Design of a Haptic Language for Gestural Control of Smart Lights

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Ubiquitous haptics draws from ubiquitous computing and aims to integrate haptics in everyday life to render interaction with technology seamless and intuitive. We describe an explorative design process that takes ubiquitous haptics as a starting point and aims to discover opportunities for haptics in a near future in which smart objects and haptic feedback are omnipresent. Through hands-on experimentation and brainstorming, we conceived a concept for the use of haptic feedback as part of a gestural language for interactions with connected devices, and more specifically with smart lights. The concept was developed and validated by exploring usage scenarios and experimenting with low-fidelity Wizard-of-Oz prototypes and high-fidelity prototype in virtual reality. This process led to the design of an intuitive and seamless user experience for smart lighting control based on a synergy between gestures and haptic feedback.

INTRODUCTION

The emerging ubiquitous technologies around us may soon demand and allow for new ways of interacting [13]. Screens may no longer be the preferred medium for intuitive information communication, given their demand for attention. This demand leaves us focused on our screens instead of being in and interacting with the world around us. Opportunities remain to make interaction more seamlessly and elegantly intertwined within everyday life. An example is Poupyrev et al.'s pioneering work on Jacquard [11], a conductive thread that allows for touch and gesture-based interactions with clothing and textiles.

In this work, we aimed to explore and prototype applications of haptic feedback that would improve the user experience of interactions with ubiquitous computing and smart, connected devices. We began with an explorative design study that used hands-on experience of haptic feedback and ideation activites such as brainstorms to generate ideas for the use of haptic feedback in ubiquitous computing. Through this process, the use of haptic feedback as part of a gestural language for the control of smart lighting emerged as a promising concept. We imagined a gestural language operated through free-hand gestures, with haptic feedback produced on a smartwatch, as a seamless, efficient solution for interactions with a set of smart lightbulbs in the home. The concept was first prototyped with a Wizard-of-Oz simulation, before implementing a higher-fidelity prototype in virtual reality (see Figure 1). Throughout this process, efforts were made to develop a universal haptic language by consistently varying parameters to communicate specific information.

This work shows that rapid prototyping and user-centered design are valuable approaches to reveal opportunities for haptics. Analysis of an interaction in terms of user needs reveals several ways in which haptics can make interactions clear. Many scenarios were found in which the user would get lost without any form of feedback or status update.

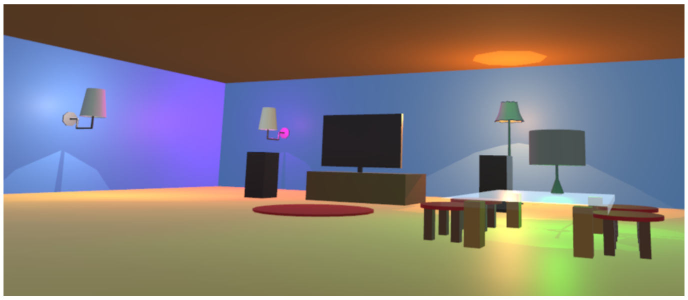

Figure 1: High-fidelity prototype in virtual reality, with four smart light bulbs in a virtual living room.

For many such moments, haptics proved useful to provide the necessary information. For example, haptics can be used to communicate the current state of the system, the confirmation of a user action and affordances for interaction. It was found that haptic signals are better understood when they resemble a phenomenon or GUI element that is known to the user. This work contributes to a future of ubiquitous computing in which haptics may play a significant role. By concretizing this future via rapid prototyping, this work identified possible applications for haptics in everyday usage scenarios.

RELATED WORK

HAPTICS FROM A DESIGN PERSPECTIVE

In his PhD dissertation [10], Moussette describes the history and characteristics of haptics, compares the sense of touch to the other senses, and highlights its strengths and weaknesses. The term haptics encompasses all aspects of the sense of touch and its study [3]. Two major perspectives can be distinguished: the human-centric perspective and the technology-centric perspective.

