices.

Message >	AB	AC	BC	BD	CD	ABC
Left Hand	61.7%	76.7%	95%	80%	65%	88.3%
Right Hand	61.7%	75%	88.3%	70%	60%	81.7%
Left Wrist	80%	65%	58.3%	65%	73%	73.3%
Right Wrist	80%	63.3%	65%	75%	46.6%	71.7%

4 EVALUATION

In order to evaluate the perceptual abilities of a 2bit tacton placed on different body positions (left/right hand and left/right wrist), we conducted two user studies. In our first study, we evaluated a set of 2bit tactons. Additionally, we sought to explore the potential of tactons in a more complex information form. Hence, in a second study, we also evaluated messages with all 4 wearable configurations.

Participants. We recruited 12 subjects (8 males and 4 females) aged between 22 and 32 ($M = 25yrs; SD = 3.16yrs$). 2 of 12 subjects were left-hand dominant.

Apparatus. We developed a pair of tactile gloves, as well as a pair of tactile sleeves (*see Figure 2*), both driven by an Arduino Microcontroller board connected to a MacBook Pro. An interactive web interface was developed to record the subjects' responses.

Task and Procedure. We carried out a training phase in which the subject had the opportunity to familiarize themselves with the system. We introduced all basic tactons to the participant (*see Figure 1* - 'A', 'B', 'C', 'D'). They were presented 5 times, to increase the participant's confidence. After this familiarization phase, we carried out two studies with the same participants. The participants were asked to sit and keep their hand with on top of the table in both training phases and the two studies.

Data Gathering. We collected quantitative data by recording the subject's responses. We evaluated the accuracy based on the perceptibility, the number of manually triggered repetitions, and the response time. We did not consider the response time in our evaluation as the experimenter, at times, was required to help the participant submit their responses. After the experiment, we recorded qualitative feedback using a questionnaire, which requested basic demographics, previous experience with vibrotactile feedback displays, impression on accuracy, the overall experience of the system in terms of perceivability, as well as including an open-ended discussion between the participant and the experimenter.

Study 1: Tactons

We randomly presented a single vibrotactile tacton (*see Figure 1* - 'A', 'B', 'C', 'D') to the participant and asked them to identify it. The participant was allowed to replay the stimuli multiple times before submitting their final decision. In total, we presented 20 trials (5 trials each for 4 tactons). All 20 trials were evaluated on different body parts for comparison, which were right hand, left hand, right wrist, and left wrist. To minimize the impact of a learning effect on our data, we randomized the order of the presented tacton.

Results. We calculated 4 overall confusion matrices, accumulated across all 12 participants, for each body position. We summarized the outcome in *Table 1*. The average accuracy for the right hand (RH) was the highest, which was M=94.6% (SD=3.7). The left hand (LH) scored M=93.2% (SD=3.4), while the mean accuracy for the right wrist (RW) was M=80.12% (SD=7.78). The left wrist (LW) reached a similar range M=82.9% (SD=2.5). Furthermore, one-way ANOVA , showed a main effect (($F_{3,12}$=9.102; $p < .01$). A Tukey's HSD test confirmed that the differences occured between these pairs: LH-LA, RH-LA, RA-LH, RH-RA (*see Figure 4*). Moreover, there was no significant difference in RH-LH and RA-LA pairs. This shows that the hand configuration is significantly better for identifying tactons compared to Wrist. Also, there were no significant differences between right hand and left hand.

Study 2: Messages

In our second study, we presented messages to the subject in a randomized order, which we limited to 6 messages ('AB','AC','BC','CD', 'BD','ABC'). Similar to the first study, the participants were allowed to re-play the message multiple times before submitting their final decision. In total, we presented 30 trails (5 trails each for 6 messages). Again, all trials were evaluated on all 4 body positions for comparison which are the right hand, left hand, right wrist, and left wrist. To minimize the impact of a learning effect on our data, we randomized the sequence of all configurations.

