ExoBuilding – Breathing Life into Architecture

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ABSTRACT

ExoBuilding explores the novel design space that emerges when an individual's physiological data and the fabric of building architecture are linked. In its current form ExoBuilding is a tent-like structure that externalises a person's physiological data in an immersive and visceral way. This is achieved by mapping abdominal breathing to its shape and size, displaying heart beat through sound and light effects and mapping electro dermal activity to a projection on the tent fabric. The research is positioned in relation to previous work and the iterative development of ExoBuilding from to-scale to full-size prototype is described. The design process, feedback gathered alongside and observations allow the discussion of wider issues: the different scales possible, the temporal nature of the data, ownership and ambiguity of that data, ranges of control and the aggregation of data in a building context. This leads to the presentation of directions for future research at this exciting boundary between Architecture, HCI and medical science.

Keywords

Physiological Data, Biofeedback, Adaptive Buildings, Iterative Prototyping

Classification

J.5[COMPUTER APPLICATIONS]:Arts and Humanities --- Architecture

INTRODUCTION

Over the last decades, various initiatives spanning the disciplines of Architecture, Engineering and Computer Science have explored how to design buildings specifically for flexibility, interactivity and reactiveness. Sometimes this is concerned mainly with providing flexible infrastructure that allows adaptation over the long term [12]. More commonly, control technologies are being employed to be able to respond to various sets of data. Environmental controls for temperature, lighting and shading, as well as technologies for home automation and control are becoming more widespread, with considerable interest in both the architectural and the HCI research community [16, 26].

Beyond this, there are also much more fundamental developments such as smart materials. These have the potential to be used on interior surfaces and external facades, thereby making use of building surfaces as communication media to enable interactivity [5]. Partly inspired by Price's work on reconfigurable buildings in the 1960's [22]and made possible by new technologies, architects are exploring physically dynamic buildings that change shape, orientation and even location [3, 15, 16].

Developments in this area are frequently referred to as Adaptive Architecture, an area that is concerned with buildings that are adaptive to their environment, their inhabitants and objects contained within them. Adaptiveness is achieved by drawing on various types of data streams. Environmental data (internal and external) might control the ambiance of a building; person related data (e.g. presence, identity, activity) might drive the 'permeability' of a place and object related data might be used to configure the infrastructure of a warehouse, for example

Physiological data such as heart rate, skin temperature and respiration might be considered one such data stream and it has seen considerable interest recently alongside the traditional use of obtaining physiological data for diagnostic information in health care. For example, educational and theatrical projects have used physiological data to drive visual displays [1], arts projects like Breathe, have explored how respiration of one person can affect that of another [13] and the nature of Thrill has been investigated through the visualisation and study of physiological data [24, 31]. In addition, the treatment of a wide variety of disorders with a psychosomatic component have been explored through the non-medical process of measuring and conveying a person's physiological data to them, in real-time, commonly referred to as biofeedback [8].

Beyond conveying physiological data, the area of affective computing is concerned with deriving emotional state from physiological data and the use of the state information in building and controlling devices and systems [28]. One key motivation for research in this area is to simulate empathy. A system should be able to interpret the emotional state of humans and adapt its behaviour accordingly, giving an appropriate response to those emotions [17]. More recently, affective computing has seen criticism because of the difficulty of deriving emotional state merely based on physiological data. Cohn argues that “efforts at emotion recognition, however, are inherently flawed unless one recognizes that emotion – intentions, action tendencies, appraisals and other cognitions, physiological and neuromuscular changes, and feelings – is not an observable.” [7]. Boehner et al also argue that methodological rendering of emotional experience in informational terms, though convenient, tends to neglect or obscure a range of considerations that are critical to understanding not just what emotion is, but also what it does [4].

In response to the limitations of substituting objective measures for subjective experiences of emotions, some researchers have responded by eliminating direct representation of emotions altogether. Systems like eMoto [27], Affector [25], and MoodJam [19] explicitly avoid modeling emotions; rather they focus on communicating emotion through ambiguous and evocative aesthetics derived from captured images of users and/or from user-selected parameters. As we describe below, the work presented here must be seen in this context, as it deliberately side steps the automatic interpretation of physiological data and focuses on the relationship between its display and the user experience.

PHYSIOLOGICAL DATA – THE FABRIC OF BUILDINGS

The development of ExoBuilding began with a speculative research question: In which ways can physiological data be related to the fabric of a building? This was posed in the context of previous work highlighted prior, with the emphasis placed on Architecture, where this relationship has not been investigated so far to the best of our knowledge.

The term ExoBuilding then refers to the idea that buildings might externalise some otherwise internal functions of the human body, make them visible and may be support the person themselves, similar to the concept of the artificial Exoskeleton. To explore the design space, an iterative development process was followed, that included sketching and physical prototyping in turn interspersed with review and feedback sessions, a process very commonly adopted in Architecture and Design.