The human-centric perspective is about our active exploration of the world around us and relates to body-based processes that take place in order to understand and interact with the environment. It focuses on the skin, the process of learning sensory-motor skills and action-perception couplings. The sense of touch works as no other sense around a collaboration between action and perception. An example of this is Lederman and Klatzky's work on explorative procedures [8], which studied characteristic explorative movements made in order to learn about specific qualities of objects. Examples are unsupported holding to explore an object's weight and static contact to explore an object's temperature. Such fundamental insights are interesting for designers, as they could be used to design intuitive interactions with objects.

The technology-centric perspective is concerned with the environment in which the human acts, an environment that has seen drastic changes because of technological development. Before the industrial revolution,

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humans had full control over their tools and there were clear action-perception couplings. These couplings have however become more hidden or abstract due to automation and digitization, which sometimes caused interaction with technology to be complex and unclear. This led to a recognition of the importance of haptics and the human side of interaction. From then on, fields from the human-centric and technology-centric perspectives started working closely together, focusing for example on ergonomics and feedback systems to improve human-machine interaction.

According to [10], the greatest challenge for haptic technologies is currently accessibility and democratization, since both perspectives have developed with a focus on complex niche devices and applications.

STRENGTHS AND WEAKNESSES OF HAPTICS

The haptic sense is fast and sensitive compared to the other senses. It is also spread across the whole body, in contrast to the other senses, and has close connections with muscles. This is logical, given haptics' role in reflexes and complex, fine movements. To hold and interact with objects, constant feedback loops are involved between the applied muscle force and haptic feedback, as explained by Johansson and Flanagan [6]. In this way the haptic sense is particularly used to obtain information about material qualities of objects, such as weight and texture. The haptic sense is the sense to actively interact with and explore the world around us, more so than any other sense. Another interesting characteristic of haptics is that it is not forward-oriented, since the skin is everywhere on the body. Lastly, haptics are particularly good at delivering intimate and personal experiences, since it is very close to a person, and only this person feels it, as opposed to the other senses, that are shared easier and are generally more distant.

The haptic sense also has some weaknesses, the first being its range. Near or direct contact with the skin is indispensable to perceive haptics, which means that anything outside this short reach cannot be sensed immediately. In addition, haptics is bad at recognizing and memorizing context, and thus at perceiving an overview of an object, as Jansson states in [5]. In other words, perception at the contact point is accurate and detailed during contact, but this information is hard to remember and to compare, in scan-like movements, without sight. This demands a high cognitive load. Because of this lack of haptic memory, small differences in haptic qualities of objects are hard to compare.

From a designer's perspective, knowledge about the pros and cons of haptics compared to other senses is essential to design haptic experiences that add value. Such knowledge can for example help determine when to apply haptics in an interaction, instead of another modality.

VIBROTACTILE FEEDBACK

Haptics in the form of vibrations are popular and widely used in various devices, in part because vibrotactile actuators are small, inexpensive and effective [2]. A common application of vibrations is to guide a user, which is often used in game controllers, prosthetic hands and teleoperation. Repulsive feedback sends the user away from a target, while attractive feedback attracts the user towards a target. Vibrations also have many parameters that can be altered, such as amplitude, frequency and rhythm [9, 12]. By varying these parameters, large sets of different haptic feedback signals can be obtained. Each such signal is called a haptic icon, tactile icon or tacton [9, 12, 1]. Tactile icons are used to communicate more detailed information than a binary signal, such as incoming message urgency, sender identity, or an emotion. The downside is the often abstract mapping between a tactile icon and the message it conveys, which needs to be learned and demands a high cognitive load to recognize. In [1], Brewster and Brown design and find applications for such a set of tactile icons by varying haptics parameters.

HAPTICS IN VIRTUAL REALITY

A specific application for some of the above-mentioned haptic technologies is in virtual reality (VR), an application domain that has become increasingly popular and accessible over the past decade. It has long been recognized that the immersiveness of a virtual reality simulation can be severely compromised by a lack of haptic feedback upon interactions with virtual objects. Alleviating this problem has been a popular research problem, and several solutions have been proposed in the literature. One of many examples is Shifty [14], a device that changes its center of mass to generate a feeling of weight. Another way to implement haptics is by giving the user a real object that represents a virtual object, with manipulations of the real object having consequences in VR (e.g., [4]). Because vision tends to override haptics, minimal haptic devices can already cause convincing experiences, as long as the haptics are in accordance with what is seen.