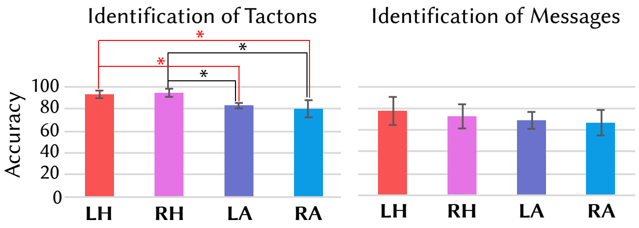

Figure 4: For Tactons one-way ANOVA showed a main effect for the pairs:LH-LA, RH-LA, RA-LH, RH-RA. For Messages, one-way ANOVA did not reveal a main effect.

Results. Similar to the previous study, we calculated 4 confusion matrices for each body position, accumulated across all 12 participants, for each body position (*see Table 2*). The mean accuracy for the left hand was the highest, which is M=77.78% (SD=12.94%). The right hand only scored an accuracy of M=72.78% (SD=11.14%). The mean accuracy for the left wrist was M=69.11% (SD=7.77%) and for the right wrist, M=66.94% (SD=11.71%). Although, perception at the hand appears to be increased over the wrist, a one-way ANOVA did not show a main effect ($F_{3,20}$=1.106; p>.5) (*See Figure 4*).

In order to determine the preferred stimuli, we created a scatter plot (*see Figure 5*) for each message, showing the number of correct trials without any repetition against the overall accuracy of that message. In this plot, we only considered the results of the the hand configurations as yielded higher accuracy and 9 out of 12 participants had the impression that the hand configuration was easily perceivable. Using a k-means clustering algorithm, we grouped all data points into three categories: Low Repetitions High Accuracy (LRHA), High Repetitions Medium Accuracy (HRMA) and High Repetitions Low Accuracy (HRLA). Messages understood quickly and accurately, fall into the LRHA category, which are tactons 'A', 'B'. Critical applications requiring an immediate identification of minor-complex notifications, should rely on these tactons. When conveying more complex information, such as identifying an incoming message, the accuracy demonstrated a decline, while the number of required trials raises. Overall, most messages >2bit fall into the third category, HRLA, and are less reliable to distinguish. However, these messages can still be used for applications, which are not crucial for time and accuracy purposes, such as ambient information.

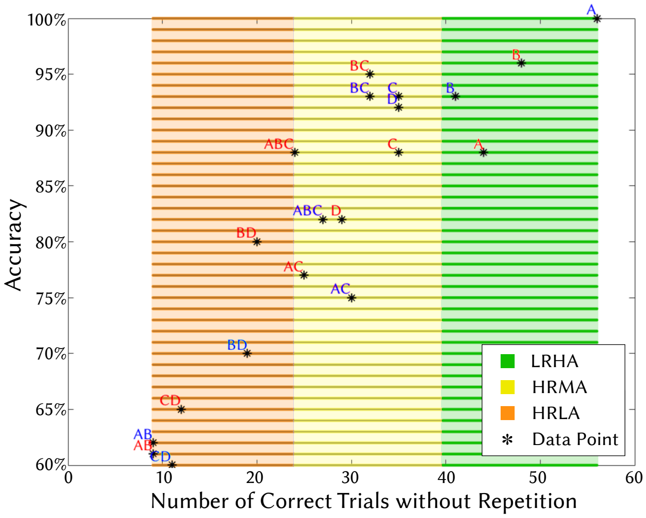

Figure 5: ***Overall Accuracy*** **against** ***Number of Correct Trials without Repetitions.*** **Blue = Right Hand, Red = Left Hand.**

5 DEMONSTRATED USE CASES

Encoding Ambient Information, such as the State of a Scene in a Virtual Environment

In a virtual environment (VR), encoding ambient information can contribute to increasing immersion and improving the user experience [53]. For instance, in gaming, this ambient information could be the player's stamina or the remaining ammunition during a shooting scene. This type of information is usually displayed visually by a digital Head Up Display (HUD) overlay. However, in a VR, it can be difficult to monitor visual overlays. The arrangement of a digital HUD may be tricky in a CAVE [13]. In these situations, we can project low resolution ambient information onto the user's body.

Figure 6: VR shooting game: the status of the ammunition and the recoil was provided via tactons.

