OM: A Comprehensive Tool to Elicit Subjective Vibrotactile Expressions Associated with Contextualised Meaning in Our Everyday Lives

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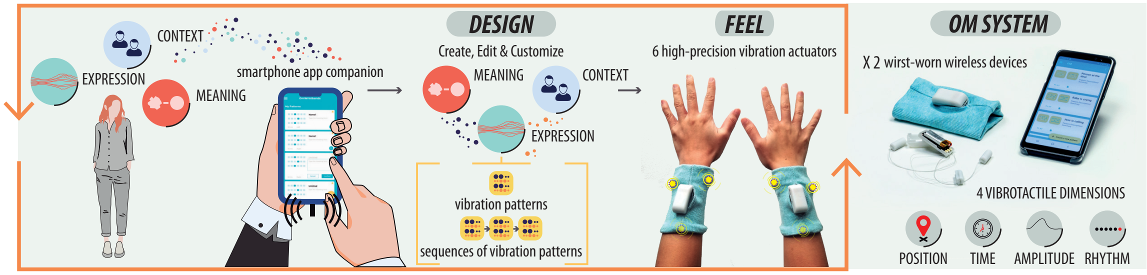

Fig. 1. OM System. Users can create and customise their own vibrotactile expressions in their everyday contexts using a smartphone app editor (i.e., *OM Editor*) and feel those expressions using our custom-made wrist-worn vibrotactile display (i.e., *OM Wearables*).

The sense of touch offers interesting possibilities as a robust and ubiquitous communication channel. In this paper, we present *OM*, a tool that enables users to design subjective vibrotactile expressions associated with contextualised information relevant to them. *OM* consists of a pair of wrist-worn devices that can reproduce complex vibrotactile symbols and a companion editor smartphone app that allows users to create, customise and store personalised expressions. We studied *OM* in real-world contexts by allowing 13 participants to explore the functionalities of *OM* throughout their daily interactions with complete autonomy. We highlight relevant scenarios, design considerations, and future directions towards a tool that can help people unveil an alternative, ubiquitous and private communication system accessible to all.

CCS Concepts: • **Human-centered computing** → **Haptic devices**; *Empirical studies in HCI*.

Additional Key Words and Phrases: Haptic feedback; wearable vibrotactile display; programmable haptics; vibrotactile symbolic mappings; field study

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1 INTRODUCTION

Over the years, the sense of touch has been widely investigated as a bridge between technological applications and human perception. Continuing to explore the spectrum of possibilities that this sense has to offer could lead to discovering interesting mechanisms to communicate with each other and interact with the world [50].

To date, research has shown that the sense of touch can be effective in providing high information throughput [59]and rich expressions [50] while favouring important usability factors (e.g., flexibility or adaptability) [20, 81]. The domain of touch-based applications include rehabilitation aids [10, 37], direction awareness accessories [19, 51], sensory substitution systems [4, 15, 61, 66], and learning assistants [42, 72].

Vibrotactile stimulations have been used as expressive stimuli to facilitate sound, context, and speech awareness [15, 48, 61]. Some strategies to encode this information include vibrations modulated in intensity [22], frequency [24], or rhythm [61]. This plasticity has contributed to the emergence of vibrotactile symbolic mappings (VSM) that encode complex information and have been used as a vehicle of meaning [1, 24, 43, 44].

Developing systems that can facilitate the transmission of information through vibrotactile stimulation is a demanding yet prolific and evolving enterprise [15, 43]. Articulating effective VSM poses a number of challenges: 1) devising custom equipment capable of evoking meaning via skin stimulation, 2) understanding the capabilities and limitations of the sensory neurons of touch, 3) exploring unique psycho-physical associations (i.e., subjectivity in perception), and 4) discerning effective modulations of VSM from others that are not sufficiently expressive or hold limited communicative value.

Prior work has investigated mechanisms to allow people participate in the elicitation of expressive VSM to account for subjectivity in perception and to help scan through potential modulations of VSM. Some of these solutions include novel vibrotactile editor interfaces that allow individuals to create personalised vibrotactile symbols [69], or wearable technologies that can induce vibrations modulated in different dimensions on specific parts of the body [61]. However, there appears to be a disconnect between 1) studies analysing editor interfaces, and 2) research investigating the possibilities of specialised vibrotactile wearable displays in-the-wild.

Therefore, to investigate these two aspects in conjunction, this paper proposes the development of a high-fidelity wearable vibrotactile display that can be programmed through an editor interface to allow individuals to create and feel their customised VSM. Drawing inspiration from languages where expression, meaning, and context are used to effectively encode and communicate information [39, 64, 67], we evaluate the effectiveness of our system as a tool that users can use to elicit expressive, meaningful, and contextualised VSM throughout their day-to-day lives [14, 45, 52, 58].

In this paper, we present the considerations to realise the *OM* system (Figure 1), a programmable wrist-worn vibrotactile display (i.e., *OM Wearables*), and an editor software app companion (i.e., *OM Editor*) that together intend to offer users enough flexibility and design opportunities to create, customise and maintain a library of personalised vibrotactile symbolic mappings (VSM).

We aim to understand 1) how users engage with a programmable haptics system, 2) what foreseeable opportunities they infer from its use, and 3) whether utilising comprehensive authoring tools in real-world settings can help advance VSM elicitation. We evaluated *OM* in a field study with 13 participants, where each of them had the autonomy to explore the *OM* system in their everyday lives for three days. Next, using both the collection of VSM generated by participants and information extracted from follow-up semi-structured interviews, we identify emerging themes, common strategies, engagement, and usability factors. Finally, we provide insights into how our participants envisioned using a ubiquitous and customisable vibrotactile communication technology throughout their day-to-day contexts.

2 RELATED WORK

2.1 Haptic displays:

Various techniques have been explored to convey complex tactile symbols through skin stimulation. For example, matrices of plasters embedding shape memory alloy filaments can target slow actuating mechanoreceptors and enable the emulation of gentle sensations such as caressing or stroking [56]. Leveraging fast actuating mechanoreceptors associated with discriminative touch (i.e., the ability to perceive, discern, identify and quickly react to external stimuli [50], Azadi et al. [1] and Brewster & Brown [4] have demonstrated that vibrotactile displays can be used to render intricate symbols through excitations modulated in multiple dimensions (e.g., space, time, or frequency). A number of studies have resorted to single-actuator vibrotactile stimuli to communicate rhythm [61] or haptic textures [73]. Others have used vibrotactile actuator arrays to encode text, characters, and abstract symbols [44, 59]. Furthermore, well-timed and strategically distributed vibrotactile actuators have been used to evoke tactile illusions, such as movement or phantom actuators [34]. The wide availability, simplicity, and diverse form factors of vibrotactile actuators facilitate design opportunities and integration. In this paper, we implemented a custom wearable vibrotactile display that embeds miniature high-precision 2D Eccentric Rotating Mass (ERM) actuators to help users elicit expressive vibrotactile symbols modulated in multiple vibrotactile dimensions.