From a designer's perspective, two major problems of such devices are accessibility and applicability. It is at least time-consuming to obtain or replicate a version of such devices to use in a prototype, which are often not open-source, 3D-printable, or plug-and-play. If accessible, there is the issue of applicability. Such devices tend to focus on implementing a specific form of haptics, for a specific application or scenario. In spite of good performance in one use case, such devices could be ineffective or hard to use for other applications. A third, more general, point of attention is how a device influences the interaction in unintended ways. A handheld device, for example, may create tactile haptics in the hand that are not congruent to the VR experience. In addition, the hand may need to be in a specific, perhaps unnatural, position to hold the device. Lastly often such devices use motors that produce sounds that do not come from the VR application. All these small factors influence how the user interacts within the experience, arguably negatively.

EXPLORATION AND CONCEPT DEVELOPMENT

This section describes the explorative design process used to explore haptics in ubiquitous computing, the concept selected for further development, as well as early experimentation with a low-fidelity prototype.

EXPLORATIVE DESIGN PROCESS

We began this work with an exploration of the role of haptic feedback in future interactions with ubiquitous computing and smart devices. Our goal was to integrate haptic feedback in an everyday user experience such that it adds value for the user in an understandable and seamless way. Through an iterative process of brainstorming and hands-on experimentation, we aimed to (1) better understand the characteristics, strengths and weaknesses, and current applications of haptics, (2) identify user experiences in ubiquitous computing that could benefit for haptic feedback, and (3) select a representative use case that would enable rapid experimentation and iteration.

Figure 2: Exploration through hands-on exploration with the Lofelt Basslet (left) and brainstorming (right).

We experimented with several haptic devices in order to personally experience the haptic sensations delivered and the impact of form factor and body location. This hands-on experimentation was a source of inspiration during brainstorms, and led to a better understanding of the possibilities offered by haptic feedback and the specificity of the different devices in terms of portability and ease of integration in a prototype. Through this process, the Basslet (Lofelt, Germany) was identified as a promising haptic device for further experimentation. The Basslet is a wrist-worn, wireless haptic device with a wide-bandwidth vibration actuator (see Figure 2). The device can produce a wide range of vibrotactile patterns and is driven by audio signals, thereby making it possible to experiment quickly. The use of a wrist-worn device is moreover comfortable for users, and a realistic proposition given the prevalence of smartwatches and activity tracking bands on the market.

Various applications of haptic feedback in ubiquitous computing were explored through extensive ideation activities, such as brainstorming and mindmapping (e.g., see Figure 2). Efforts were made to approach the problem from different starting points and perspectives in order to produce a wide range of ideas, e.g. by separately listing available technologies, characteristics of haptics, applications of haptics and promising ideas and insights gathered through hands-on experimentation and a review of the related literature. This process led to the selection of an application concept for further experimentation.

Selected Concept

One concept was chosen as the outcome of our explorative design process. We chose to further explore the gestural control of smart home devices, with an initial focus on smart lighting. We considered the use of smart light bulbs with three parameters that can be adjusted to create an ambiance: the light intensity, the light temperature (a range from warm orange to cold blue) and light color. Haptics are used in this concept to provide users with information and feedback, guiding them through interactions. First, scenarios of use were written to identify user requirements and imagine concrete step-by-step interactions. This process revealed the design space and design choices that needed to be made. For example, two separate modes were identified for the system: *ambiance* mode and *copy-paste* mode. *Ambiance* mode allows adjusting the parameters of bulbs, while *copy-paste* mode allows copying and pasting the parameters of one bulb to other bulbs.

Alongside these choices, we identified a variety of gestures and opportunities for haptics that could be used at the different stages of the interaction flow. To select a bulb, for example, the user could point to it, make a grasping gesture, or draw a circle arount it. Haptics could be used to confirm gestures made by the user, to communicate the different stages of the interaction, or to indicate intermediate values and boundary values along parameter scales.

