Sensory Augmentation Devices: Insights from a Research Through Design Process

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Abstract

Sensory augmentation devices are designed to innovate the human sensorium. This is achieved by designing real-time sensor-to-sense mappings. How to best facilitate learning to make sense of the world with such devices, however, is an open scientific and design problem. For a long time, sensory augmentation devices have been seemingly promising. However, very few real-world applications have been designed and produced. In this work-in-progress, we present the process and learnings of an ongoing experiment using custom tactile interfaces to facilitate learning. We propose a 6-step design guideline and present the possibilities and difficulties of working with tactile sensory augmentation devices in an aesthetic context.

Keywords

Learning, Self-Experimentation, Sensory Augmentation, Tactile Interfaces, Design Research.

Introduction

Sensory augmentation devices are physical interfaces designed to integrate within a user's sensorium such that their functioning and experience is similar to their biological sensory apparatus, yet extends its capabilities [1][2]. Unlike neural interfacing, which seeks to achieve augmentation by directly hacking into the nervous system [3], sensory augmentation is largely non-invasive [4]. This is achieved by designing so called sensor-to-sense mappings, where artificial sensors that capture signals that our biological sensory apparatus cannot (e.g., electromagnetism), are mapped in real-time to signals our biological sensory apparatus does respond to (e.g., tactile vibrations on the skin) [5]. By making sense of the world around us through a combination of these kinds of artificial and biological senses, and through prolonged exposure [6], the sensory augmentation becomes part of our everyday experiences, and ultimately integrated in its user's sensorium [4].

Experimental research suggests that sensor-to-sense mappings can be designed to augment a user's ability to make sense of their environment in novel ways [7]. Exteroceptive augmentations have expanded the ability to perceive more of our external environment, e.g., by a north sense that emerges from experiencing vibrations on the skin indicating where the earth's magnetic north is [4]. Proprioceptive augmentations have augmented the ability to sense the position of our own bodies within space, e.g., using a body movement to tactile feedback mapping can improve control over postural sway [8]. Interoceptive augmentations have enhanced people's ability to sense the signals their own bodies emanate, e.g., through enhanced sensing of changes in our neuroendocrine system via a pupil size-to-sound mapping [9][10].

One major challenge, which we begin to address in this work-in-progress paper, is the substantial time and effort investment that is needed to learn to make sense of the world through a sensory augmentation device [5][13].

The work-in-progress: A series of prototypes for developing design guidelines

Design decisions made about the sensor-to-sense mapping are critical for the user's ability to learn to use sensory augmentation devices. Furthermore, the construction, placement, and type of stimulus as well as the presence of salient features of a sensory augmentation device are crucial in this learning process. Over the past years we designed, built, and tested multiple hardware interfaces that gave us valuable insights in the transfer of information in vibro-tactile interfaces and seek for the possibilities and difficulties in sensory augmentation devices. We used low resolution information transfer devices to keep the technical complexity manageable and focus on the design and decision-making process.

To this end, we used research through design (RtD) process to construct a series of prototypes to investigate three things: (1) the relationship between complexity of a signal and the transfer of information, (2) the importance of a strong relationship between the set information (e.g. sensory or numerical) and the stimuli and (3) the role of physical properties of a sensory augmentation device.

Design Making Process

Different from most research methods, a design process is often messy and intuitive [17]. Prior to involving a target group, prototypes are mostly tested by the designer and their direct surroundings to check for overall robustness.

For this study most experiments have been conducted by the researcher himself in order to find flaws, possibilities and to test the effectiveness of a specific prototype. Data was only collected from a broader group of participants when a specific question needed to be answered, usually in a comparative study.

As a researcher and designer with a hands-on approach, it is important to understand the design making process of physical sensory augmentation devices. Not only from a technical point of view but also regarding sensor to actuator mapping, salient actuator features and sensor and actuator placement.

A series of 7 devices were designed and prototyped using a 6-step design guideline (figure 1) to get personal insights in this process. Each prototype was based on the previous one.