2.2 Body location:

Individual sections of the skin are not equally effective in evoking specific sensations [24]. This variability is mainly due to mechanoreceptor concentrations, tissue composition, and anatomical reference points, such as the elbow [11]. Consequently, different body locations and skin types have been explored for different purposes, each with their own benefit. For instance, non-glabrous skin has been stimulated as a means to target CT-Afferents [2, 49]. The soles of the feet [16, 51] or fingertips [26, 74] are sensitive areas of the body that can provide both a high spatial acuity and resolution. The back [15, 59] and torso [23, 35, 66] offer large interaction spaces. The wrist [40, 47, 61] and forearms [31, 33, 36, 47] can provide relatively high sensitivities while factoring in usability factors. Lastly, other locations of the body, such as the back of the hand [17, 44], waist [13, 19, 30], neck [3] and even the body as a whole [53, 57, 80] have been employed as alternative channels to receive information or enhance specific experiences. In this work, we chose the forearm as a practical location with the potential to convey a reasonably high information throughput.

2.3 Haptic elicitation tools:

The emergence of high-dimensional encoding opportunities has expanded the set of vibrotactile mappings that can be communicated through the sense of touch. Nevertheless, these ample design possibilities are tethered to the subjective perception of haptic stimuli. Thus, to effectively chart meaningful constellations of VSM and identify impressions that may correlate among individuals [71], researchers have 1) encouraged both individual and collaborative participatory design [68], 2) highlighted the need for authoring tools [6, 28, 77] and support interfaces [18, 70, 82], 3) investigated vibrotactile sensations in everyday contexts [8] and analysed their impact in participants' daily routines (e.g., disruption, and recognition rates) [8], and 4) suggested design guidelines that can help users link content with mental frameworks (i.e., facets) [71]. Fusing these aspects into a single high-fidelity Hardware-Software authoring solution could provide a conducive medium to foster participant involvement in unveiling functional VSM in-the-wild.

Currently available VSM elicitation tools include: 1) Software editors [18, 69, 75, 82], 2) custom Hardware-Software combinations [6, 77], or 3) Hardware-only direct manipulation vibrotactile displays [28]. Although these investigations offer valuable insights on how to support VSM customisation, they are limited by 1) the specific software implementation (e.g., lack of cross-platform support or granularity), 2) being too specific for one particular application (e.g., for blind/deaf users), or 3) intrinsic hardware capabilities. Overall, these user-centred studies provide valuable insights to understand user perception, explore the plausibility of common semantic themes, and possibly, reveal scenarios that are useful and interesting. Thus, building on prior research, we implement *OM*, a hybrid Hardware-Software high-fidelity authoring tool. *OM* consists of a mobile-based editor software solution (i.e., *OM Editor*), and a custom wearable vibrotactile display (i.e., *OM Wearables*). *OM* aims to provide users with sufficient opportunities to create and personalise VSM that are expressive, meaningful, and contextually relevant in their daily routines.

3 *OM* SYSTEM

The goal of the *OM* system is to enable users to create, feel, and customise their own VSM in their day-to-day contexts. The system consists of a custom-built hardware solution (i.e., *OM Wearables*) and a dedicated software tool (i.e., *OM Editor*).

3.1 *OM Wearables*

3.1.1 Stimuli sensation: We aimed to support diversity of sensation and to maximise information throughput and technical response times. Thus, *OM Wearables* was designed to target fast-actuating mechanoreceptors highly sensitive to vibrations (i.e., Pacinian Corpuscles and Lanceolate Endings), as these sensory neurons are associated with discriminative touch [54, 78]. Furthermore, *OM Wearables* was optimised to reproduce vibrotactile signals modulated in multiple dimensions (i.e., amplitude, time, and space) [59, 62].

OM required 1) fast response times to improve the quality and resolution of vibrotactile expressions, 2) consistent vibrotactile feedback among users regardless of the actuator orientation, 3) sufficient vibration power to accommodate different contexts and situations, and 4) a small form factor that could facilitate the design of a wearable vibrotactile display. Thus, we selected high-precision 2D EMR motors (i.e., Precision Microdrives Model 304-121) centred at 340Hz@3V/33mA, lag time (i.e., 3ms), rise time (i.e., 16ms), and stop time (i.e., 22ms) as they were able to satisfy all these conditions. Alternatives such as 1D Linear Resonant Actuators (LRA), or Piezoelectric elements were not selected due to their limitations. For example, LRA tend to have a long latency, and since the quality of the sensation depends on a proper alignment of their force vector, they pose challenges in creating consistent vibrotactile feedback in-the-wild. Piezoelectric elements, in turn, require precise calibration and display a relatively lower actuation power.

3.1.2 Body location: We selected the forearm as the preferred body location to devise *OM Wearables*. To select this body location, we considered: 1) areas of the body densely populated with mechanoreceptors associated with discriminative touch, 2) existence of anatomical reference points (e.g., wrist or elbow) [11], 3) tissue composition (e.g., bones, or tendons), and 4) usability and social acceptability factors that favour engagement and utilisation. The forearm presents lower sensitivity and spatial acuity than alternative body locations (e.g., fingertips). However, poorer sensitivities can be offset with more powerful stimuli, and lower spatial acuity compensated through a larger spacing between actuators. Lanceolate endings operating on an independent ion channel [41, 76] present a viable alternative to low frequency