Low-Fidelity Prototype

To begin experimentation, we developed a low-fidelity prototype in Processing (processing.org). Gesture detection was simulated in a Wizard-of-Oz approach [7], with an operator clicking on buttons to trigger actions (e.g., turning on a light) and haptic feedback (e.g., a tactile icon on the Lofelt Basselt). The prototype consisted of four light bulbs with adjustable intensity, temperature and color (see Figure 3). Buttons allowed several actions to be simulated, such as selecting a light bulb, and haptic feedback to be produced, such as reaching the limit of a range. The prototype could be rapidly modified to experiment with various uses of haptic feedback at different steps in the interaction. This allowed us to evaluate gestures and the role of haptics in the scenarios, and experience the possible interactions as a whole. This helped to reveal several points of attention and early mistakes regarding interactions.

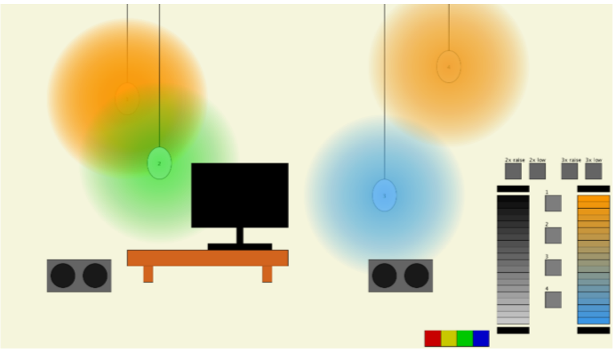

Figure 3: Low-fidelity prototype developped in Processing.

High-Fidelity Prototype in Virtual Reality

To further experiment with the concept, we developed a high-fidelity prototype in virtual reality. This solution makes it possible to quickly experiment with various room configurations and use contexts, and greatly facilitates the recognition of gestures and the localization of interactive objects in the user's environment.

Development Platform

The high-fidelity prototype was developed in Unity with the Oculus Rift Virtual Reality headset and the Oculus Touch handheld controllers. Gesture recognition was performed using the Oculus Touch controllers. Simple gestures, such as pointing or raising a thumb, were made through a combination of natural hand postures and button presses. More complicated gestures were detected using the miVRy gesture recognition Unity asset, which allows arbitrary gestures to be learned. These gestures were initiated with the press of a button, and recognized once the button was released. The high-fidelity prototype approximated the gestures that would be made with free hand movement, but differed in the use of a handheld object and the need to press buttons.

The haptic feedback was produced using the Lofelt Basslet, a haptic wristband with a high-bandwidth vibration actuator. Tactile icons were created as audio files with the Reaper digital audio workstation (DAW).

Early Insights

The haptics used in the high-fidelity prototype were designed based on insights gained throughout the early phases of the project. Haptic feedback can quickly become annoying and its meaning can be unclear. The user should always know which actions has triggered haptic feedback, or may otherwise feel that the feedback is uncontrollable and obtrusive. The meaning of haptic feedback also becomes vague when too much feedback is produced in a short amount of time. Such a haptic overflow can cause the user to pay less attention to the haptic feedback. Haptics require relatively much time to play compared to the speed with which users can follow up actions. So even though there seem to be not many haptics, fast users can still experience an overflow. As just said, haptics can quickly take up too much attention when misused. However haptics also tend to fade away in the background. This happens mostly when the user is not in need of any more information. For example the user might already get strong visual feedback, or the user just knows the system's state and is in the middle of a standard interaction.

Next to this, several new opportunities for haptics in the interaction were identified, based on insights while developing. For example all light bulbs worked perfectly without any delays or unpredictable behaviour. In reality, control of smart devices can experience delays, given the often wireless nature of such systems. When a user sends a command

