Expressive Wearable Sonification and Visualisation: Design and Evaluation of a Flexible Display

Kirsty Beilharz[1], Andrew Vande Moere[2], Barbara Stiel[3], Claudia Calo[1], Martin Tomitsch[2], Adrian Lombard[2]
[1] UTS DAB Sense-Aware Lab CB06.50.48, NSW 2007 Australia
[2] Faculty of Architecture, Design and Planning, The University of Sydney, NSW 2006 Australia
[3] Research Group for Industrial Software (INSO), Vienna University of Technology, 1040 Vienna, Austria
kirsty.beilharz@uts.edu.au

ABSTRACT
In this paper we examine a wearable sonification and visualisation display that uses physical analogue visualisation and digital sonification to convey feedback about the wearer's activity and environment. Intended to bridge a gap between art aesthetics, fashionable technologies and informative physical computing, the user experience evaluation reveals the wearers' responses and understanding of a novel medium for wearable expression. The study reveals useful insights for wearable device design in general and future iterations of this sonification and visualisation display.

Keywords
Wearable display, sonification, visualisation, design aesthetics, physical computing, multimodal expression, bimodal display

1. INTRODUCTION
The idea of the folding metaphor to represent data visually casts back to mythological origins of giving voice to fabrics and the tradition in drapery and arts of creating folds to signify embedded meanings. Our project explores the inter-textuality and inter-modality of drapery (found originally in painting) as the context for sonic drapery or sonification of material in motion and a novel wearable visualisation able to sense and externalise environmental data about the wearer using a deliberately subtle and ambiguous representation metaphor. Folds in fabric, clothes, materials that were historically painted and drawn, as well as folds in the house (sheets, indentations in chairs, cushions), folds in the geological landscape and layering of contoured stone each convey traces, remnants, memories or an embedded history of events or people that have led to the present state. The representation or physical state of the folds captures the immediate past and the present and is less ephemeral than a non-cumulative real-time display only capable of representing transient information at the moment it occurs. The physical representation captures a blend of immediate real-time response and an analysis of cumulative historic transactions sampled over the previous ten-minute interval. For example, a display that responds to the level of motion activity in the moment does not reveal anything that is not immediately obvious to the user but it may be interesting to reflect on levels of activity, social interaction, noise levels over a period of time and in comparison with the sonification of the previous interval, observing change. These kinds of sensed data correlate to more subjective, socially relevant experiences, such as: being in a noisy place, meeting friends, sleeping, relaxing, playing sport, etc.

The first iteration of the folding wearable expression took the form of felt pouches that revealed coloured layers as slits were stretched open by muscle wire (Figure 1, left) in response to social interactions. Some technical modifications led to a second iteration that added sonification capability in the sensing microphone, computation and rendering through a small on-board synthesizer and speaker as well as reduced heat emission of the muscle wires and power source. A significantly smaller battery and more efficient circuit design were implemented to overcome weight and temperature concerns that affected the user's comfort and mobility. The power source, visualisation, and sonification were integrated into a single encapsulation material design, worn over the shoulder, with no external wires or controls (Figure 1, right).

The first part of this paper describes modifications in design to address some ergonomic and information mapping issues raised in the first iteration of this folding display and motivations behind the device design. The second part examines the responses of a small group of subjects and how the designers' intentions transpired into real everyday experience. In considering this analysis and user feedback, we conclude with design modifications necessary for future iterations of this device and also considerations for wearable expression, particularly in the realm of information representation (sonification, visualisation, etc.) that may be helpful in the design of wearable expression more broadly.

2. WEARABLE DISPLAY
The wearable visualisation and sonification display represents live sensor-based information (processed against cumulative time-based calculations) to the wearer and people in her/his immediate vicinity, with the aim of augmenting social interaction and interplay. Information is represented through physical as well as auditory means with an emphasis on the aesthetic integration of the display to support wearable expression. Because the wearable display crosses over the territories of clothing, fashion, adornment, decoration, expression, individuality and intimacy of a kind of body extension, human qualities, emotive qualities and the device is a form of expressivity (revealing a bit of self through the externalisation of lifestyle) these aesthetic considerations are fore-grounded. We hypothesised that users may attribute greater importance to appearance, sound, aesthetic materiality over utility and familiar technologies in a wearable display.