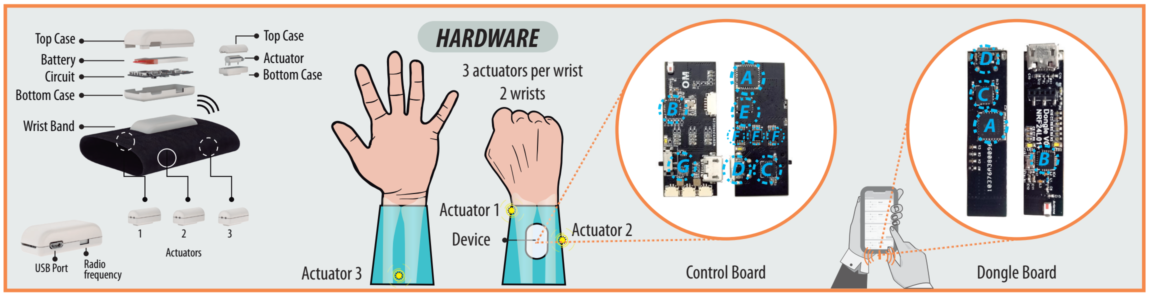

Fig. 2. Components of custom-made hardware *OM Wearables* & dongle circuit board: A) MPU:DSPIC33CH64MP202T, B) RF:nRF24L01+, C) USB comms:FT230XQ-R, D) Voltage Regulator:TLV75533PDBVR, E) I2C multiplexer:TCA9548ARGER, F) Haptic Driver:DRV2605LTDGSRQ1, G) LI-Po battery management:MCP73831T-2ACI/MC

responsive sensory neurons at the fingertips (i.e., Meissner corpuscles). Inter-stimuli and tissue conduction interference can be minimised through optimal actuator distributions across the surface of the forearm. Furthermore, this body location is a socially accepted location for wearable technologies [47, 51, 81].

3.1.3 Pulse driver location: We distributed three actuators across the anterior and posterior forearm to support the discernibility of the sensation locations. We also maximised the distance gap among actuators to minimise interference, masking, and to ensure that each motor could be felt independently (i.e., forearm two-point discrimination $> 4cm$) [51]. Additionally, to minimize the spread of unwanted vibrations across the forearm through bone conduction, only one actuator was placed in the environs of the Radius (i.e., Lateral Cutaneous nerve) and Ulna (i.e., Medial Cutaneous nerve) bones, respectively. The third actuator is placed in the anterior side of the forearm proximal to the elbow to maximise the distance from the bones. The envisioned solution is a coordinated dual-arm six-actuator vibrotactile display (i.e., 2 wristbands, 3 actuators per wristband), that aims to provide a large enough input space, maximise discriminability, and minimise inter-actuator interference.

3.1.4 Implementation: *OM Wearables* (Figure 2) consists of a pair of custom-built wrist-worn sleeves made out of cotton and spandex tube ribbing fabric. Each sleeve is worn on one forearm, is adaptable to different wrist sizes, and offers a medium that helps hamper the propagation of vibrations (i.e., cross-talk among actuators). Each sleeve incorporates a Printed Circuit Board (PCB) that embeds the drivers to control three 2D high-precision ERM actuators. Both the electronics and the actuators are encapsulated in individual custom 3D-printed casings. Additionally, an accessory dongle was designed to allow the sleeves to establish a dedicated wireless connection with *OM Editor*.

3.1.5 Control circuit board: Size: $4 \times 2 \times 0.8cm$, PCB layers: 4. This board incorporates an I2C multiplexer (i.e., TCA9548ARGER) to interface independently with each haptic driver (i.e., DRV2605LTDGSRQ1). Each driver controls a miniature ERM actuator (i.e., Precision Microdrives Model 304-121). Voltage regulator (i.e., TLV75533PDBVR), LI-Po battery management (i.e., MCP73831T-2ACI/MC), USB communication (i.e., FT230XQ-R), Wireless Communication Module (WCM) (i.e., nRF24L01+) and Main Processing Unit (MPU) (i.e., DSPIC33CH64MP202T). The board is powered by a 200mAh/3.7V Li-Po battery, and in the absence of user input, the board will automatically enter energy-saving mode (i.e., ~60 hours of operation, MPU @3.2mA, nRF24L01+ @26μA). Assuming functioning at the maximum capacity (i.e., ~1.5 hours battery life, MPU @26mA, nRF24L01+ @13.1mA, ×3 actuator@99mA), the total communication delay between the control board and the dongle including wake-up time is ~500μs (i.e., ~300μs transmission, ~190μs wake-up).

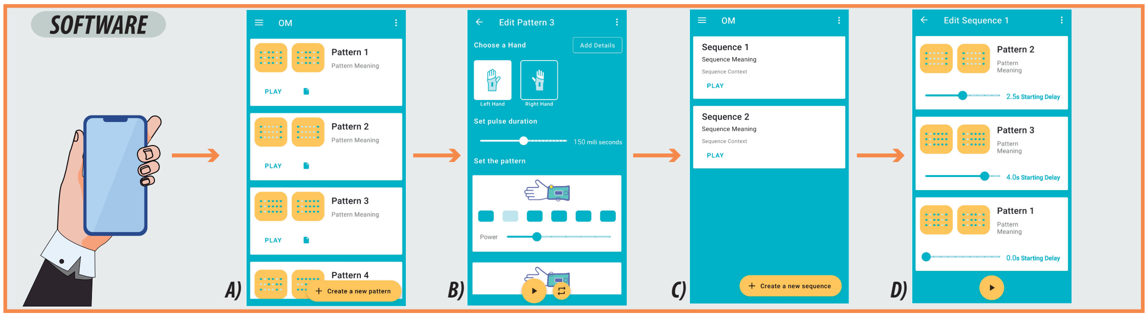

Fig. 3. *OM* Editor smartphone editor app enables users to create and edit vibrotactile impressions. The UI consists of: A) list of patterns, B) edit a pattern, C) list of sequences, D) edit a sequence

3.1.6 Dongle circuit board: Size: $2 \times 4 \times 0.8cm$, PCB Layers: 2. This board enables the *OM* hardware to be plug-and-play (i.e., establishing a wireless connection with a smartphone without requiring pairing). The device is powered directly through the phone. It incorporates USB communication (i.e., FT230XQ-R), voltage regulator (i.e., TLV75533PDBVR), WCM (i.e., nRF24L01+) and MPU (i.e., DSPIC33CH64MP202T). In energy saving, the dongle drains ~3.5mA (i.e., MPU@3.2mA, nRF24L01+@26μA, FT230XQ-R@125μA) while in active mode, and under continuous operation, it drains ~45mA (i.e., MPU@26mA, nRF24L01+@11.3mA, FT230XQ-R@8mA).

3.2 *OM Editor*

The requirement for the editor app was to enable users to create and customise basic impressions (i.e., patterns) and possibilities to combine them to create richer expressions (i.e., sequences of patterns). To meet our research aim, the *OM Editor* should enable the end-user to: 1) customise their own vibrotactile impressions (i.e., patterns and sequences), 2) associate their expressions with a *meaning* and a *context*, and 3) store and maintain their previous entries.