Formulation of ideas

Initially, sketches of general ideas were formulated and a range of different possibilities were explored graphically. The use of heart beat, skin conductance, body temperature, breathing and physical interaction were briefly considered in this context. They were hypothetically mapped to sound output, changes in lighting, sizes in extent of space, environmental temperature and the movement of elements. The following concept sketches illustrate some of these possible mappings (see Figure 1).

Sketch A shows the mapping of an individual’s pulse to audio signals emitted from a sound system embedded into the building. Sketch B details Electrodermal Activitiy (EDA (GSR)), Heart Rate or even Heart Rate Variability mapped to the ambiance of a space; in the case shown here this is achieved through changing the colour of the lighting. In sketch C, the respiration of a person drives the size or form of the building fabric. Sketch D suggests how a person’s body temperature (core and/or skin temperature) might be used to adapt the cooling or heating of a space.

These initial ideas were presented for discussion at an internal workshop centred on the exploration of physiological data in the context of previous work within the theme park environment [24, 31]. From the feedback gathered informally during the session and comparisons to existing background work, it emerged that the most interesting and innovative aspect of the investigation was the mapping of the physiology data to building extent, shape and form.

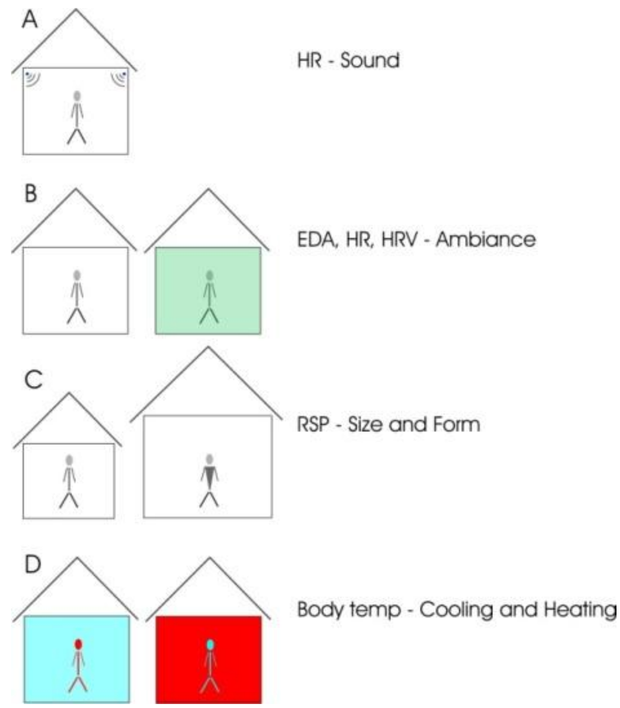

Figure 1 Physiological Data Mappings explored

Conceptually, this was also of greatest interest, because buildings tend to be physically static in the majority of cases. However, when they do physically adapt, this is typically motivated and driven by other considerations, for example adapting to different environmental conditions, differences in event requirements, or artistic endeavours [2, 14, 23]. To the best of our knowledge, investigations into the direct connection between physiological data and the extent, shape or form of building fabric have not yet been conducted to date. The contribution of this research can therefore be described as the exploration of this novel design space at the boundary between Architecture, HCI and medical science, the resulting working prototype and the discussion of the issues that are emerging.

To-scale prototype
Following the sketches, a physical prototype was built. The aim was to create a building-like enclosure that could accommodate an individual in a sitting or lying position. In that regard, a functional to-scale prototype seemed an ideal starting point. This was designed such that it could be scaled up to a much larger size in the future.

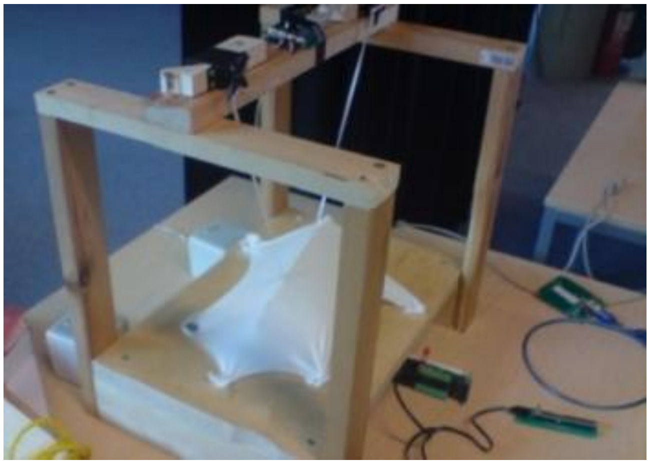

Figure 2 To-scale Prototype Front

Figure 3 To-scale prototype Side

Stretchable fabric was chosen because of its malleability and also because of previous experience working with such materials [10]. The prototype constituted a tent-like structure of approximately 20 by 30cm in base dimension mounted on a wooden platform at five fixed points (see Figure 2 and Figure 3). The centre of the fabric was re-enforced with a 'spine' made from flexible plastic. Two points on the 'spine' where attached to two servos, mounted on a wooden frame attached to a base platform, subsequently creating a deformable enclosure.