To demonstrate the feasibility, we connected our glove prototype to a shooting game (*see Figure 6*), in which the user had to shoot random targets within a given time period. We informed three ammunition levels of the gun, which are high, medium, and low by using tactons 'A, 'B' and 'C'. Successful shoots were indicated by tacton 'D'. A pilot study with 3 users, 2 male, 1 female, (31, 21, 24*yrs*), using an Oculus Rift [43] was conducted, while we asked them to elaborate on their experience. In summary, all participants enjoyed the feeling of perceiving additional tactile feedback. P2: *"It was more fun when you feel the feedback that you have shot the target"*. Also, the participants understood the mapping of the level of the remaining ammunition .

Encoding Implicit Information, such as Plantar Pressure to Improve Workout Exercises

Visualizing plantar pressure can be useful to improve posture, namely while running or performing certain workout exercises [12, 16]. Current approaches displaying plantar pressure mainly rely on high resolution visual information presentation interfaces [1]. In various scenarios, however, the information density can be reduced to a 2bit display. For example, when drawing attention to an unhealthy walking style. Also, providing the user with recommendations to improve his gait, usually relies on <=2bit instructions, such as: *"strike the heel", "put weight on the mid stain", "lift your toe off"*. Conveying such binary information via tactons can also contribute to less interruptions while multitasking, enabling greater concentration on the primary task.

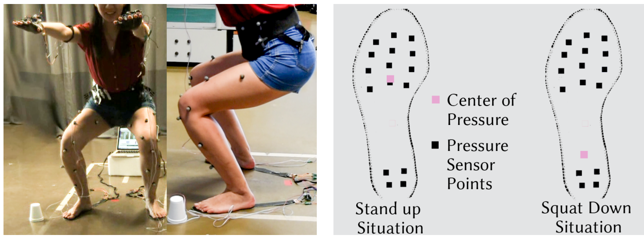

Figure 7: Squat exercising: Location of the CoP was provided via tactons (left). Sensor points and location of CoP when standing up and squatting down (right).

To determine whether 2bit-TactileHand is useful for such purposes, we selected a squat exercising scenario and conducted a pilot study (*see Figure 7*). Usually, in squat exercises there are only 2 critical pressure states: 1. Centre of Pressure (CoP) moving to rear foot when squatting down, and 2. CoP moving to distal foot when standing up [20]. We used the glove prototype to encode this information and asked 3 participants, 1 female and 2 male, ($26, 26, 25yrs$) to perform a squat exercise. CoP at distal foot encoded as tacton 'A' and CoP at rear foot encoded as tacton 'B'. We measured the plantar pressure distribution using the sensing.tex insoles [36]. An optical tracking system [4] was used to assess the participant's body posture. This pilot was accompanied by a professional trainer, who initially instructed the participants on a correct execution style. By motion tracking data, we identified an impovement of the participants' body posture when visualizing the CoP. Participants also stated TactileHand's visualization of the CoP movement to increased their confidence in performing proper squats. In an a subsequent work, we could confirm a significance in posture improvement for squats as well as for dead-lifts [18].

Encoding Explicit Information, such as the Type of an Incoming Message

The desire to read an incoming message or answer a call immediately is a common habit. This can produce dangerous consequences in situations such as when not paying attention to the road when involved in traffic. In other less critical situations, notifications may create unwanted interruptions, which disturb the user's flow [40]. Therefore, it would be of interest to first identify the importance of an incoming notification and to convey it in a less obstructing manner.

Figure 8: Encoding context of a message: glove prototype (left), tactons (right).

Using TactileHand, we encoded the importance of a message: 1. Very important, 2. Not very important 3. Unimportant. We conducted a pilot study (*see Figure 8*) with three participants (2 male, 1 female with age $31, 22, 30yrs$). They were asked to identify the importance of an incoming message while they were playing a simple computer game. Three of the 4 basic tactons were assigned ('A', 'B' and 'C') to encode the aforementioned scenarios. These messages were presented 10 times in a random order. We discovered that the accuracy was M=93.33% (SD=11.18). Most importantly, all users were confident in identifying incoming messages without disengaging from the primary task.