The *OM Editor* app is a tool to generate VSM that can be perceived through *OM Wearables*. Through *OM editor*, users can also assign *meaning* and *context* to their vibrotactile expressions. The app was developed in Java using the native Android SDK (Android version compatibility: ≤ 10). The app architecture consists of a serial communication (SC) module and a Model-View-Controller (MVC) framework. The SC module initiates the USB host mode[1] when the Android device is connected to the FT230XQ-R@dongle circuit board, which in turn enables a low-latency dedicated wireless connectivity with *OM Wearables*. The MVC is implemented using the RecyclerView[2] library, and custom data models were created to represent the pattern and sequence data structures. The data is stored locally on the device in JSON format. The MVC paradigm displays information dynamically and provides users with an interface to edit their data. As seen in Figure 3, the app consists of four views: A) list of patterns, B) edit a pattern, C) list of sequences, and D) edit a sequence.

3.3 *OM*-Enabled vibrotactile impressions

3.3.1 Patterns: We define patterns as customised VSM that occur during a user-defined period of time. Within this user-defined period, participants had fine control to set the individual force and program distinct rhythms for each actuator. The vibration frequency is fixed at 340Hz, which is adequate for near-optimal perception of vibrotactile

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[1] https://developer.android.com/guide/topics/connectivity/usb/host
[2] https://developer.android.com/jetpack/androidx/releases/recyclerview

sensations [33]. Specifically, each pattern occurs during a period of 6 time intervals. The duration of each time-interval is identical within a pattern, and the user can set the duration of this time interval (i.e., 50ms to 250 ms with a resolution of 5ms). Hence, the overall duration of a pattern ranges from 300ms to 1500ms. At each of the 6 time intervals, the user has the binary option to enable or disable each of the 6 actuators. If enabled, an actuator will vibrate with the chosen intensity, of which there are 7 power levels to choose from. A duration of 50ms was chosen as the minimum actuation time, as stimuli above 45ms demonstrated good recognition rates in untrained subjects [59]. Although longer stimuli durations, up to 2500ms, have been shown to yield higher recognition rates, the upper limit was fixed at 1500ms since prolonged actuation periods negatively impact information throughput and increase inter-stimuli adaptation recovery times [1, 33, 59]. In addition, the incorporation of multiple time intervals within a pattern offers end-users options to adjust inter-stimuli intervals, facilitate the modulation of information using different rhythms, and can even allow users to adjust precise timings to produce tactile illusions, such as apparent haptic motion [33]. The number of theoretically possible pattern combinations that *OM Editor* offers is substantial (i.e., $40 \times 7^6 \times 2^{6 \cdot 6}$), providing a 'blank canvas' for our participants to create their own VSM.

Sequences: We define sequences as collections of patterns. The user can individually adjust the intervals between patterns within a sequence. Sequences can be used to design effects that span over longer periods and explore compelling transitions of patterns; this can open up possibilities to construct hierarchical VSM inheriting properties of previous symbols [4], and the structuring of VSM into morphemes and syntactic units [44].

Meaning & Context: Meaning and context are text fields that can be assigned to each pattern or sequence. The user uses these fields to describe what the pattern or sequence means to them. For example, a hypothetical meaning of a pattern could be described as *"I am singing out of tune"*, while a context of this pattern could be described as *"I am performing"*.

4 EVALUATION

4.1 Participants & procedure

We recruited 13 participants (aged between 18-65: $M = 30.69$, $SD = 8.40$; 5 male, 8 female). Table 1 shows participants' demographics and their background. We provided each participant with a complete *OM* set consisting of a pair of wrist-worn devices (i.e., *OM Wearables*), an Android phone with the *OM Editor* app installed, a dongle to establish a dedicated wireless connection between *OM Wearables* and *OM Editor*, and for participants' familiarisation, a tutorial booklet on how to operate the *OM* System.

Due to the COVID-19 lockdown restrictions, the *OM* system was shipped to participants' postal address, and they received a remote introduction about the system via a Zoom[3] video conference call. The induction call was as follows: 1) Introduction about the project. 2) Demo on how to operate the app and how the wrist bands are worn to ensure appropriate actuator placement. 3) Show an example of how to create a pattern and a sequence. 4) The following instructions are given: a) Identify scenarios throughout your daily routines in which you would like to access information through VSM. Record the meaning that you want to convey, the context in which it has significance to you, and design a VSM that can express this information to you. b) Create the VSM at your own convenience. c) Create both patterns and sequences of patterns if possible.

This study aimed to draw insights from users in real-life situations. Thus, we restricted our intervention to daily technical check-ups to ensure experiment integrity: this included checking if 1) the system is functioning as expected,

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[3] https://zoom.us/

	GENDER	AGE	OCCUPATION	HOBBIES & INTERESTS
P1	Male	30	Engineer	Outdoor Activities
P2	Male	20	Student	Music
P3	Female	29	Student	Outdoor Activities
P4	Male	41	Assistant Principal	Arts & Crafts
P5	Female	23	Retail Sales & Nanny	Social Events
P6	Female	29	Social Work	Social Events
P7	Male	23	UX Designer	Outdoor Activities
P8	Female	23	UX Designer	Outdoor Activities
P9	Female	45	Human Resources	Outdoor Activities
P10	Male	48	Operations Manager	Outdoor Activities
P11	Female	31	Teacher	Outdoor Activities
P12	Female	29	Accountant	Outdoor Activities
P13	Female	28	Auditor	Outdoor Activities

Table 1. Participants' background information

and 2) the participant remembers to wear the device correctly. The participants were not told to create a specific number of VSM, nor was their progress monitored during the call. Each participant was asked to use the system for three days, informed they were free to create and customise VSM at their own convenience, and it was not specified whether the design should occur ahead of time (i.e. prospectively) or once a specific event had happened (i.e., retrospectively). Upon completion, we obtained a collection of VSM (i.e., patterns and sequences of patterns) created by each participant, measured system usability with a System Usability Scale (SUS) questionnaire [5], and conducted a semi-structured follow-up interview. We confined the experiment to a three-day period to limit participant exhaustion and favour experiment adherence [83].

4.2 Findings

We analysed data gathered from participants using thematic coding [25]. The transcripts were coded independently by two researchers to outline preliminary themes. Next, we reviewed and contrasted the data to refine the final high-level themes and sub-themes. Using a deductive approach, we organised the data into four categories: 1) strategies that participants used to express information, 2) meanings and information that participants were interested in expressing, 3) contexts in which participants want to be aware of this information, and 4) participants' first impressions on the system).