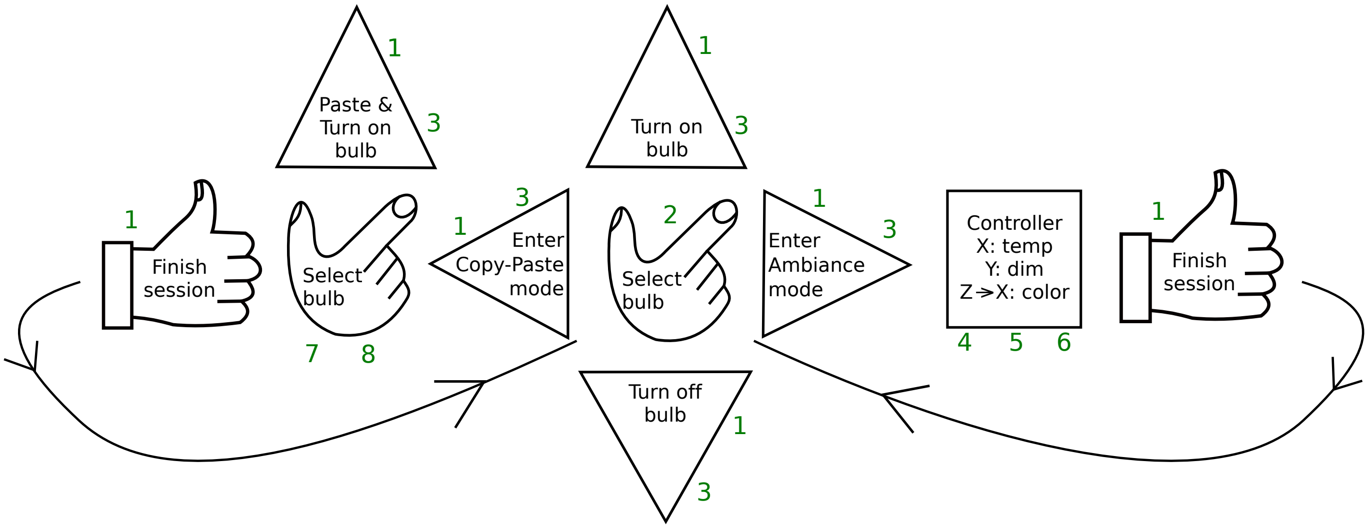

Figure 4: Interaction flow used in gestural language, with numbers indicating possible tactile icons.

via a smartphone app, it can take some time before the smart device responds. This is a period of uncertainty in which the system's state is not clear. Furthermore, first all light bulbs in the prototype were interactive and had the same adjustable parameters. In reality, a user may have all sorts of lights in his/her house. Some may be not interactive at all, some may only have adjustable intensity and no temperature or color. Regarding these aspects, the prototype did initialy not resemble the real world. Here haptics could help to inform the user about the functionalities of the device and occurring delays.

INTERACTION FLOW

The living room in VR can be seen in Figure 1 and the interaction flow of the final prototype can be seen in Figure 4. The different gestures are represented by different icons. Pointing, thumbs up, swiping in one of four directions, and the controller position can be distinguished. The moments where haptics play are indicated with numbers, each representing different information that is communicated (see Figure 5).

The interaction flow of the final prototype is as follows (see Figure 4). The user starts by pointing to a bulb in order to find out if it is interactive and, if so, what are its available parameters. This is communicated via haptics. When pointed at, the bulb is selected. Then the user can swipe in one of four directions to either turn on or off the bulb, or go into one of the two modes. Although not necessary, generally a bulb is turned on first with an upwards swipe, before one of the modes is entered. Turning on a bulb is confirmed with haptic feedback. In case of connection delays, the user is notified by haptic ticks as long as the delay persists. In the prototype, one bulb was artificially given a delayed response.

When the user swipes to the right, he or she enters *ambiance* mode, and gets a specific confirmation via haptic feedback. Then, each parameter, if available for this bulb, gets linked to the position of the right-hand controller. The light intensity is linked to the y-position. The light temperature is linked to the x-position. The light color is also linked to the x-position, but on a different position on the z-axis. When the user reaches a maximum or minimum value along a parameter scale, a haptic message notifies the user. When the user switches his movement direction, and thus starts adjusting another parameter, he or she is notified by this via a haptic message as well. When the user moves his hand/controller in a direction that does not influence a parameter in that bulb, a haptic error message is played. This happens, for example, when the user moves his hand horizontally while controlling a dim-only bulb. If the user is satisfied of the created light effect, he or she can make a thumb-up gesture, to leave *ambiance* mode and return to the neutral system state.