6 CONTRIBUTION AND LIMITATIONS

Quantitative results showed that identifying tactons at the hand configuration is significantly more accurate than at the wrist configuration. This is also confirmed by the qualitative feedback as 9 out of 12 participants had the impression that the hand configuration is easily perceivable than the wrist configuration. In summary, we can conclude that 2bit tactons are applicable at both the arm and the wrist configurations. In contrast, messages suffer from a substantial accuracy drop (minus 15% accuracy) and thus may only have a limited use, such as for displaying vague ambient information.

Wearing Comfort: The implementation of TactileHand still yields certain limitations. 5 out of 12 participants stated the glove prototype as uncomfortable to wear. Although we opened the fingertips of the glove, the tightness of the glove was an issue. To overcome this, vibrational feedback could be implemented on the device being grasped, such as a computer mouse, steering wheel, cycle handle, etc. Another option is utilizing smart finger rings penetrating the market now.

One-Size: As human bodies are individually pronounced, our prototypes did not offer the optimal fit. We selected a tight glove and used velcro straps with the sleeve to ensure that the vibration motors rested securely. A product could rely on stretchable or individually adjustable garments.

Visualizing Ambient Information: Participants stated to have enjoyed playing our VR game while perceiving ambient information on their hand. However, other applications and characteristics, such as whether visualizing ambient information has a performance impact on the primary task, is worth investigating further. Also, it remains unclear whether the user has a positive learning curve, or if perception decreases with over-stimulation from a longer time period. Exceeding the 2bit bandwidth and conveying multiple types of ambient information, such as the status of ammunition, level of stamina, a shooting recoil, at a single spot etc., may not increase immersion, but confuse or irritate the user.

Visualizing Implicit Information: According to the users' qualitative feedback from our second pilot study, visualizing plantar pressure information with vibrotactile tactons at the hand increased confidence when executing a correct squat exercise. In addition, using an optical tracking system, we confirmed the participants to have an improved body posture with TactileHand. We continue our research in this direction.

Visualizing Explicit Information: We specifically designed TactileHand to be useful when multiple tasks rival the user's attention, mainly to support continuous multitasking for Peripheral Interaction [7], in particular Reflexive Interaction [37]. We believe that 2bit vibrotactile tactons as proposed can be successfully conditioned and internalized with short training. This can be highly advantageous in decreasing the cognitive load when multitasking occurs with a critical primary task, such as driving a car, riding a bicycle, or operating a machine etc.

7 CONCLUSION

In this paper, we presented the design and the development of a general vibrotactile display relying on a 2bit information throughput. With 12 participants, we evaluated our tactile display at the hand and wrist. Our results indicate the hand to be the preferred position. Furthermore, we demonstrated 2bit-TactileHand's versatility by three use cases. We piloted these scenarios with three users each and gathered initial impressions on the user experience with tactons in an application context. With our contribution, we sketch how attention drawing feedback systems could recede to the background. This would prevent over-straining the user's attention resources, which is desirable as described in Weiser's and Brown's vision of calm technology [60].

REFERENCES

[1] Abdul Hadi Abdul Razak, Aladin Zayegh, Rezaul K Begg, and Yufridin Wahab. 2012. Foot plantar pressure measurement system: A review. *Sensors* 12, 7 (2012), 9884–9912.

[2] Motoyuki Akamatsu, MacKenzie I Scott, and Thierry Hasbroucq. 1995. A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. *Ergonomics* 38, 4 (1995), 816–827.

[3] Jessalyn Alvina, Shengdong Zhao, Simon T Perrault, Maryam Azh, Thijs Roumen, and Morten Fjeld. 2015. OmniVib: Towards cross-body spatiotemporal vibrotactile notifications for mobile phones. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2487–2496.

[4] OptiTrack Applications. 2018. Retrieved August 28, 2018 from https://www.vicon.com/.

[5] Mojtaba Azadi and Lynette Jones. 2013. Identification of vibrotactile patterns: Building blocks for tactons. In *World Haptics Conference (WHC), 2013*. IEEE, 347–352.