Mechanically, this setup allowed the fabric to be pulled upwards causing it to expand, and let back down, inversely causing it to contract. LEDs were added to the base under the fabric to facilitate the exploration of lighting effects. A stereo speaker system was also connected to the setup in order to explore a range of sound effects.

The servos and LEDs were connected to a PC via the Phidgets toolkit [21]. The Phidgets toolkit provides standardised, plug and play sensing and control connected to PCs via USB. A Mindmedia Nexus 10 physiological monitoring and feedback platform [18] was used to pre-record heart beat and respiration data (see more details about this equipment below). This was played back through the ExoBuilding prototype using an open-source middleware platform [9] [11]. This platform allowed the connection of sensors, software components and actuators using a graphical programming approach. In this instance it was used to read in the heart rate, EDA and respiration data from the Biotrace software.

In this initial to-scale prototype, the respiration trace, i.e. the data generated by monitoring the extent of the abdomen of a breathing person, was directly mapped to the dynamic extent of the tent-structure. At this initial stage, the breathing data was recorded and replayed, the structure expanded during inspiration and contracted during expiration. Each heart beat was directly mapped to the LEDs lighting up, as well as to a heart beat sound being played through the speakers.

The result was an artefact that attained some properties of an animate organism and externalised those properties for others to view. As already mentioned, breathing was displayed through movement, but also through the sounds of the servo motors driving the structure. The artefact was illuminated with a red light which appeared in synch with the replayed heart beat sound.

Prototype discussion
The first proof-of-concept demonstrator described above was subjected to an informal internal review. The idea was deemed to be unusual and it certainly prompted discussions around the range of possible mappings between physiological data and building, issues of data ownership and privacy and the temporal and spatial dimensions of the data stream. There was also consideration of whether data (in a building context) would come from individuals or whether it could be aggregated. In addition, the potential ambiguity of data ownership during the display caused further debate.

The audio component appeared to have some interesting potential. As a speaker system with a subwoofer was used, the sound play-back actuated some vibration in the floor and table, highlighting the potential for a more visceral feedback than was previously envisaged.

For the design process, the most relevant issue was that of scale. The intention was always to build a room-sized prototype. The to-scale version prompted speculation about the potential differences between, an artefact visualising physiological data seen from outside, versus an immersive environment. Although potential for the smaller version was identified (e.g. It could more easily be assembled into larger feedback installations, visualising data from multiple people and to larger audiences); an immersive version had the possibility to give a much more private experience, while data could also be visible from the outside [10, 32]. Its immersive properties could only be investigated once a full-size prototype was available and only this would then allow experimentation with different design options and usage scenarios.

Scaling up to a room-sized prototype

The scaling up process started with taking measurements of the to-scale prototype and translating those into the volume of the available space (approx 6mx6mx2.70m) while making sure that the resulting structure was still 'inhabitable'. A working drawing for the fabric was produced (see Figure 4) in addition to sketches for the mechanism and ceiling mount.