2.1 Physical Visualisation
Introducing the concept of analogue representation into the digital mobile/wearable computing domain, we attempt to preserve the affordance of the physical medium by avoiding the

Figure 1. Iteration 1 - felt pouch revealing coloured slits in response to motion (left; photo by Monika Hoinkis) and iteration 2 - integrated power, sensors and analogue visualisation (right; photo by Kirsty Beilharz).

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anti-ubiquitous communication crutch of a pixel-based screen. Instead of the common integration of the desktop metaphor in many miniaturised devices of today, we found it important to reinterpret the portable display medium and to try to return some of the tangible, emotive, yet subtle and semantic, expressive attributes of analogue media in order to gain the power of self-representation, expression, reflection and control of privacy.

We argue that purposely avoiding common pixel-matrix representations increases creative freedom, at least in terms of natural affordances, aesthetics and the deliberate exploitation of ambiguity in design [5]. What a normal pixel-less display might lose in objectively measurable resolution, is replaced with a richer and more intriguing user (and audience) experience when being exposed to it. By implicitly inviting people to interpret an aesthetically pleasing physical display, emotional involvement is created without pressure nor preconceived expectations.

For example, Kodama and Takeno's *Protrude, Flow* [6] and Frey's *Snoil* [4] are physical displays that use the same medium, *ferro-fluid*, a liquid that becomes strongly polarised in the presence of a magnetic field. Whereas one ferro-fluid "display" is based on simulating an underlying 10x10 pixel-matrix, the other is specifically exploring the material's physicality and behavior, to create abstract, unpredictable shapes that require intense and emotional involvement of the viewer. The resulting pixilated and extruded outcomes utilise very different techniques expressed through an identical presentation medium.

We try to elicit an emotional response and imply expressive qualities through folded fabrics and dynamic textile design. Our display method is not meant to convey precise information to the public, but rather aims to simulate a subtle form of visual expression that is not intruding the wearer's physical or emotional presence. This ambiguous representation highlights the user's own responsibility in deriving a suitable interpretation [13].

2.2 Sonification

Sonification uses non-speech sound to represent data, i.e. it is auditory encoding or auditory graphing, primarily for informative purposes, such as scientific monitoring. We consider here the re-contextualising of abstract sonification for wearable computing. The research also queries the interaction between auditory and visual display in this bi-modal scenario, the abilities of sound to reinforce the information being shown in the visualisation and the potential for visualisation to capture a "permanent state" or lasting memory condition of system status that triggers a momentary audio event. Sounds may be ephemeral, coming and going, stored only in the computational and human memory, displaying only for a matter of seconds but their message can communicate either immediate information or a summary of the preceding period in a short, efficient burst.

In consideration of the fact that sound influences social interactions, behaviour, and is subject to etiquette, the sonic representations of behavioural data are emitted only periodically every 10 minutes in a conflated burst whose attributes represent a concatenation of events and time/activity analytical calculations in the preceding interval of wear. Distinctive and clearly identifiable sound specimens were selected to represent data captured in the user's immediate environment.

The sonification was new to the representation in the current iteration of the hardware device. It affords a new perspective because it can be peripherally absorbed without requiring the user to view the device directly and thereby operates in a partially ambient way.

2.3 Aesthetics for Wearable Expression

The wearable display acts as an interpretation of the nature of one's individuality by interpreting environmental features captured through parallel, real-time sensor readings. The wearable display is capable of revealing an historical view of the contextual states to the wearer's environment and its inhabitants by using folding as a dynamically altering form of visual and auditory self-expression. Thus, it travelled with them to work, social encounters, outdoors, in individual home contexts and highly interactive crowded spaces, capturing through proximity, motion and sound-sensing attributes of both the wearer and her/his environment.

We coin *wearable visualisation* as a research field that conceptually relates to "wearable computing", "smartwear" and electronic fashion technology (e-fashion). E-fashion typically addresses issues ranging from embedded system hardware and software, to high-tech reactive electronic fabrics. However, instead of focusing on sensor and signal analysis, real-time context recognition or hardware development and miniaturisation, wearable visualisation is specifically concerned with the visual and auditory communication of information to the wearer, or any people present in the wearer's physical vicinity, in a truly pervasive way.

Some research projects have already implemented simple forms of wearable visualization displays interpreted as notification interfaces [7]. Other creative initiatives have explored more artistic application purposes, while investigating radically alternative technical means to convey sensor data publicly on or around the human body. These approaches tend to experiment beyond the use of simple pixel-based displays, for instance by utilising subtle forms of LED lights [2], so-called 'e-textiles' [8], electroluminescent wires (e.g. [11]), thermo-chromatic inks, shape-changing materials such as shape memory alloys (e.g. [3]), or even air inflatables (e.g. [1]).