Then, if the user wants to copy the parameters that he or she just set to another bulb, he or she can use *copy-paste* mode. First, the user points at the bulb of which he or she wants to copy the parameters. Then, a swipe to the left enters *copy-paste* mode and copies the parameters. The user gets notified of the parameters that he or she copied by a continuous haptic signal that plays softly in the background. This haptic signal is different based on the number of parameters copied. The user can then point at a bulb to which he or she wants to paste the parameters. When pointing correctly at a bulb, the user gets notified of this via the soft, continuous haptic feedback that plays stronger then, with a larger amplitude. To paste the parameters and turn this light on, the user needs to make a swipe upwards. If the user has pasted the parameters to all bulbs that he or she wanted to, the session can be ended by making a thumb-up gesture, which is confirmed with a haptic message.

HAPTIC LANGUAGE

The tactile icons are described visually in Figure 5. A black line represents an individual vibration pulse. The x-axis represents time and the y-axis represents frequency. The length of a line thus represents the duration of the vibration, its horizontal position represents its order in a temporal sequence, and its height represents its relative frequency. The thickness of the line represents the signal's intensity. If the icon plays continuously, a 'repetition' mark is added in the top-right corner. The following describes some of the parameters that were used in the design of this haptic language.

Repetition. The number of vibrations is used as a distinguishing feature for otherwise similar tactile icons. Gesture confirmation icons for entering or exiting the *copy-paste* and *ambiance* modes, for example, are identical except for the number of final vibration pulses (one or two; see (1) in Figure 5). Similarly, the number of vibration pulses is used to indicate the number of available parameters (dimming, temperature and color) when pointing at a bulb or copy-pasting parameters (one, two or three; see (2,7,8) in Figure 5). The number of vibration pulses is finally used to indicate the importance of a state change: entering or leaving a mode is indicated with five vibration pulses, while switching parameters in *ambiance* mode is indicated with only two vibrations and toggling a light is indicated with three vibrations (see (1,4) in Figure 5).

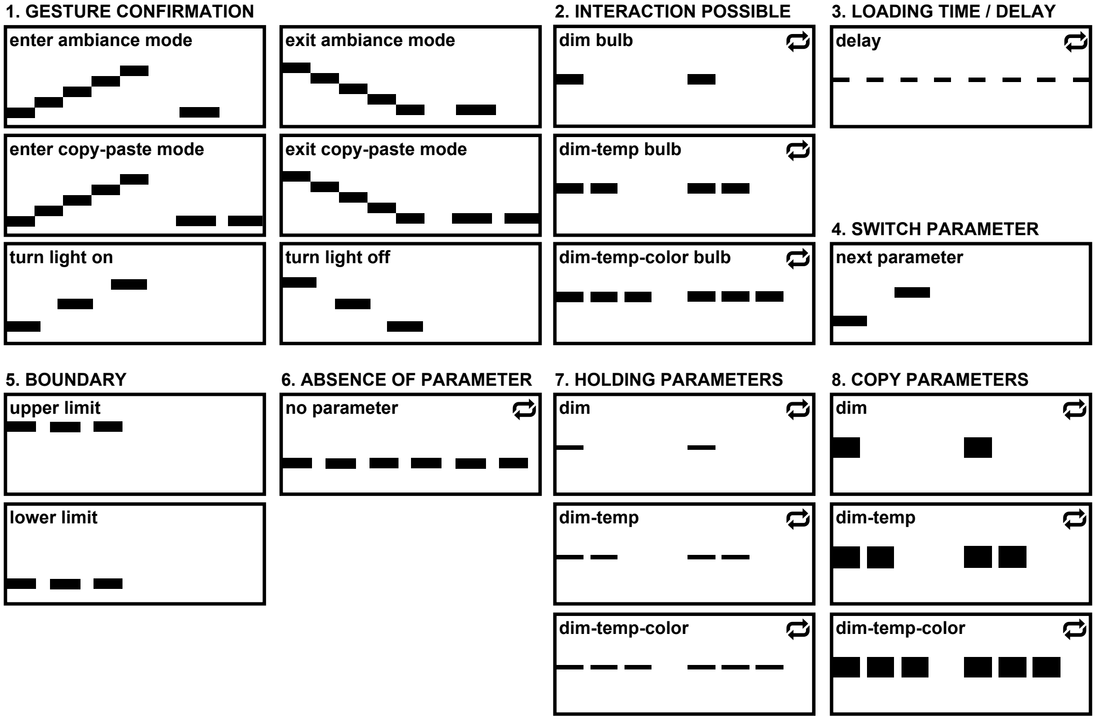

Figure 5: Visual representation of tactile icons used in gestural language.