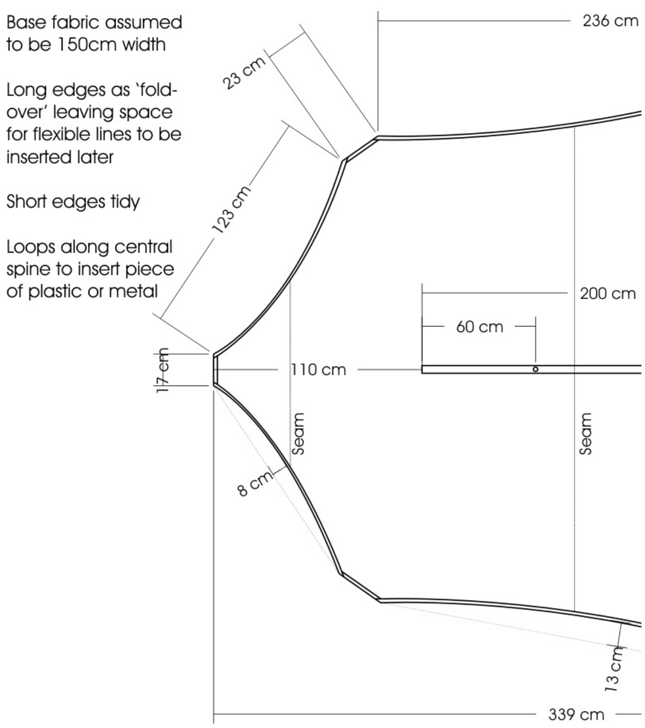

Figure 4 Front section of fabric layout

The fabric was scaled up, sewn together from stock stretchable jersey material in white, using a domestic sewing machine. In a similar way to the to-scale prototype, the spine of the structure was re-enforced, this time using aluminium tubing. At two points on that spine, the fabric was pulled up towards a ceiling-mounted sub-frame. At five points on the floor, the fabric was pinned down with the help of cast iron stage weights. Counterbalanced drive arms pull the fabric up and then release it back down, with the tension in the fabric providing the downward pull. The arms were driven by large but standard model servo motors strengthened by additional gear boxes which were in turn driven through the Phidget interface kit [21].

EXOBUILDING

The resulting physical prototype (see Figure 5) was a tent structure of roughly room-size. It is large enough to sit in on a reclined chair or to lie in on the floor or a low bench.

ExoBuilding has the following adaptive features: Its shape and size can be altered using the drive mechanism. A data projector can be used to project dynamic information on the tent surface. LEDs embedded into the fabric can be used to display further information. A sound system can be used to display sound through audio and associated vibrations of the floor.

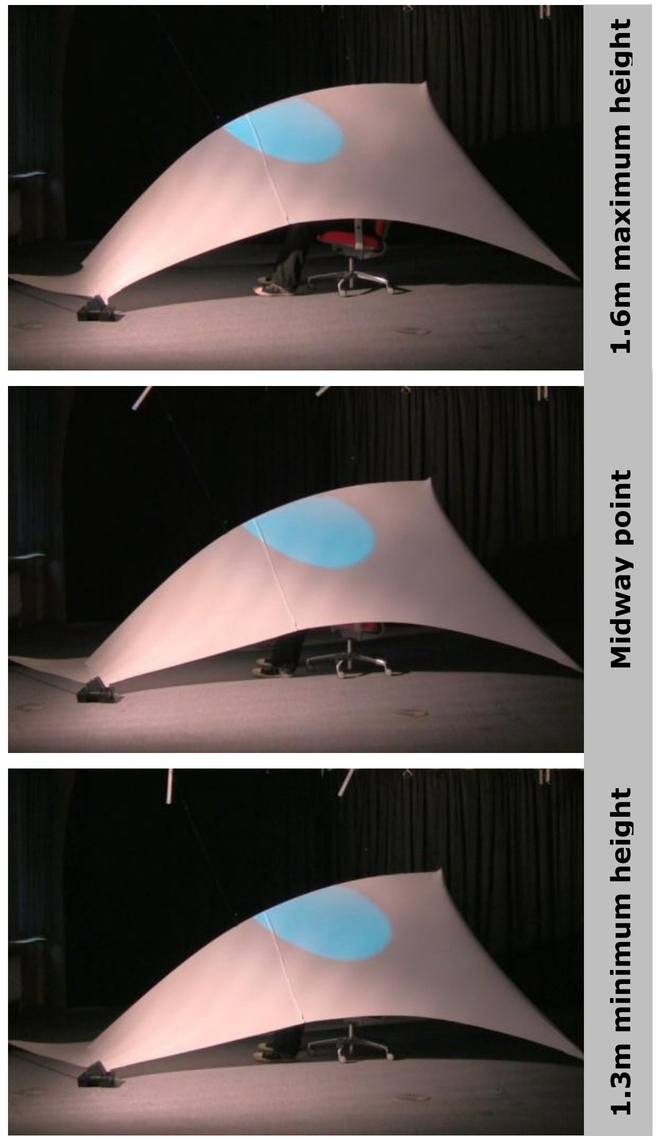

Figure 5 ExoBuilding movement sequence expanded (top) and contracted (bottom)

Figure 5shows the range of the physical movement of the prototype, from 1.3m to 1.6m shoulder height. The seemingly subtle change in size belies the effect felt inside ExoBuilding, as the change in overall volume is much larger than the photos could illustrate.

A Mindmedia Nexus 10 device was employed to gather live physiological data. [18]. The Bluetooth enabled and battery powered device is roughly 10cmx10cmx4cm and easily portable. It offers 10 hardware channels which allow measurement of physiological data (e.g. EEG, ECG, respiration and skin temperature). Via Bluetooth it was connected to a PC running the associated Biotrace software. Biotrace takes the 10 hardware channels and provides a series of live data channels. As an example, one data channel derives heart rate and heart rate variability from ECG. Taking this one step further, the combination of data from different hardware sensors then also allows the analysis of derived channels such as HR/Respiration coherence.