Using a RtD process, we developed and used 7 prototypes (figures 2, 7). All these prototypes have in common that we used low resolution information transfer so the interfaces could be tested in a situated manner. Many studies have shown that for high resolution interfaces [18], information transfer is relatively high, but mostly do so in a controlled lab environment. The iterative design process enabled us to make quick alterations based on short tests. The designer/ researcher used these interfaces mainly himself and despite the bias in self experimentation, for interface design it has the benefit of short iterative steps and easy trial and error test phases.

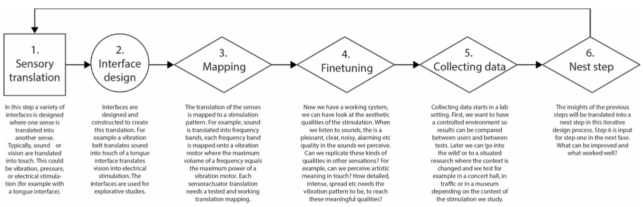


Figure 1: The design process of interface development: A six step process.

Tactile Vision

Following this six-step design process, the first experiment pertains a very low-resolution Bach-Y-Rita-like device (figure 2). We wanted to investigate how visual stimuli are interpreted when presented in a tactile way.

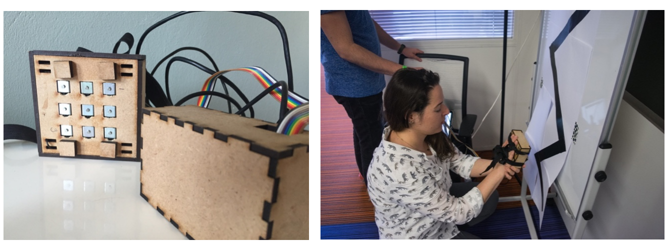


Figure 2: A low-resolution portable interface with 9 motorized pixels using solenoids and a camera input. This interface was flexible in placement.

Lessons Learned

Based on an evaluation of this device and the participants we found that low resolution motorized pixels can work well when sensorimotor contingencies are retained. For high resolution motorized displays (Bach-Y-Rita et al, 1969) this might not be necessary. Considering that this interface cannot replace vision, it has little benefits to use it as an augmentation device because of our reliance and dominance of our vision. Enlarging the resolution and breaking out of the set vision mapping interface might open up some new applications.

The Artistic Potential of Tactile Vision Interfaces

After evaluating the previous interface, we found that interpreting a 3x3 grid display is very difficult regardless of how the stimulus is presented, visually or tactile. This was probably due to the high resolution of our vision that our brain is used to. Also, the limitations of a 3x3 grid restricts most translation to image like interpretations. In our next iteration (figure 3), we removed the camera input and broke down the grid into individually addressable and flexibly placeable pixel. Moreover, we added intention instead of binary on/off actuators. Our next goal was to see how artist and scientists could generate and share ideas using sensory augmentation devices.


Figure 3: During a workshop, students with different backgrounds used this sensory augmentation device to generate, discus and share ideas about sensory augmentation.

Lessons Learned

This prototype gave us insight in how artists and designers can work with sensory augmentation devices in an early ideation stage. However, as a device that tells us something about information transfer it was too limited since there was no meaningful relation between input and output. In a next step we would like to focus more on information transfer such as in the previous interface.

Simple vs Complex Stimuli

Evidently, simple stimuli are easier to process than complex ones. However, they give us less information about our environment which might make it more difficult to use this stimulus for sensemaking purposes. In our next experiment (figure 4) we created (or used of the shelve) and tested 3 different devices in small iterative steps.

Lessons Learned

We found that a single stimulus works better than a double stimulus. In this case we must take into account that both stimuli in case of the double stimulus gives the same piece

Figure 4: Three different interfaces were used in a blindfolded experiment to recognize 3-dimensional cardboard shapes. All three devices translated distance into vibration intensity. Left: Hip-worn double device. Middle: Hand-held double device. Right: Hand-held single device.

of information, distance. Furthermore, we see that handheld devices work better than devices worn on the hips.

To get a better understanding of the processing of these signals we want to elaborate on this for our next experiment. Instead of using handheld single actuator devices (which would be the obvious way to proceed based on these outcomes), we want to proceed by elaborating on the hip worn and multi actuator devices to better understand the processing principles. This is also driven by the limitation in information for a single actuator device and the limitation of hand-held devices because they occupy both hands.

