In Control - Heart Rate-driven Architecture

Nils Jäger
MIxed Reality Laboratory
University of Nottingham
Wollaton Road, Nottingham
psxnj@nottingham.ac.uk

Holger Schnädelbach
Mixed Reality Laboratory
University of Nottingham
Wollaton Road, Nottingham
holger.schnadelbach@nottingham.ac.uk

Kevin Glover
Mixed Reality Laboratory
University of Nottingham
Wollaton Road, Nottingham
kevin.glover@nottingham.ac.uk

We describe the design process of a formal study that investigates the potential of adaptive architecture to directly influence or control the physiology of its inhabitants. We depict two pilot studies that inform the design process of the formal study. These studies raise questions regarding the effects of such environments, including the benefits and potential dangers. The formal study will also be an initial step towards introducing the built environment as an active agent in environmental (architectural) interactions.

ExoBuilding, adaptive architecture, biofeedback, control, experimental study, physiological data, heart rate variability.

1. INTRODUCTION

This paper introduces two pilot studies situated in the context of adaptive architecture, responsive and biofeedback environments. We use specific, well-studied physiological phenomena to focus on the question whether it is possible under certain conditions to control an inhabitant's physiological processes through interventions of the built environment. Possible scenarios of participant behaviour, implications for computing and architectural research and design, as well as benefits and dangers of environments with such capabilities will be briefly discussed.

1.1 Developing the formal study

The environment used for this study is called ExoBuilding [12] (shown in Figure 1), which is a single-person, tent-like structure that changes its height, volume, and shape based on its inhabitant's real-time physiological data. Schnädelbach, Glover and Irune [12] describe the rationale, design process and finished result in detail. For the purposes of this paper, a brief description of the environment follows below.

ExoBuilding is driven by servomotors that receive signals through a middleware platform called ECT [3]. ECT allows data processing and manipulation as well as communication with physical actuators. It is the combination of physical structure, sensing technology and middleware platform(s) that allows direct physiological interaction between inhabitant and environment. More specifically, white jersey fabric is stretched over a central spine made from thin aluminium tubing. This spine is suspended from two servomotors mounted to a wooden ceiling structure. The servomotors allow for a motion range (up and down) of about 30 centimetres (Figures 1 and 2).

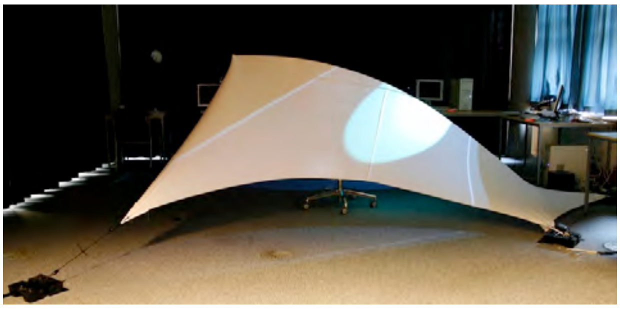

Figure 1: *ExoBuilding in "down" state*

Figure 2: *ExoBuilding in "up" state*

The structure is ca. 1.3-1.6 metres high, about 3.5 metres long, and about 3.5 metres wide. The single inhabitant of ExoBuilding first sits down on a reclining chair, which itself is mounted to a wooden platform equipped with coasters. The inhabitant is then rolled into ExoBuilding by the experimenter, entering the structure from the back (Figure 3). The inhabitant or participant then sits underneath the stretchable jersey fabric onto which a circle of blue light is projected for the duration of the experiment (Figure 4). Fur the duration of each trial, the lights are extinct and only residual light coming through the window curtains and the light of the projection illuminates the environment (Figures 3 and 4).