4.2.1 Aggregated Library of vibrotactile symbolic mappings: Participants created a total of 128 patterns (*average per user* = 9.85, *SD* = 2.88) and 49 sequences of patterns (*average per user* = 3.77, *SD* = 4.06). The collected constellation of VSM and their associations of meanings and context can be observed in Table 2. Based on the collection of VSM and semi-structured interviews, we observed that 23% of the participants did not create any sequence and exclusively relied on patterns to represent information (e.g., P3: *"Perfect conditions at my favourite beach to practice beach volleyball"*). In contrast, 7.7% of the participants only created patterns that were meant to be used as building blocks for sequences (e.g., P8: *"Question"*). 69.3% of the participants created both independent patterns with specialised associations of meaning and patterns that were meant to be used as building blocks for sequences (e.g., P8: *"Reminder to Lock the Door"*). Figure 4 shows a sample of these patterns and sequences.

4.2.2 OM-enabled strategies to communicate and express vibrotactile symbolic mappings: We asked participants to show us their favourite pattern and sequence, their meaning, and why they had decided to express the information in that particular way. Our data shows that participants used a wide repertoire of strategies as mentined below.

CLUSTER - CONTEXT											
A	B	C	D	E	F	G	H	I	J	CLUSTER - MEANING	DESCRIPTION
5	10	2		2	1		2			**Data Summarization**	Specific concepts (e.g., house, or sky)
3	3	1		4	1	5	4			**Events & Notifications**	Events or notifications (e.g., new message on social media)
2	1	2	3	2		3		2		**Passive Monitoring**	Monitoring people or situations (e.g., presidential election progress)
6		3	3					3		**Emotions - People**	People's emotions (e.g., my partner is feeling down)
4	4	1	4		1					**Reminders & Urgency**	Situations that need intervention (e.g., my baby is unwell)
7		3	3					1		**Wellbeing - People**	Health and comfort of other people (e.g., heart rate of my yoga students)
1	2	2		2		1				**Business & Work**	Work (e.g., a client is requesting information)
		4		4						**Productivity**	Performance increase (e.g., access key information during a presentation)
4			2		3		1			**Wellbeing - Personal**	Health of the user (e.g., I haven't drank enough water today)
			3	5				2	4	**Communication Cues**	Subtle hints to enhance communication (e.g., interesting conversation topics)
			2	4	2					**Danger & Risk**	Hazardous situations (e.g., there is a motorbike at my blind spot)
1			1							**Emotions - Personal**	Emotions of the user (e.g., I am feeling stressed)
					4	1				**Navigation**	Navigation cues (e.g., turn left in the next roundabout)
1										**Learning**	Facilitating learning processes (e.g., feedback when learning a dance move)
				20			VSM			**Musical Cues**	Musical performance (e.g., increase the intensity in the next section)

LEGEND	
A	**Home**
B	**Busy**
C	**Work**
D	**Anywhere/Anytime**
E	**Eyes/Ears Busy**
F	**On The Go**
G	**Phone Inaccessible**
H	**Free Time**
I	**Human Interactions**
J	**Private Communications**

Table 2. VSM meaning-context pairs collection. A) Home, B) Busy, C) Work, D) Anywhere/Anytime, E) Eyes/Ears busy, F) On-the-go, G) Phone inaccessible, H) Free time, I) Human Interactions, J) Private communications

Distinct vibrotactile sensations: These techniques were the most common among participants. This category includes tactics, such as individual and combined motor actuation, modulating vibrations through unique rhythms, choosing softer or steeper power transitions, or spatially encoding information.

Use of metaphors: We observed that some participants used more sophisticated methods and sought to recall information by associating it with specific metaphors. For example, P3 created a pattern based on how a volleyball feels on the arm while setting the ball (i.e., *"the first vibration I use is two motors, just like the movement, like brushing over my arm"*) to indicate *"Perfect wind conditions at my favourite beach"*. Also, P2 created a pattern that, according to him, felt *"like a circle going through my arms"* to illustrate *"repeat the last section"*. Finally, P1 attempted to render an alarm to convey danger (i.e., P1: *"I recreated the feeling of a fire alarm, it was like wee woo wee woo"*).

Elicitation of emotions: Some participants fine-tuned their VSM to be evocative of certain emotions. P4, for instance, tried to depict distinct feelings *"sad faded away, but happy was building up in crescendo"*, and P6 attempted to translate *"My client is about to break down"* by associating it with a specific vibration sensation *it's small and then it becomes deeper and deeper to give me a slow downward effect"*.

Creation of codes and arbitrary rules: We noticed that most participants chose to structure information by devising code systems of their own. P2 and P3, for example, used repetition to emphasise or introduce information. P7 mentioned that *"I tried to assign meanings to the intervals, like playing a musical instrument, the gaps have intrinsic meanings"*), and most interestingly. P8 created a comprehensive grammatical structure, *"I generally tried to keep to a fixed structure of intent (usually a verb, like Ask, Navigate, Meet, Remind, etc.), subject (e.g., Me, You), object (e.g., Home, Car, Phone)"*.

4.2.3 *Context-enabled associations of meaning:*

We deduced governing themes by analysing participants' VSM and the answers obtained through the follow-up semi-structured interviews. Our findings are as follow:

Emotional states & well-being of individuals: We observed a general interest in patterns associated with the emotional states of people with whom participants interact in their daily lives (e.g., P6: *"This technology can help me empathise with my patients and to feel what they are feeling"*). Furthermore, participants identified promising opportunities where customised VSM notifications sent to the user could help actively monitor the health status of people (e.g., P12: *"my sister's baby has a fever"*) or living beings that do not have the capacity to communicate (e.g., P11: *"my pet is sick while I am away"*).

Ubiquitous access to information: We identified a recurrent interest in having ubiquitous access to precise information. Some participants chose to summarise content-heavy information into concise VSM (e.g., P3: *"I created two sequences for one plant A getting sold and plant B getting sold"*, or P10: *"I want to be aware of relevant events while I am busy"*). Others, however, created patterns that would allow them to stay tuned through simple notifications, reminders, and emergency alerts (e.g., P1: *fire*, or P10: *tsunami alert*).

Discreet communication cues: Beyond simple notifications, users envisioned this system as an interesting way to access data in specific situations discreetly (e.g., P4: *"I want to know whether I am connecting with my audience", Context: "during a business presentation"*, P6: *"I want to know whether I am being inappropriate", Context: "having a conversation with another person"*, or P2: *"I want to have a communication channel with my musical conductor"*.