[6] Mojtaba Azadi and Lynette Jones. 2014. Evaluating vibrotactile dimensions for the design of tactons. *IEEE transactions on haptics* 7, 1 (2014), 14–23.

[7] Saskia Bakker, Doris Hausen, and Ted Selker. 2016. *Peripheral Interaction: Challenges and Opportunities for HCI in the Periphery of Attention.* Springer.

[8] Stephen Brewster and Lorna M Brown. 2004. Tactons: structured tactile messages for non-visual information display. In *Proceedings of the fifth conference on Australasian user interface-Volume 28.* Australian Computer Society, Inc., 15–23.

[9] Lorna M Brown, Stephen A Brewster, and Helen C Purchase. 2005. A first investigation into the effectiveness of tactons. (2005).

[10] Daniel Chen. 2017. *Weak at the Knees: Wearable Haptic Feedback Device for Real-Time Gait Retraining for Slowing Knee Osteoarthritis.* Ph.D. Dissertation. ResearchSpace@ Auckland.

[11] Roger W Cholewiak and Amy A Collins. 2003. Vibrotactile localization on the arm: Effects of place, space, and age. *Perception & psychophysics* 65, 7 (2003), 1058–1077.

[12] GTX Corp. 2015. Retrieved August 28, 2018 from http://gtxcorp.com.

[13] Carolina Cruz-Neira, Daniel J Sandin, Thomas A DeFanti, Robert V Kenyon, and John C Hart. 1992. The CAVE: audio visual experience automatic virtual environment. *Commun. ACM* 35, 6 (1992), 64–73.

[14] Rosado CX and Simone L. 2007. Translational haptic feedback for post-stroke rehabilitation. In *Bioengineering Conference, 2007. NEBC'07. IEEE 33rd Annual Northeast.* IEEE, 259–260.

[15] Dimitrios Dakopoulos, Sanjay K Boddhu, and Nikolaos Bourbakis. 2007. A 2D vibration array as an assistive device for visually impaired. In *Bioinformatics and Bioengineering, 2007. BIBE 2007. Proceedings of the 7th IEEE International Conference on.* IEEE, 930–937.

[16] Digitsole. 2017. Retrieved August 28, 2018 from https://www.digitsole.com.

[17] Rayan DM. 2000. Pilots: Close Your Eyes and Fly!. In *Proceedings of Navy Medicine.* 29.

[18] Don Samitha Elvitigala, Denys J.C. Matthies, David Loic, Chamod Weerasinghe, and Suranga Nanayakkara. 2019. GymSoles: Improving Squats and Dead-Lifts by Visualizing the User's Center of Pressure. In *CHI'19.* ACM.

[19] Jan BF Van Erp, Meppelink R, and HAHC Van Veen. 2002. *A touchy car.* TNO Human Factors.

[20] RAFAEL F Escamilla. 2001. Knee biomechanics of the dynamic squat exercise. *Medicine & Science in Sports & Exercise* 33, 1 (2001), 127–141.

[21] Robert H Gault. 1926. Touch as a substitute for hearing in the interpretation and control of speech. *Archives of Otolaryngology* 3, 2 (1926), 121–135.

[22] George A Gescheider, John H Wright, and Ronald T Verrillo. 2010. *Information-processing channels in the tactile sensory system: A psychophysical and physiological analysis.* Psychology press.

[23] Eric Gunther and Sile O'Modhrain. 2003. Cutaneous grooves: composing for the sense of touch. *Journal of New Music Research* 32, 4 (2003), 369–381.

[24] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. 2018. TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation. In *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference.* ACM, 273–280.

[25] Eve Hoggan, Sohail Anwar, and Stephen A Brewster. 2007. Mobile multi-actuator tactile displays. In *International Workshop on Haptic and Audio Interaction Design.* Springer, 22–33.

[26] Eve Hoggan and Stephen Brewster. 2007. New parameters for tacton design. In *CHI'07 Extended Abstracts on Human Factors in Computing Systems.* ACM, 2417–2422.