Breathing life into Architecture

As already highlighted, we made use of a subset of the available channels to drive ExoBuilding.

The ECG signal, measuring the heart muscle activity, was gathered using three electrodes placed on the participant's chest and torso. Biotrace only made the signal available as heart rate, which was then converted to heart beat events inside the aforementioned middleware platform. The heart beat was played through the speaker system using a pre-recorded heart beat sample and displayed on the tent fabric via the embedded LED. Via a subwoofer the floor was made to vibrate in sync with the sound output.

Respiration data was gathered using a respiration belt fitted around the participant's torso, measuring the rising and falling extent of their abdomen. Through Biotrace and our middleware, this was converted to the full range of the servo motors to be able to change the extent of the fabric structure. The participant's respiration drives the shape and size of ExoBuilding, so that the spatial volume expands during inhalation and it contracts during exhalation. This also creates air flow into and out of the structure which can be felt by the participant.

Sensor	Signal	Actuation
ECG	Heart beat	Heart beat sound and LED
RSP belt	Extent of abdominal breathing	Extent of ExoBuilding
EDA	EDA	Visibility of graphic projected on ExoBuilding

Table 1Physiological data - Actuation mapping

Finally, using two finger electrodes, electrodermal activity (EDA (frequently called GSR)) was measured. Over brief periods, EDA is useful for detecting events that impact a person, such as when they get startled. Over longer periods, a falling trend can indicate that a person is in a relaxed state. The participant's EDA drives the display of an image on the outside of the fabric. When their EDA signal rises, the image fades in and when the signal declines, the image fades out.

UNDERSTANDING EXOBUILDING

This project began with an open research question: how could physiological data and the architectural building fabric be connected? This was the key overarching interest running through the project. This question and resulting iterative prototyping process lead to an interesting artefact and new building type, exemplified through a full-scale and fully working demonstrator. This aspect of ExoBuilding was already of great interest and the paper will return to the potential of this idea in the discussion. In addition to the above, ExoBuilding can also be described as a different type of display for physiological data. Deliberately, it does not interpret physiology to derive mental or emotional state; it is not an affective computing device for that matter. Instead, it allows a person to explore and maybe better understand aspects of their physiology in a specific manner.

Figure 6 Back view of the ExoBuilding during use

Figure 7 View of participant inside ExoBuilding

It is worth summarising its most interesting properties:

Multi-sensory

The data display is **multi-sensory**, as information can be seen (e.g. the projected graphics and movement of the fabric), heard (e.g. the sound system) and felt (e.g. vibrations of the floor, air flow generated by the moving fabric and the fabric occasionally touching the faces of people).

Immersive

The data display is **immersive** in the sense that it physically immerses the entire body of an end-user into the data to be displayed, in this particular case their own physiology.

Visceral

Taken together, this resulted in an almost **visceral experience**. Especially when the sound was turned up and the floor started to vibrate, it clearly felt that one's whole body is affected by the experience.

In a similar manner to the to-scale prototype, informal tests were conducted throughout the development process of the full-scale prototype described above. Reaction to the full-scale version was positive and it seemed pertinent to capture some of these reactions to shape our ideas and inform future work.

Formative study

To understand the effect of the ExoBuilding on people, a formative study exploring the issues that appeared most relevant was conducted. This study was aimed at gauging and fully understanding the functionality of the prototype and getting a very initial idea of people's reactions to it. It was also hoped that the feedback gathered would inform and guide future research. In what follows, we describe the study and the implications of the results obtained for the ExoBuilding design.

The prototype was mounted in a dark space with a desk light pointing towards the ceiling placed within the same space. Three participants between 30 and 50 years of age, all with a technical background, volunteered to take part in the study. Two different conditions were explored with each condition lasting exactly 3 minutes. The first condition required participants to sit on a fully reclined office chair within the tent (see Figures 6 and 7), while the second condition required participants to lie on the floor, inside the tent. Participants were briefed on the study procedure, kitted up and then placed inside ExoBuilding.

After each condition, participants were requested to leave the tent. In addition, each condition was followed by a very simple structured questionnaire, posing three questions: 'What did you like about the experience?', 'What did you not like about the experience?' and 'Other comments?'. The Questionnaire was designed to prompt but mainly to allow participants as much space as possible to describe their experience freely. All physiological data necessary to drive the prototype as well as evaluate the participant's reaction to the ExoBuilding were recorded.

Questionnaire feedback

All three participants found the experience relaxing in both conditions. One commented: '… a moment of real calm', while another stated '… very relaxing – almost asleep – soporific!'. Two participants expanded this by commenting on how unusual and interesting the experience was and this was mainly a result of their breathing and the movement of ExoBuilding being in sync. One participant stated:

> '(The) synchronised motion and breathing is really nice and very relaxing … heartbeat was very comforting (inducing almost womb-like feelings) … may be it was because it wasn't my own heart, but someone else's beating in time to mine that made it so re-assuring.'