4.2.4 In-the-wild associations of context: Participants expressed interest in having the power to determine when to access the information of interest. Thus, we classify VSM in three big categories: 1) location-based, 2) situation-based and 3) general use. Participants reported that some of these VSM emerged after having encountered specific situations (i.e., retrospectively), while others surfaced as a result of reflecting over potential alternative applications for this technology (i.e., prospectively).

Location-based VSM: In this category, we can find a number of impressions that were intended to be exclusively used at work (e.g., P9: *"it is time to stretch"*, or P4: *"how many staff members are currently on campus"*), or at home (e.g., P6: *"take your medicines"*, or P9: *"plants need water"*).

Situation-based VSM: In this classification, we outlined instances, such as *"busy"*, where the person is occupied but still requires access to specific information (e.g., P3: *"something I am looking for has been posted online"*), or *"on-the-go"* (e.g., P7: *"potential hazard while biking"*).

General use VSM: In this class, we grouped VSM that were meant to be used *"anytime-anywhere"* (e.g., P7: *"I reckon this would be useful to continuously monitor the status of a patient"*), or VSM that, according to participants, could be useful to enhance *"human to human interactions"* (e.g., P4: *"is my audience concerned or excited?"*, or P5: *"someone is talking to me and I am unaware of that"*).

Background & interests: Generally, participants created VSM aligned to their interests and occupations. Although there are 20 instances of VSM used for musical cues, it all came from P2 who has keen interest in music. Similarly, P7 emphasised VSM that could unlock an alternative channel to access information while riding a bike. Others built a number of VSM around their favourite outdoor activities (i.e., P3: volleyball, P10: water activities, P11: running). Some of the participants with jobs that require a high degree of interaction with people, specifically P4, P5 and P6, designed a number of VSM that could enhance awareness and communication. Finally, participants created VSM associated with other hobbies and interests, such as side-businesses (i.e., P3: online-selling, P9: yoga), plants (i.e., P9, P11, P12), or TV shows (i.e., P10).

4.2.5 Participants' perceptions of the system: Through our interviews, we noticed that participants generally emphasised the following aspects of the overall experience:

Creating VSM is challenging: Participants found the task of creating VSM challenging, especially when they first started interacting with the system (e.g., P1: *"there are too many things to adjust, you just get lost"*). Thus, it was suggested that having had the device for a longer period would have permitted a more extensive exploration (e.g., P2: *"I think if I had the time to use the app over a longer period I'd definitely start using different patterns"*).

Learning requires practice: It was indicated that practice is required if the objective is to learn and recall these expression with ease (e.g., P13: *"learning it is more difficult than I imagined, it is like picking a new language"*, or P3: *"This* *feels like learning another language and language is complex"*). Interestingly, some participants expressed that they would be able to recognise a number of their personalised expressions instinctively (e.g., P11: *"I know what vibration to expect and what information should be transmitted"*, or P2: *"it is really effective in getting information across even while you might be busy with other things"*).

Customisation is a key feature: All participants reported a great interest in being able to customise their own symbols (e.g., P4: *"I liked the challenge of trying to create meaning from the sensations*, P2: *"being able to choose patterns yourself also means that you can pick things that are intuitive to yourself"*, or P2: *"the ability to create the pattern helps me memorise and to relate to it"*).

OM can display customised VSM: Participants found the vibrations enjoyable and pleasant, agreed that the arm was an ideal body location to perceive these sensations, and reported that the vibrations of each actuator could be perceived distinctively. Specific comments of some participants suggest that the sense of touch can evoke powerful sensations (e.g., P1: *"the location of the third motor was meant to be used for intimate sensations right?"*, or P6: *"I am very sensitive to touch sensations, I have positive associations with this sense"*). Also, it was considered reasonable to wear two sleeves to express customised VSM (e.g., P5: *"At first I didn't get why two sleeves were involved, but as I made patterns I realised why"*, or P6: *"Two sleeves allowed me to adjust the patterns and sequences better"*), but at the same time, the general opinion converges towards a solution that is as discreet and sleek as possible.

Interest in a discreet, private, and secure communication channel: Participants showed great interest in having a discreet, private, and secure communication channel at their disposal (e.g., P4: *"yes discrete, like the worm that they sometimes use in election debates"*). Participants also emphasised that vibrations should not be perceivable to others in social settings, as it would hinder organic interactions (e.g., P3: *" I think if it's not discrete it breaks the momentum of many things and it draws attention, so they would become cautious of the things they say and do and it may create tensions in any form of relationship"*, or P4: *"feels rude if I am communicating with people face to face"*).

Incorporating specific features can open up interesting possibilities: All participants identified alternative missing features within the design space that could have helped them express nuances in meaning. Some popular suggestions included more time within a pattern, more actuators, more power, and more independent control over each pulse in terms of time and power.

4.2.6 Rate of utilisation: We further analysed utilisation rates throughout the study by looking at the log files. In relation to productivity, 5 out of 13 participants created their patterns in a single day, which corresponds to 36.7% of the patterns (i.e., 47/128). 6 out of 13 participants designed patterns over 2 days, which corresponds to 44.5% of the patterns (i.e, 57/128). Lastly, 2 out of 13 participants produced patterns for all three days of the study, which represented 18.8% of the patterns (i.e., 24/128). Beyond creation, the participants had the option to edit their patterns as many times as they wanted. We observed that 77.3% (i.e., 99/128) of the patterns were only edited on the first day after they were created. 20.3% (i.e., 26/128) of the patterns were modified throughout 2 days. Finally, 2.3% (i.e., 3/128) of the patterns were tweaked every day. The last factor to consider when analysing the utilisation rate was the number of edits that participants made to their patterns. Participants made a total of 1071 changes (average per pattern = 8.37 $SD = 8.38$). The spread is considerable, as some participants edited some of their patterns as much as 46 times, while others only performed one edit. Thus, the confidence interval is ($p = 0.05, 8.37 \pm 1.45$). Within the same study, we can see polarised results. For instance, while P2 (i.e., 12 patterns, 204 edits) and P3 (i.e., 13 patterns, 206 edits) have a rate of 17 and 15.8 edits per pattern respectively, P1 (i.e., 4 patterns, 11 edits) has a rate of 2.75 edits per pattern. Contrasting these results with the semi-structured interviews, we observed a general lack of interest in haptics, creative endeavours, and