Linear vs Symbolic Information Representation

One pattern that emerges in the literature is that a mapping can be continuous, i.e. the mapping continuously translates the sensor data into sensory information, e.g. decrease in distance yield more intense tactile stimulation [19], or categorical, i.e. a mapping designed to detect specific (combination of) sensor signals that triggers an arbitrary sensory stimulus, e.g. signals that together capture one emotion, over another, trigger a predefined actuator [20]. In terms of learning, these mappings produce varying results under different situational demands. In [2], learning a continuous magnetic north-to-tactile vibration device mapping was facilitated by daily 90+ minutes training for 7 weeks. Whereas in [19], learning to use a continuous distance-to-vibration intensity mapping happened after only a few interactions with the environment. Findings such as these raise questions about when and why continuous and categorical mappings can facilitate learning.

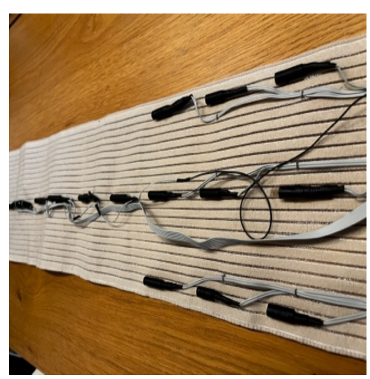
It might be that a continuous mapping is quickly learned by association with pre-learned cross-modal concepts [21]. When moving around blindfolded with a distance-to-tactile vibration device [19], an unexpected bump into a wall (prediction error), while the vibration's intensity had been increasing, creates a direct association between distance (less distance) and the salient vibration intensity (more vibration). A mapping consisting of arbitrary categories, e.g., when different distances actuate vibrations at arbitrary locations on the skin, could also enable people to learn to navigate space. However, the inability to quickly associate the mapping with a pre-learned cross-modal category, may well lead to more difficulty learning the meaning of such mappings initially. Continuous mapping would appear advantageous here.

When taking sensory augmentation devices outside the lab and 'in situ', however, new challenges arise [13][15][16]. The signal-to-noise ratio reduces due to a multitude of stimuli that affect the sensor measurements, the signals of interest are more complex and varied than under lab conditions, and the sensory augmentation itself might interfere with the biological senses which we also need to rely upon. Using predefined categories, where signal processing is used to categorize increasingly complex and varied signals into distinct categories, can prevent the need of people to do this categorization themselves, e.g. [5]. Here, arbitrary categorical mappings might facilitate learning more than continuous mappings. Despite their difficulty to learn, these mappings could facilitate learning because the technology is assumed to handle some of the challenges introduced by varying signal-to-noise ratios. Then again, people will likely derive a meaningful categorization of signals themselves as part of their learning process [22]. It is not known whether learning an arbitrary categorization done by a designer, compared to a natural process of categorization by the user using a continuous sensor-to-sense mapping, facilitates learning more when the signal-to-noise ratio of an augmentation reduces.

Despite the centrality of sensor-to-sense mappings to how people learn to make sense of their environment with a sensory augmentation device, relatively little is known about what, when and why different kinds of mappings facilitate learning [13][15]. The aim of the present work-in-progress is to begin to shed more light on this open scientific and design problem. Therefore, we seek to give a preliminary answer to the following research question: How do continuous and categorical mappings facilitate learning?

To study this we translated sound (harmonic frequencies) into a nine-pixel vibration representation (figure 5).

We conducted an experiment in which a participant was confronted with a random frequency (there were 9 different frequencies). This was either presented to the participant as a continuous or symbolic pattern. After 5 pairs of audible frequency with corresponding vibration pattern, the 6th frequency was only presented as a vibration. The participant than had to guess what frequency was presented (figure 6).



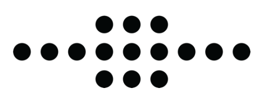


Figure 5: Top: pattern of the motor placement. Bottom: A elastic waist band fitted with 16 vibration motors. The motors are placed in such a pattern that they can be used both as a 3x3 grid and a 9 in a row.