Conceptually, a wearable visualisation can be interpreted as a fashionable accessory that augments *self-representation*, similar to jewellery or high-tech gadgetry. Such objects are often deliberately chosen to reveal, or hide, personal aspects, such as one's mood or social status, to the outside world. However, the sensor readings that are externalised by the visual and auditory display cause this peculiar form of self-representation to become completely autonomous and inherently uncontrollable and uncensurable. In contrast to everyday modern life, during which people have the inherent power to make their fashion choices, a wearable display is capable of altering its form over time by a computational process that stands independently from the wishes and desires of the wearer. Normally, people contextualise their choice of

clothes based on their desired self-expression, which in turn is determined by external or contextual factors such as planned activities, subjectively perceived moods or personal preferences. These personal choices often are motivated by emotional reasoning or individual human motives, for instance whether the wearer wants to reveal her actual state to others (e.g. black when sad), or, in contrast, wishes to influence her personal condition by wearing a seemingly conflicting fashion choice (e.g. bright red when sad). In essence, this means that a wearable display counteracts the natural ability to "pretend", to deliberately choose conflicting messages between the fashion statement and what an objective observer, or an ideal faultless, computational system considers to be truthful based on its sensor readings.

2.4 Technical Execution

The sensing part of the wearable expression captures ambient noise levels and executes a time-based concatenation using a small microphone; a light sensor whose purpose is to distinguish between an indoor or outdoor environment; and multi-dimensional gyroscopic sensor to capture physical activity. The programming side was used to examine this data as a factor of time, e.g. amount of activity and whether that represents an increase or decrease, whether sustained or momentary, and comparative ambient noise levels. The Soundgin synthesiser and small 5V sensors were used in conjunction with an Arduino microprocessor and integrated into a custom board that operated the controllers and output. Output consisted of the sound speaker and moving fabric slits revealing different mounts of underlying colour. Muscle wire (extremely fine conductive thread that contracts when charged with electrical current) was used as the mechanism to pull the material, counter-released by elastic threads for returning openings to their original state (because there is no "undo" operation for muscle wire). A consequence of this physical construction was its quite fragile nature, acceptable for an interface that does not need to be touched or manipulated by the wearer.

3. USER EXPERIENCE

To evaluate the user's as well as the onlooker's experience of the wearable and sonification display, we conducted a user study that involved a small user group. The methodology pursued aimed to capture the hidden and underlying needs of users in order to develop a product that will best meet the consumers' expectations and desires. The main purpose was to understand users' requirements and impressions and then modify the device to reflect the user's thoughts and satisfy their requests.

3.1 Participants and Methodology

Five participants took part in the evaluation process, including: four students (female: two; male: two; age range 26-40) and one employee (female, age 28). All participants were selected based on their demographics and background, working in an environment that would allow wearing our display for most part of the day and being interested in new technologies and gadgets.

The evaluation participants were asked to wear the foldable display for three days during their normal daily activities. They were also asked to complete a diary in which they captured their responses: what they understood about the visualisation and sonification represented in the display; and the reactions the device provoked from onlookers (e.g. family, friends and strangers) in order to keep track of their interaction with the wearable display.

Users participated in a brief daily one-to-one interview, useful to review their experience with the wearable device. Finally, they completed a questionnaire in which they were asked to describe the device in their own words and to offer tips and suggestions for future iterations. All subjects were fluent using technologies. They were not aware of the device's purpose and they did not receive any incentive for their contribution.

3.2 Results and Discussion

By gathering comments and thoughts from the recruited users, it was hoped to detect critical issues in the system and increase its usability and ergonomics. During the evaluation study, different kinds of qualitative data were collected.

First impressions were collected that bridge the associative gap between wearable devices, fashion and consumers. It is not surprising that some users suggested transforming the wearable system into a fashion accessory. For instance, P1 and P5 recommended making the system similar to a scarf. P2 thought that the device could be a belt. P1 and P3 would like the wearable system to be more colourful and stylish because the neutral or monochromatic device did not appeal to them and consequently they thought it did not fit well with their clothes.

In effect, subjects indicated that merging wearable systems with fashion design (e-fashion) would be strongly effective for both gathering data and revealing information about wearers during their daily activities. Doing that, users could wear the device with greater naturalness and without feeling different from other people. Ironically, this turned out to be quite the opposite view to the designers' hypothesis that an attention-seeking, conspicuous approach might be novel, interesting, evoking curiosity and expressiveness.