[27] Robert D Howe, Thomas Debus, and Pierre Dupont. 1998. Haptic identification of remote environment properties. In *Telemanipulator and Telepresence Technologies V*, Vol. 3524. International Society for Optics and Photonics, 123–131.

[28] Ali Israr and Ivan Poupyrev. 2011. Tactile Brush: Drawing on Skin with a Tactile Grid Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11).* ACM, New York, NY, USA, 2019–2028. https://doi.org/10.1145/1978942.1979235

[29] David L Jaffe, David A Brown, Cheryl D Pierson-Carey, Ellie L Buckley, and Henry L Lew. 2004. Stepping over obstacles to improve walking

in individuals with poststroke hemiplegia. *Journal of Rehabilitation Research & Development* 41 (2004).

[30] Maria Karam, Carmen Branje, Gabe Nespoli, Norma Thompson, Frank A. Russo, and Deborah I. Fels. 2010. The Emoti-chair: An Interactive Tactile Music Exhibit. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM, New York, NY, USA, 3069–3074. https://doi.org/10.1145/1753846.1753919

[31] Thorsten A Kern. 2009. *Engineering haptic devices: a beginner's guide for engineers.* Springer Publishing Company, Incorporated.

[32] Jacob H Kirman. 1974. Tactile perception of computer-derived formant patterns from voiced speech. *The Journal of the Acoustical Society of America* 55, 1 (1974), 163–169.

[33] Ville Lehtinen, Antti Oulasvirta, Antti Salovaara, and Petteri Nurmi. 2012. Dynamic tactile guidance for visual search tasks. In *Proceedings of the 25th annual ACM symposium on User interface software and technology.* ACM, 445–452.

[34] Joanne Leong, Patrick Parzer, Florian Perteneder, Teo Babic, Christian Rendl, Anita Vogl, Hubert Egger, Alex Olwal, and Michael Haller. 2016. proCover: sensory augmentation of prosthetic limbs using smart textile covers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology.* ACM, 335–346.

[35] Granit Luzhnica, Eduardo Veas, and Viktoria Pammer. 2016. Skin reading: Encoding text in a 6-channel haptic display. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers.* ACM, 148–155.

[36] Sensing Mat. [n. d.]. Retrieved August 28, 2018 from http://www.sensingtex.com/.

[37] Denys JC Matthies. 2018. *Reflexive Interaction - Extending Peripheral Interaction by Augmenting Humans.*

[38] Anita Meier, Denys J.C. Matthies, Bodo Urban, and Reto Wettach. 2015. Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation. In *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction.* ACM, 11.

[39] Matthias Mielke and Rainer Brück. 2016. AUDIS wear: A smartwatch based assistive device for ubiquitous awareness of environmental sounds. In *Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of the.* IEEE, 5343–5347.

[40] Richard Munoz. 2018. 8 Advantages And Disadvantages of Smartphone Technology. Retrieved August 28, 2018 from https://www.mobilecon2012.com/8-advantages-and-disadvantages-of-smartphone-technology/.

[41] Suranga Nanayakkara, Elizabeth Taylor, Lonce Wyse, and S H Ong. 2009. An enhanced musical experience for the deaf: design and evaluation of a music display and a haptic chair. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, 337–346.

[42] Suranga Nanayakkara, Lonce Wyse, and Elizabeth A Taylor. 2012. The haptic chair as a speech training aid for the deaf. In *Proceedings of the 24th Australian Computer-Human Interaction Conference.* ACM, 405–410.

[43] VR Oculus et al. 2015. Oculus rift. *Available from WWW:¡ http://www.oculusvr. com/rift* (2015).

[44] Sabrina Paneels, Margarita Anastassova, Steven Strachan, Sophie Pham Van, Saranya Sivacoumarane, and Christian Bolzmacher. 2013. What's around me? Multi-actuator haptic feedback on the wrist. In *World Haptics Conference (WHC), 2013.* IEEE, 407–412.

[45] Benjamin Petry, Thavishi Illandara, Don Samitha Elvitigala, and Suranga Nanayakkara. 2018. Supporting Rhythm Activities of Deaf Children using Music-Sensory-Substitution Systems. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.* ACM, 486.