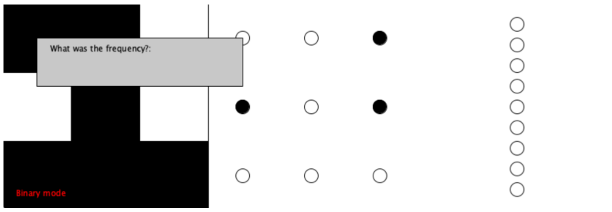


Figure 6. This interface allowed participant to enter an estimated frequency after a random frequency was presented 4 times with sound and vibration stimulus and the fifth time with only the stimulus. Participant had to fill in the estimated frequency of this fifth instance and proceed to the next trial.

Lessons Learned

We noticed that it was much harder to guess the frequency in the symbolic representation than in the continuous representation because there is no relationship between the signal and the pattern. The next step would be to keep using the continuous representation but with a more complex signal.

Vibration Supported Speech

A natural audible signal is very complex. Meaning, emotion, timbre etc are alle included in this vibration pattern. Breaking this up in 9 different vibrations will not cover the complexity of the signal. Still, there is evidence that a natural speech sentence can be distorted a lot and still people can make sense of it. Especially when they first heard the sentence without distortion [23]. We want to know how information of a vibration pattern based on speech can help to understand a sentence.

We noticed that with the current setup and hardware it is very difficult to exactly synchronize the motors and audio correctly. Initially we used Arduino and processing for audio analysis and motor handling. For the audio analysis we switched to Pure Data in order to have more possibilities to analyze and distort the audio. The timing and communication between the three platforms means that the synchronization is very difficult. We also found that without (almost) perfect synchronization it is almost impossible to process the information in a meaningful way such that the meaning of the distorted sentence will become evident sooner.

For this experiment (figure 7) we used the belt of the previous experiment but with only the 9 vibration motors in line. There was also a turning knob with which a participant could alter the amount of distortion of an audible sentence. The third part of the interface was a GUI where the participant could see sentences and click on a specific sentence that he/she thought was the correct sentence. Also, there was feedback on the screen about the correctness of the input.

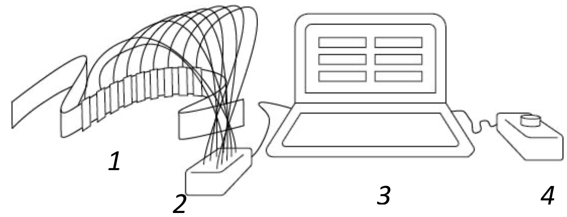


Figure 7. The setup of the experiment consisted of the physical belt with vibration motors (1) including the electronics box to control all the motors (2). There was a screen-based interface which produced the randomly picked and distorted sentences and input fields (3) and the was a turning knob to adjust the distortion (4).

Lessons Learned

We found no significant difference between recognizing the sentences with or without vibration assistance. We noticed that the lack of context (random sentences without contextual frame or facial expressions) might not be the best test case. Therefor the next step would be to take it out of the lab context and do the experiment in situ.

Future work

Based on the lessons learned three directions for future work seem particularly promising. Firstly, we found the relationship between input and output and the mapping is crucial for optimal information transfer. This supports earlier findings about sensory contingencies.

Secondly, previous research on how people learn to make sense of their surroundings with a sensory augmentation device has largely been quantitative [13][15]. However, the research logs containing the researcher's personal experiences also hinted upon a novel perspective on learning continuous sensor-to-sense mappings. Which is that salient differences between actuators plays a key role in learning, possibly by supporting users to learn meaningful categories. Further qualitative research on a larger scale is needed to confirm and expand on these findings.

Finally, the finding that reduced signal-to-noise ratio deteriorates learning when using the continuous mapping suggests that further design research is needed. This to develop interfaces that are more robust to the challenges imposed by using sensory augmentation devices 'in situ' [13][15][16]. This, e.g., requires scaling up the resolution of the interfaces to deal with increasingly complex stimuli from the environment [14].

Furthermore, it may well be that under those conditions, and with prolonged exposure [6], categorical sensor-to-sense mappings will become beneficial [5][20]. Future research is needed to explore this further. This future work will help to better understand how people can best learn to make sense of their environment by using sensory augmentation devices - with the ultimate aim of enabling designers to help achieve sensory augmentation's potential for innovation.

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