All three participants commented on how the sound of the ExoBuilding machinery (servos and mechanism) was also relaxing. It appeared that as the machinery was in sync with the participants' breathing, the similarity to a breathing sound was re-enforced. However, one of the participants characterised the sound as 'not quite' right and occasionally too loud.

One participant commented on the physical nature of the prototype. They liked the fabric caressing their face in the sitting condition, and they contrasted the warmth at the top of the tent inside with the occasional breeze coming in generated by the movement of the fabric. They also commented on how the prototype seemed to have become an extension of their body:

> '… when the tracking was turned off and the tent rose to its default position, I physically felt my chest muscle tighten in sympathy (as if the tent were controlling my chest) – or at least, it felt very odd that the tent was moving and my chest was not.'

A number of issues were also raised in relation to each condition. All three participants preferred the sitting condition. They commented that lying down on the floor was too hard, too cold and much less immersive as they could see out through the gaps of the fabric at the bottom. They were also much more aware of the machinery (wires, fixings, etc.) and one participant stated that it was difficult to get in and out with the Nexus device already attached to them.

Participants did not find the LED visualisation of their heart beat attractive or useful. Also, the display of the EDA signal as a projected image appeared to be unreadable by participants. When asked they were not able to interpret the mapping of signal to display, but they liked the aesthetics of the overall effect. Finally, all three participants stated that they felt that the correlation between their breathing and the fabric was not exactly accurate, with the occasional delays.

Physiological data

The physiological data recorded provided another important source of information. Although both conditions were recorded, the data analysed below only concerns the latter, lying on the floor. The reason for omitting the first condition, although people clearly preferred it, was the fact that people used it to get acquainted with the system. This typically involved playing with the range of the physical movement mapped to the movement of their abdomen and with general responsiveness, for example by holding breath for a little while. It was visible in the data, but more importantly, all three people verbally reported that there were periods in the first condition, when they 'played around', simply a result of the interface being so unusual.

Each session lasted for 3 minutes. As it could not be guaranteed that recording and the start of the operation of the prototype were in sync. The first 15s of each of the data samples was rejected. The following 2min 45s were retained for the following analysis. As there are only three data sets, no statistical analysis was conducted. It is important to point out that the analysis is purely descriptive with the aim to inform the development during prototyping.

Electrodermal activity (EDA)

The following graph represents a typical EDA trace from all three participants. Time is displayed on the X axis and the raw EDA value in microsiemens on the Y axis.

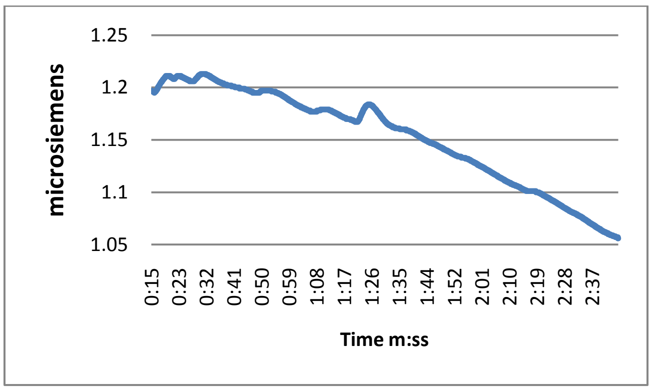

Figure 8 EDA - Participant 1

A simple visual inspection of the EDA traces confirms what participants had indicated in the questionnaire responses. The falling overall trend without many significant shorter-term upwards spikes is an indication of their relaxation during their experience. All three EDA traces recorded exhibited this same basic pattern.

Respiration and heart rate

The following graph shows a HR and Respiration trace over 2mins 45s for a single participant. As before, time is displayed on the X axis. HR computed from ECG is displayed on the left hand Y axis fixed to 40-100 BPM. Raw respiration values (RSP) are displayed on the right Y axis, with the axis being scaled in a way that ensures readability. Over the measured period of 2min 45s, the participants averaged approximately 6.75. The measured breathing rates are substantially lower than average standard breathing rates which are around 18 per minute [6]. These lower rates are an interesting indicative finding. A visual inspection of the data and a superficial comparison to data we collected in other situations, also suggests that breathing is much deeper and more regular than we observed previously. This is an interesting area for future investigation. Finally, the graphs also show that HR oscillates as one would expect and that those fluctuations are mostly in sync with the respiration trace, an effect known as Respiratory Sinus Arrythmia (RSA).

Study summary

The short trial reported here was part of our overall iterative design process. The aim was to decide on design features, ideas for further research questions and types of possible evaluation. Clearly, because of the small number of study participants and the uncontrolled nature of this study, the results are not directly generalisable.