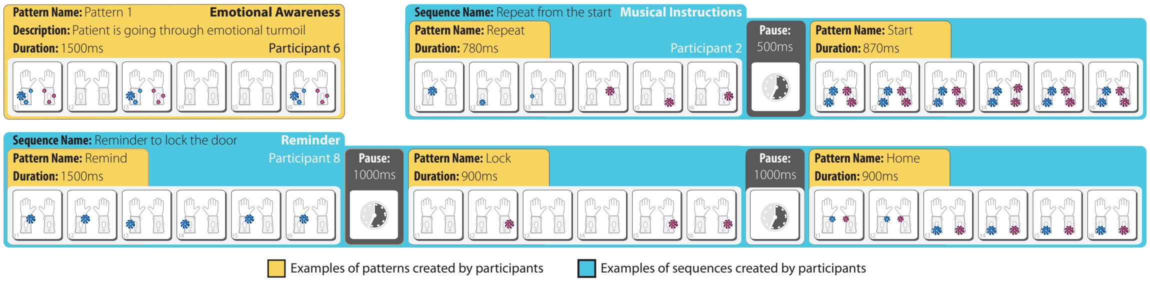

Fig. 4. Real examples of patterns and sequences collected from participants

wearable consumables in P1. With P2 and P3, however, they expressed greater intrigue about the various possibilities that haptics could potentially unfold in their daily interactions and the options that *OM* System offered.

4.2.7 System usability: *OM* received a SUS score of 70.19 ($SD = 18.17$) which is above the threshold of 68 [5]. However, based on one tail t-test ($t(n = 12) = 0.42,\ p = 0.3417$), it cannot be inferred that SUS score is significantly higher than the threshold. During the follow-up interview, we found that 3 participants gave very low ratings to the SUS questionnaire due to missing features they would have liked the system to offer (e.g., the ability to group their VSM into personalised collections, having access to a random VSM generator, or connecting the system to actual events). Thus, these scores seem to be associated with missing features rather than the ability to use the system to conduct the study. In contrast, nine participants indicated that the system was well integrated, intuitive, and neat. If we consider those three participants as outliers, the SUS score would be 77.75 ($SD = 13.16$), which is significantly higher than the threshold of 68 ($t(n = 9) = 2.36,\ p = 0.027$).

4.3 Discussion

4.3.1 Vibrotactile illusions and rhythms are promising building blocks for expression: When given the freedom to explore and customise vibrotactile symbolic mappings, all participants instinctively used a wide variety of strategies to express information, including 3D apparent haptic motion [33]. While these types of tactile illusions require fine control over the timings, non-expert users constructed the sensations, essentially contravening the belief that meaningful haptic interactions require specialist supervision [6]. Also, participants naturally bounded their VSM to mental frameworks, such as metaphors, elicitation of emotions, or specific haptic sensations to evoke complex meaning [71]. This rich compilation of strategies seemed necessary, considering the wide-ranging clusters of meaning and contexts of use that participants found interesting. Furthermore, participants appeared to recognise the intricacies involved in creating distinct VSM. Therefore, they wished for greater control, flexibility, and possibilities to allow them to achieve greater expressiveness in the patterns. Interestingly, not all participants recognised available design opportunities, such as utilising sequences to emulate longer patterns. Based on the participants' comments, we hypothesise the following causes: 1) participants were looking for simpler solutions to accomplish what they wanted, 2) participants needed more time to explore more functionalities, and 3) participants lacked exposure to examples or VSM created by other people. Therefore, more intuitive tools, more time, and access to reference designs could incentivise the appearance of haptic communities and foster the co-creation of haptic libraries [82], and lead to the emergence of complex communication cues. After all, it is not unusual for human behaviour to favour enterprises that offer rich possibilities for communication and expression, such as music, art, or literature [38, 46].

4.3.2 Early evidence that vibrotactile patterns can support linguistic structure: According to the Universal Grammar hypothesis, language is a capacity inherent in the human brain. Language ability enables people to organise and combine a finite number of fundamental components into an infinite number of expressions capable of conveying meaning [12]. Advancements in science, such as functional magnetic resonance imaging (FMRI), have enabled neurolinguists to investigate interactions of underlying neural structures in the brain to test the validity of these presumptions [21]. Data obtained from *OM* users show incipient structures in a number of the VSM compiled throughout the study (i.e., essential morphological units, specific phonetic structures and basic syntactic patterns). A limitation and strength of this research is how the design of *OM* and the instructions for creation supported users in generating their own vibrotactile linguistics structures. All participants assigned meaning to their VSM, some of them used sequences as a vehicle to structure grammatical sentences, and others created their own arbitrary rules to structure their expressions. Altogether, these behaviours suggest a possible innate ability that would have immediate applicability in haptics [36]. We believe these results could have been more promising if we had offered more intuitive opportunities to group patterns with similar properties or functionalities, structure sequences, and customise personal libraries of expressions. Future research is permitted to tease apart the effects of the design and instructions on generating VSM. If these findings replicate with various designs at a larger scale, it could yield valuable data to help advance the inception of a prospective vibrotactile communication system [71].

4.3.3 The customisation of subjective vibrotactile sensations can reinforce perception ability, familiarisation, and adaptability to individual user needs: Rather than being assigned general predefined VSM, participants valued the ability to program individualised expressions [70]. Also, users found the idea of unlocking an alternative medium to access information attractive. Aligned with prior research [29], some participants thought that this technology could be particularly useful when other senses are busy or overloaded. However, beyond a complementary role, participants saw value in extending the limits of their perceptual and cognitive capabilities [32] through an additional communication channel that is discreet, subtle, and private [9, 63]. Furthermore, the ability to customise and personalise VSM appears to be important to accommodate for subjectivity in perception [6, 71], and to establish familiar links with the VSM of their own creation, presumably enhancing learning and recognition. This notion is reinforced by considering all the strategies participants used to design VSM, the perceptual differences that were reported throughout the study, and special associations that some participants established with specific VSM. Finally, based on the experience of two of our participants who are profoundly deaf, we underline the positive impact that programmable haptics connected to actual sound events could have in the lives of individuals who are deaf or experience hearing loss.

4.3.4 Affective qualities of vibrotactile sensation lend themselves to social meaning: The findings show that several clusters of meaning have components that focus on human connection. In addition to explicit groupings, such as the well-being and emotional states of other individuals, participants suggested avenues that would allow them to monitor, receive notifications, and help them interact and communicate with people. Generally, touch is regarded as an important tool for survival, development, learning, and socialising [27, 60, 65]. Specifically, emotional touch (i.e., sensations such as affection, pleasure or pain) has been associated with areas of the brain devoted to social interaction [7, 50, 79]. These associations were common across different scenarios proposed by participants. Furthermore, some participants expressed that there seems to be a strong correlation between touch and their ability to connect and empathise with people. Ubiquitous programmable haptics hold great potential to redefine the way in which we empathise and interact with other individuals and living beings.