[46] Benjamin Petry, Thavishi Illandara, and Suranga Nanayakkara. 2016. MuSS-bits: sensor-display blocks for deaf people to explore musical sounds. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction.* ACM, 72–80.

[47] Ivan Poupyrev, Shigeaki Maruyama, and Jun Rekimoto. 2002. Ambient Touch: Designing Tactile Interfaces for Handheld Devices. In *Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology (UIST '02).* ACM, New York, NY, USA, 51–60. https://doi.org/10.1145/571985.571993

[48] Anil K Raj, Steven J Kass, and James F Perry. 2000. Vibrotactile displays for improving spatial awareness. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 44. SAGE Publications Sage CA: Los Angeles, CA, 181–184.

[49] Robert A Reeder. 1998. Detecting knee hyperextension using goniometric inclinometer sensing with vibrotactile feedback. In *Instrumentation and Measurement Technology Conference, 1998. IMTC/98. Conference Proceedings. IEEE*, Vol. 2. IEEE, 863–867.

[50] Mark Schrope. 2001. Simply sensational. *New Scientist* (2001).

[51] Fabrizio Sergi, Dino Accoto, Domenico Campolo, and Eugenio Guglielmelli. 2008. Forearm orientation guidance with a vibrotactile feedback bracelet: On the directionality of tactile motor communication. In *Biomedical Robotics and Biomechatronics, 2008. BioRob 2008. 2nd IEEE RAS & EMBS International Conference on.* IEEE, 433–438.

[52] Kalisvaart SH, Garcia Lechner EMC, and Lefeber FJ. 2004. System for monitoring and coaching of sportsmen. In *European Symposium on Ambient Intelligence.* Springer, 88–91.

[53] Norbert A Streitz, Peter Tandler, Christian Müller-Tomfelde, and Shin'ichi Konomi. 2001. Roomware: Towards the next generation of human-computer interaction based on an integrated design of real and virtual worlds. *Human-Computer Interaction in the New Millenium, Addison Wesley* (2001), 551–576.

[54] Hajime Uchiyama, Michael A Covington, and Walter D Potter. 2008. Vibrotactile glove guidance for semi-autonomous wheelchair operations. In *Proceedings of the 46th Annual Southeast Regional Conference on XX.* ACM, 336–339.

[55] Jan BF Van Erp, Ian Saturday, and Chris Jansen. 2006. Application of tactile displays in sports: where to, how and when to move. In *Proc. Eurohaptics.* Citeseer, 105–109.

[56] Jan BF Van Erp and HAHC Van Veen. 2001. Vibro-tactile information presentation in automobiles. In *Proceedings of Eurohaptics*, Vol. 2001. Eurohaptics Society Paris, France, 99–104.

[57] Ronald T Verrillo. 1992. Vibration sensation in humans. *Music Perception: An Interdisciplinary Journal* 9, 3 (1992), 281–302.

[58] Philipp Wacker, Chat Wacharamanotham, Daniel Spelmezan, Jan Thar, David A Sánchez, René Bohne, and Jan Borchers. 2016. VibroVision: an on-body tactile image guide for the blind. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems.* ACM, 3788–3791.

[59] Bernhard Weber, Simon Schätzle, Thomas Hulin, Carsten Preusche, and Barbara Deml. 2011. Evaluation of a vibrotactile feedback device for spatial guidance. In *World Haptics Conference (WHC), 2011 IEEE.* IEEE, 349–354.

[60] Mark Weiser and John Seely Brown. 1996. Designing calm technology. *PowerGrid Journal* 1, 1 (1996), 75–85.

[61] Gi-Hun Yang, Moon-sub Jin, Yeonsub Jin, and Sungchul Kang. 2010. T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device. In *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on.* IEEE, 5245–5250.

[62] Koji Yatani and Khai Nhut Truong. 2009. SemFeel: a user interface with semantic tactile feedback for mobile touch-screen devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology.* ACM, 111–120.

[63] John S Zelek. 2005. Seeing by touch (haptics) for wayfinding. In *International congress series*, Vol. 1282. Elsevier, 1108–1112.