Frequency. Frequency is used to intuitively communicate the meaning of a tactile icon. In a sequence of pulses, an increasing frequency is used to indicate a positive action, such as taking a step forward or starting something, while a decreasing frequency is used for the opposite effect. Entering or leaving a mode, for example, is indicated with a sequence of five vibrations of increasing or decreasing frequency, respectively (see (1) in Figure 5). Frequency is also used to naturally indicate parameter boundaries in *ambiance* mode, with high and low frequencies indicating the upper and lower limits, respectively (see (5) in Figure 5). Finally, a low frequency is used to communicate 'heavy', important messages that need to be clearly communicated. For example the vibrations that indicate entering or exiting modes are longer, clearly-separated, low-frequency pulses (see (1) in Figure 5).

Intensity. The intensity of vibrations is used to distinguish between background and foreground signals. Weaker vibrations are used for background information that is useful, but that could easily become distracting or irritating as the user focuses on other tasks. While holding parameters in *copy-paste* mode, for example, low-intensity vibrations are repetitively felt to remind the user of the current mode and number of parameters copied (see (7) in Figure 5). Once a target light bulb has been identified and pasting is possible, the intensity of the vibrations increases (see (8) in Figure 5).

Artificial versus metaphorical meaning. The tactile icons are designed to create meaning either artificially or metaphorically. The meaning of a single vibration (*ambiance* mode) or two vibrations (*copy-paste* mode) at the end of a gesture confirmation icon is, for example, artificial and arbitrary, and must be learned by practice (see (1) in Figure 5). Some other messages however, are based on known phenomena. An example is the delay icon, with short, fast and low amplitude signals that resemble a ticking clock (see (3) in Figure 5). Similarly, boundary icons consist of a rapid sequence of short pulses that resembles an object bumping into a solid surface (see (5) in Figure 5). Moreover, reaching the highest value is indicated with a high frequency signal, while the lowest value is indicated with a low frequency signal. The signal intensity difference in *copy-paste* mode mimics other signals that increase in intensity when an object is detected, such as a metal detector's sound.

Continuity. Several tactile icons are repeated continuously while interactions remain in a certain state, as indicated by a 'repetition' mark in Figure 5. For example, a sequence of vibrations is felt as long as the user points at an interactive bulb (see (2) in Figure 5).

DISCUSSION AND FUTURE WORK

The use of a high-fidelity prototype in virtual reality proved useful to develop and validate our concept, but nevertheless presents some limitations. Most importantly, the prototype requires users to hold a controller in their hand and press buttons in order to trigger gesture recognition. This differs significantly from the intended use of the gestural language with free-hand gestures, and proved initially confusing for users. Technical limitations also limited our ability to use the most intuitive gesture in some situations. Copying a bulb's parameter using a grabbing gesture, for example, seemed intuitive but could not be implemented quickly with the selected hardware/software platform. While these limitations affected the design of the gestural language and its intuitiveness, this solution was sufficient to experiment with the use of haptic feedback at different steps in the interactions.

While our informal evaluation of the prototype has provided some valuable insights, more complete experimentation with naive users remains as critical future work. We expect this experimentation to confirm our preliminary findings regarding the value of haptic feedback in this gestural language, but to also provide valuable information for possible improvements.

We finally foresee interesting work to further consider the impact of delays and errors in the gestural language, and particularly on the value of haptic feedback in that context. We would also like to consider the applicability of the gestural language and its haptic feedback in interactions with other connected devices, such as smart speakers.