However, in what follows an outline of the most relevant features of ExoBuilding and an initial interpretation of the results obtained is provided, before discussions of wider issues and how the design of the prototype will be influenced by these findings.

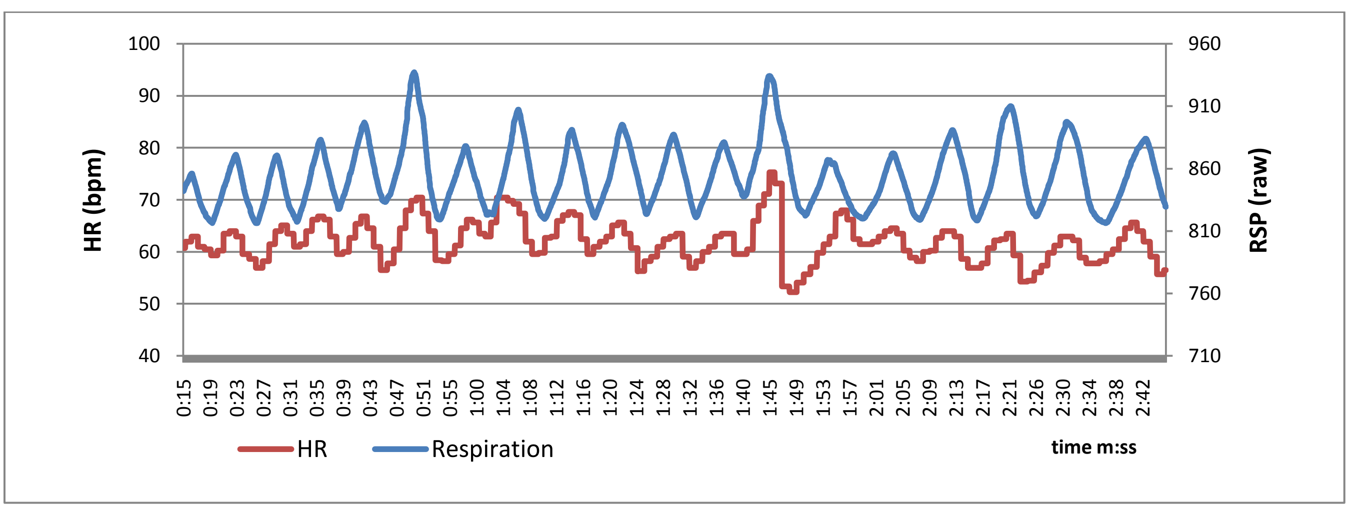

Figure 9 HR and RSP - Participant 3

A display of physiological data

ExoBuilding allows people to be aware of their own physiological data. This in turn allows the modulation of one's own behaviour to 'achieve' certain types of patterns (e.g. regular and deep breathing). This awareness is achieved through an intuitive and legible display of the physiological data, arguably in contrast to other displays which display information on a flat screen, for example [33].

Raising awareness

In particular, it externalises aspects of people's physiology that many were not aware of, similar to the art installation Sonic Body [20]. Heart beats naturally fluctuate and the level of Heart Rate Variability is a marker for certain medical conditions [29]. For many people this can sound disconcerting, as they might expect an evenly spaced series of beats. In a similar way, the prototype made people aware of their own breathing. As breathing is mostly autonomic, people tend to take no notice unless they are in specific situations where it comes to the fore (sport activities, playing a wind instrument and singing, extremely quiet environments).

A relaxing experience

The short study suggests that ExoBuilding provides for a relaxing experience. This is mainly emerging from the questionnaire feedback and seems to suggest that it is the combination of the different elements of ExoBuilding, synchronisation of breathing and movement, the various sounds and the immersive nature that make this work. The EDA traces back this up, through displaying generally a downwards trend without significant upwards spikes (see Figure 8).

Feedback loop

This is arguably because of the very immersive feedback loop that ExoBuilding presents people with. We did not provide any kind of prompt of what people were supposed to be doing within the structure. It seems plausible that the display itself of one's own physiological data triggered the responses that are seen in terms of relatively regular and deep breathing in sync with heart rate variability.

ARCHITECTURAL CONTEXT AND FUTURE WORK

At this point it is worth returning to where this work started out from, the application of physiological data to the physical building fabric. Across the entire development and evaluation cycle of the ExoBuilding prototype, ongoing discussions and participant feedback have highlighted a number of wider issues that it is worth returning to here.

While these are applicable to other forms of display of physiological data, they are particularly pertinent when considered in the context of building Architecture. In what follows the *scale, temporal nature, data ownership, the ambiguity of data ownership, ranges of control and the role of aggregation* in the use of physiological data in an architectural context are discussed.