Some participants proposed the integration of flashing lights and voice in the wearable system. P3 and P5 suggested that adding lights would achieve greater visibility and recognisability, unwittingly negating the physical analogue display aesthetic intended by the designers. P5 recommended an integrated LCD display.

This response could be the consequence of the *gulf of evaluation*. According to Norman, "The gulf is small when the system provides information about its state in a form that is easy to get, is easy to interpret, and matches the way the person thinks of the system" [9]. Hence, the gulf of evaluation is the difficulty of assessing the state of the system and how well the device supports the discovery and interpretation of that state. In this case, wearers did not seem to accurately perceive and interpret the meaning communicated by the flexible display in sound or visual display.

For instance, P1 wrote in the diary that, according to her, the wearable system was cheerful around food because it started to sound only when she ate. P2 said that it was uncomfortable and difficult to look down at her shoulder to check the slits' movements and consequently to understand their purposes.

Some participants found the wearable display un-ergonomic. Ergonomics refers to making artefacts comfortable and efficient, playing to the strengths, not stressing the body part interfacing with them. The most perfect ergonomic wearable device is something that the user does not notice on her/his body. For example, P2 found the device too big and uncomfortable on her shoulder because she had to be constantly careful of the fragile construction and also because the evaluation coincided with the oncoming hot season. She thought that the sound was too close to her ear [or was intrusive]. P3 said that the folding display device was difficult to wear because it slipped around too much: hence, if the

wearer wants to pick up something, it may easily fall off or slide out of position.

Most of participants complained about the impossibility of controlling the sonic volume of the device. P2 reported that the device's sound may distract the user's attention, e.g. while studying or researching. She said that it was embarrassing/inappropriate in the library. She would have preferred to have a button on the device to switch off the sound in some situations. [Actually it did have an "off" switch that each participant was shown]. P4 suggested integrating a button enabling the user to control the volume because he was bothered when the device sounded while he was working. P5 avoided going to a café because she was embarrassed by the sound of the device. She said she got startled every ten minutes when it sounded. By contrast, P3 found it impossible to hear the device's sound in a noisy location. He suggested a volume control that responds to the ambient noise.

In summary, evaluation participants asked for a device more flexible in its behaviours, which can be altered at will, allowing its use in a variety of situations.

This research has helped us to not only understand users' needs but also onlookers' behaviours and reactions. P1 said that the device was humorous when she talked with her friends because its sounds created a new topic of conversation. P4 had the same opinion. In fact, he said that the device was a good way to start a conversation with familiar people because it generated a new topic to discuss. P3 said that the device increased the likelihood of interaction with strangers because it provokes questions from onlookers and it can be interpreted in a joking, light-hearted way. The device was not recognised by everyone with whom the participants came into contact. Of all the onlookers who noticed the device, none understood its role/behaviour. As P1 reported, someone thought it was a toy and other friends asked if she had received an injury to her shoulder.

Overall, all participants and onlookers encountered difficulties in understanding the wearable device's purpose. P2 told the researcher that, according to her, the device is designed to give the same sound when the wearer does the same thing after a long time. P4 tried to guess the system's function, answering that apparently it could be a temperature sensor. P5 was vague and disappointed with the device; stating only that it reacted to the body in some way.

4. FUTURE DIRECTIONS

On the whole, the obtained data indicates that the foldable display requires further design improvements that draw from e-fashion, ergonomics and customisation, in order to communicate a stronger affordance to users and limit the gulf of evaluation [9]. There remains a significant gap between the expectations/aspirations of the designers and relative conservatism of expectations of users who generally preferred to liken the device to familiar display methods and explicit representations. Analogue, physical and subtle display aesthetics are not intuitive or easily semantic and remain more difficult to appreciate. It seems that the body-worn aspect influences users strongly to desire a fashionable, customisable, changeable and controllable device. Greater contextual awareness or intelligence on the part of the device, able to respond to different noise levels and social contexts would be a major improvement. The differences between designers' intentions and users' expectations or satisfaction corroborates the value in multiple iterative user evaluation studies throughout the prototyping development, especially as this research is trying to break into a new medium of expression converging informative and sociable, aesthetic and fashion principles in a single device. As wearable expression is clearly hugely subjective, perhaps the best approach is to emphasise customisability, configurability and greater user intervention in the sonification and visualisation wearable device.

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