CONCLUSION

Haptics can be integrated in an everyday experience in an understandable and seamless way by carefully investigating when the user is in need of information. This involves rapid prototyping and user-centered design to explore each possible step in an interaction. Haptics may prove particularly useful in cases where the system fails or the user makes an error. At such moments, information via haptics can prevent confusion. Haptics should be used sparsely to keep every message clear. Ideally, haptic messages should deliver universal sensations that are based on known phenomena, such as GUI interactions or real-world events. With an increasing amount of technology around us, haptics seems a promising way to provide information about this technological environment. On the one hand, it has the power to subtly deliver personal messages and sensations that do not necessarily require a person's full attention. On the other hand, it can actively provide information that the user needs right in the moment and that take up more attention.

This work has taken a look into the near future and explored possibilities for haptics in it. In a future where technology surrounds us, haptics could aid in navigating through this new environment without having to look at screens. This work has shown that rapid prototyping and user centered design are good approaches to reveal opportunities for haptics. Step-wise analysis of an interaction, regarding the user's needs, reveals several ways in which haptics can make all sorts of things clear. By prototyping haptics and actually building interactions with them, a feeling for the added value of haptics can be created. Moreover, haptics can be evaluated in the full context of a user product or interaction. This often involves an interplay between user actions and feedback. Feedback can come in different forms, and possible interactions from the user with the system are countless. By concretizing this complex interplay between the product and the user, opportunities for haptics can be found and evaluated in an efficient and representative way. This work contributed to the field of haptics research by exploring concrete opportunities for haptics in the near future. The work proposes rapid prototyping and user centered design to efficiently dive into the complex interplay between users and their technological environments. This work builds towards a future in which interaction with the technological environment happens as seamless and intuitive as any other everyday action. Haptics will play a large role in this, given their power to provide feedback and information in an unobtrusive yet clear way.

REFERENCES

[1] S. Brewster and L. M. Brown. Tactons: structured tactile messages for non-visual information display. In *Proceedings of the fifth conference on Australasian user interface*, pages 15–23, 2004.

[2] H. Culbertson, S. B. Schorr, and A. M. Okamura. Haptics: The Present and Future of Artificial Touch Sensations. *Annual Review of Control, Robotics, and Autonomous Systems*, 11225(1):1–12, 2018.

[3] M. Grunwald. *Human haptic perception: Basics and applications*. Springer, 2008.

[4] A. Hettiarachchi and D. Wigdor. Annexing reality: Enabling opportunistic use of everyday objects as tangible proxies in augmented reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1957–1967, 2016.

[5] G. Jansson. Two recommendations for tactile/haptic displays: One for all kinds of presentations and one for the development of haptic displays. In *Proceedings of the Conference on Guidelines on Tactile and Haptic Interaction*, 2005.

[6] R. S. Johansson and J. R. Flanagan. Sensorimotor control of manipulation. In *Encyclopedia of Neuroscience*, volume 8, pages 593–604. Elsevier, 2009.

[7] J. F. Kelley. An iterative design methodology for user-friendly natural language office information applications. *ACM Transactions on Information Systems (TOIS)*, 2(1):26–41, 1984.

[8] S. J. Lederman and R. L. Klatzky. Hand movements: A window into haptic object recognition. *Cognitive psychology*, 19(3):342–368, 1987.

[9] K. MacLean and M. Enriquez. Perceptual design of haptic icons. In *Proc. of EuroHaptics*, pages 351–363, 2003.

[10] C. Moussette. *Simple haptics: Sketching perspectives for the design of haptic interactions*. PhD thesis, Umeå Universitet, 2012.

[11] I. Poupyrev, N.-W. Gong, S. Fukuhara, M. E. Karagozler, C. Schwesig, and K. E. Robinson. Project jacquard: Interactive digital textiles at scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, page 4216–4227, New York, NY, USA, 2016. Association for Computing Machinery.

[12] D. Ternes and K. E. Maclean. Designing large sets of haptic icons with rhythm. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pages 199–208. Springer, 2008.

[13] M. Weiser. The computer for the 21st century. *ACM SIGMOBILE mobile computing and communications review*, 3(3):3–11, 1999.

[14] A. Zenner and A. Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE transactions on visualization and computer graphics*, 23(4):1285–1294, 2017.