Scale

Constructing and studying the full-scale version of ExoBuilding has indeed hinted at the powerfulness of an immersive, physically dynamic display of physiological data. The tension remains between displays as artefacts such as the to-scale model developed first, where many such artefacts could sit along side each other and be viewed externally and something larger to be viewed from the inside. Having both prototypes operational allows for comparative studies of the two models in future, but also for scenarios where both are used alongside each other.

Temporal

The initial intention of the development was always to be able to display live data, especially with the view to explore how this type of display would feed back on behaviour. On route, playing back recorded data came as a by-product. Playing back recorded data in the physically animated fashion of the to-scale artefact already felt slightly uncomfortable because the object attained a life-like appearance. This would be further reinforced whenever data is stored for longer times, potentially past somebody's death and ExoBuilding becomes an ethically questionable playback platform for someone's 'life'.

Ownership

Very much related to this, data ownership was raised in discussion. The starting point for our experimentation was always that the physiological data of the current inhabitant of ExoBuilding would be displayed. Technically, there is no reason why this data could not be of another person, whether this is live or recorded, whether that person is local to the installation or remote to it. Experimentally, it would be interesting to see how the display of somebody else's data might influence the physiology of the current inhabitant, which could be expressed as an experimental condition in future work.

Ambiguity

Can an inhabitant even be sure who owns the currently displayed physiological data? In all our current experimentation, this relationship is very clear. But it is conceivable that one might experiment with this, feeding through other inhabitants' data, switching over to people located elsewhere or to recordings, without necessarily alerting the trial participant.

Ranges of control

The prototyping process also highlighted that there are different ranges of control that one might expect over one's own physiology. For example, breathing is typically controlled autonomically, but can also be controlled voluntarily (e.g. breathing exercises). EDA and heart rate are in a separate category as control is much more indirect. With experience, one might know what to do to affect the signal (running to raise heart rate or pinching oneself to raise EDA). However, it is already much harder to lower the signals or to prevent them from rising (e.g. training to avoid detection through a lie detector). Signals such as peripheral skin temperature are perhaps even much harder to control. These different ranges of control and the ways that they are brought to the attention of building inhabitants are clearly important in the design of such environments but also in the study of them.

Aggregation

Finally, in a building context, the issue of data aggregation becomes relevant. One might speculate about more general building architecture, where building elements might be driven by physiological data, for example in entertainment or health related venues. Practically, with large populations, there would not be enough building elements to allow individual control. How could the aggregation of data streams be used to combine multiple streams of physiological data to drive a single building element and would this be meaningful to inhabitants?

We are beginning to actively explore the above issues together with architects, HCI experts and experts in medical science, and the key question in this context is: where might such a building or building element find its use?

The health club and spa segment of the built environment shows the greatest potential. Whether driven by actual physiological data or with simulated data for practical reasons (e.g. regular breathing cycles), the interior of buildings would be physically animated first of all as a teaching and exploratory environment but also to help induce a relaxed state in spa visitors, for example. Work environments present another opportunity, where structures like ExoBuilding could be set up as 'time-out' pods that are available to workers when they need a break (compare to Google's Zurich offices[30]). Both would probably need to explore less intrusive ways of capturing the physiological data to make this aspect of the experience more manageable and socially acceptable.

For this to be a viable route to explore, more evidence for the effectiveness of the concept will be required. The prototype development and initial evaluation has since taken us to pose a much more focussed research question: What is the effect of this particular form of physiological data display on occupants of the affected space? While the prototyping process provided some initial pointers, we are now proceeding to study ExoBuilding more formally in a controlled lab experiment, drawing on the experience that we have gathered so far.

A much more challenging avenue lies in the application of physiological data to Architecture more generally. While the examples above place the prototype into the building context, they do so at the current scale of ExoBuilding which is roughly room sized and the temporal horizon of the prototype, which is in minutes of use. But what about applications of physiological data to entire building structures over the entire life-time of a building with ever-changing populations. It is likely, that physiological data would take on a very different role in these circumstances

CONCLUSION

In this paper the concept, design and prototyping process for ExoBuilding has been outlined. ExoBuilding is a prototypical piece of architecture that maps a person's physiological data to its building fabric. Through sketches, a to-scale artefact and a full-size immersive lab demonstrator the potential of this idea in its various forms has been explored. ExoBuilding demonstrated clear potential as a biofeedback environment, triggering changes in people's physiological behaviour, without the need for prompting, and this is currently being investigated more formally. The contribution of this work lies in the exploration of this novel design space and the discussion of the emerging issues. These are centred around issues of scale, the temporal properties of Exobuilding, ownership and ambiguity of ownership of the data to be displayed, ranges of control and the possibilities that arise when data is aggregated.

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