4.3.5 Real-world deployment can reveal useful insights on how haptic technologies are assimilated into users' lives: In recent years, haptic research is transitioning towards participatory design to explore tactile interactions in real-world settings [6, 70]. Such methodologies can help to better understand the connection between the trigger (i.e., inspiration) and the ultimate design (i.e., purpose). We discuss the following insights: 1) Users do not stick to a one-size-fits-all approach and create context-sensitive content. As an example, participants were conscious of the vibration intensity of the motors in relation to social settings. For instance, they created subtle impressions for quiet settings and more disruptive ones for on-the-go scenarios (e.g., driving, or biking). 2) Users designed personalised VSMs that relate to different aspects of their lives. We observed that participants designed VSM associated with their hobbies, work, or social interactoins. 3) Free exploration of diverse strategies to communicate VSM. Participants used metaphors, specific sensations, and personal codes to communicate meaning. 4) Users reflect on the VSM they have created and adjust them over time. In our study, participants edited their impressions multiple times (i.e., average of 8.37 times per pattern), 8 participants created their patterns on different days and close to 25% of the patterns were edited over the course of multiple days. 5) Users do not show signs of exhaustion, and the experiment does not interfere with participants' lives. Multiple participants were eager to test more possibilities, have more time to learn, and were interested in connecting the system to real events. These findings suggest that, in general, participants were actively involved in the study. 6) Users devise VSM prospectively and retrospectively. While some VSM were purposed to satisfy specific needs participants encountered over their daily routines, some surfaced as participants were reflecting over potential alternative applications in which this technology could be useful. 7) Users provided informed suggestions that would make the technology more applicable to their lives. The majority of participants engaged with the possibilities that this technology could offer and proposed user-specific solutions to improve it so they could better assimilate it into their lives. From these results, we infer that real-world deployment offered a conducive medium to evaluate *OM*. In line with the Human-Integration paradigm [55], we argue that adhering to in-the-wild methodologies can help glean insights beneficial to advance haptic research.

4.3.6 Reflection on running remote studies during COVID-19: The study was conducted at the peak of the COVID-19 pandemic and the enforced lock-downs, which created additional challenges and limitations. First, a few participants dropped out over concerns about increased contagion risks, while others relocated cities and became virtually unreachable. Second, conference calls were tedious, as participants frequently experienced connectivity and audio issues. Third, we had restricted access to equipment, limiting our capabilities to repair potential system failures. Lastly, as participants did not have any prior exposure to haptics, they had difficulties in understanding both technical terms and more abstract concepts, such as patterns or tactile dimensions. Therefore, we had to invest a significant engineering effort to produce a more robust prototype that would not break down easily, that participants could self-install, and use effortlessly without experiencing frustration. Also, given the general agitation and uncertainty, we further confined the study by reducing the number of days. Finally, we introduced the prototype via conference calls with well-designed power-point presentations with simple animations and visual aids. Also, we included a printed guide booklet in the prototype package that was sent to the participants. Our key takeaway is that conducting any study is a joint effort between participants and researchers where both must be willing to go an extra mile (especially during a situation like COVID-19) for it to prosper – we were lucky as we had both.

5 LIMITATIONS & FUTURE WORK

The findings of this study indicate that there are aspects of *OM* that can be improved. With the usability aspect of *OM Editor*, participants suggested making navigation easier and the design of patterns and sequences more approachable (e.g., implement a comprehensive tutorial to help users understand the functionalities of the system, or create personalised collections of expressions). We plan to provide options to incorporate/subtract actuators and will offer greater control over individual vibration pulses.

Furthermore, participants were interested in connecting their VSM to actual events and information sources. In the future, *OM Editor* should integrate the aforementioned functionalities in conjunction with a cloud-enabled solution to help participants connect their designs to relevant scenarios, such as IFTTT ("If This Then That")[4] for notifications. Currently, *OM* is limited to Android-based phones and the connection with *OM Wearables* relies on a wireless protocol that is not native in commercial phones. Although the current solution minimises delay in communication, it adds an extra layer of complexity to the system. Future implementations will be extended to support cross-platform devices (e.g., iOS) and use Bluetooth connectivity. With these changes, we plan to conduct further field studies with more participants allowing them to explore the system for a longer period of time.

6 CONCLUSION

We presented *OM*, a high-fidelity vibrotactile symbolic mapping elicitation tool consisting of a vibrotactile wearable display (i.e., *OM Wearables*), and an editor app (i.e., *OM Editor*). The *OM* system enables users to elicit expressive, meaningful and contextualised vibrotactile symbolic mappings throughout their day-to-day lives. Our analysis of related work advanced our understanding of psychophysical factors associated with the sense of touch and informed the selection of a suitable stimuli strategy, body location, and form factor to develop a compelling vibrotactile wearable display (i.e., *OM Wearables*). Also, we extracted important considerations from seminal research exploring the transmission of complex information through vibrotactile impressions. To advance the exploration of viable modulations, we incorporate expression, semantics (i.e., meaning), and pragmatics (i.e., context) as valuable coordinates to help consolidate effective VSM. Therefore, through *OM Editor*, *OM* provides users with ample opportunities to freely create and customise their own VSM and further imbue them with valuable contextualised associations of meaning.

We studied *OM* with 13 participants; each participant used the system for three days with minimum supervision, enabling them to have the autonomy to create and explore VSM of their own while drawing inspiration from their everyday contexts. Initial study results showed insights related to how participants used *OM* and the usability of the system. In addition, we collected from participants usage a library of vibrotactile expressions (i.e., patterns and sequences of patterns) associated with meanings and contexts that our participants found relevant. Study findings showed general interest in 1) having wide design opportunities to design expressive and personalised VSM, 2) generating underlying governing rules to structure their VSM, 3) having access to programmable haptics to customise VSM that are subjective, discreet and private, 4) the possibility of connecting to relevant information and people through an alternative communication channel. Furthermore, we discuss the implications and benefits of studying VSM elicitation in real-world settings through high-fidelity authoring tools, and reflections derived from running a remote study during COVID-19.

Based on these observations, we believe that *OM*-like elicitation tools open possibilities for future research explorations using vibrotactile expressions to communicate complex meaning.

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[4] https://ifttt.com/

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