Figure 3: *ExoBuilding side and back*

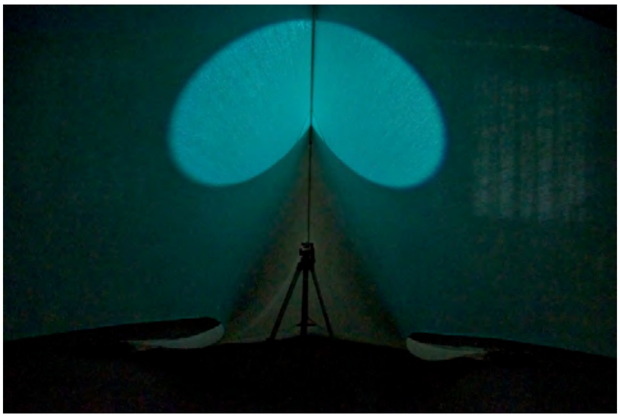

Figure 4: *Inhabitant's view during experimental trial*

An initial pilot study by Schnädelbach, Glover, and Irune [12] explored the potentials of ExoBuilding as a biofeedback environment and as proof-of-concept regarding the feasibility of using live physiological data to influence an architectural structure. Schnädelbach et al.'s based their exploration on two biofeedback conditions (respiration, heartbeat, and electrodermal activity): (1) sitting in a fully reclined office chair inside ExoBuilding, (2) lying on the floor inside ExoBuilding. Three participants experienced both conditions without instructions regarding their behaviour and reported that the experience felt relaxing, "womb-like" and extending their body "as if the tent were controlling my chest".

An as yet unpublished formal and controlled study by Schnädelbach probed into physiological effects of immersive biofeedback. Twelve participants experienced three counter-balanced conditions. They were (1) no biofeedback and no motion of ExoBuilding, (2) no biofeedback but regular motion of ExoBuilding, (3) biofeedback of heart beat, electrodermal activity alongside biofeedback motion of ExoBuilding controlled through the participant's respiration. The study revealed that on average, participants reduced their respiration rate during the biofeedback condition, while only a few participants reported this to be comfortable. Both other conditions, the no-movement and the regular movement condition, did not produce any significant effects in participants.

Based on the findings of the first pilot study, the formal and controlled study, as well as subsequent tests, we were intrigued to investigate other biofeedback conditions in the ExoBuilding environment as well as to explore whether biofeedback environments could be used to actively control inhabitant behaviour.

The interest in controlling a person's (physiological) behaviour through the environment arose primarily out of participant feedback of the first pilot study. As mentioned above, a participant had expressed a strong post-condition reaction to ExoBuilding. The participant described a sympathetic chest movement when biofeedback was disabled and ExoBuilding merely returned to its default position. That is when ExoBuilding was moving up, the participant felt the chest rise simultaneously. Subsequently, we discussed ways to replicate such a strong connection between the environment and a person as well as the architectural relevance of and interest in controlling human physiology directly through realtime architectural interventions.

1.2 Control in architectural research

Controlling people through an architectural environment has been studied in architectural research. However, research regarding control and power in the built environment does not usually involve directly controlling a person's physiology. Instead, architectural researchers describe control mainly as a top-down power structure, which has been and is being used to express governmental authority and omnipotence or to express governmental structure or political systems. This has, for example, been analysed by Kim Dovey [2] with regard to the imposing scale of Hitler's plans for Berlin, the exclusion of imperial Beijing's forbidden city and the all-inclusive nature of communist Beijing's Tiananmen Square. Dovey identifies additional expressions of power or economic and political systems in the ubiquitous office tower and modern governmental buildings (using Canberra, Australia as example).

Control has also been discussed in terms of neighbourhood and building safety. Oscar Newman [8] has argued for specific neighbourhood and urban designs to enhance, for example, visibility of entrances in order to enable increased social control and the ability to defend space against unauthorised or unwelcome visitors. Such designs would allow inhabitants to better visually and physically control their immediate urban environment.

As Schnädelbach has described in "Physiological Data in Adaptive Architecture" [11], there are architectural projects utilising the human body to create interest (e.g., varying degrees of façade transparency of the Laban Dance Centre revealing dancers' movements to the outside world) or technical adaptations to react to external data sources (e.g., the shutter mechanism of the Institut du Monde Arabe reacting to increasing or decreasing daylight levels). But we are not aware of projects were real-time physiological data is being used to actively change the building fabric or parts thereof. Our research in this area is on-going and therefore currently incomplete.

1.3 Physiological background

In order to study control between participant and the environment, we utilise the physiological phenomena of heart rate variability (HRV) and respiratory sinus arrhythmia (RSA).

Heart rate variability (HRV) describes the phenomenon of varying time intervals between heart beats. Respiratory Sinus Arrhythmia (RSA) links heart rate and respiration. On inhalation, heart rate rises, on exhalation heart rate slows down [4]. This effect is strongest at low respiratory frequencies as shown by Song and Lehrer [14] who indicated that HRV amplitude is highest at 4 breaths per minute. Figure 5 shows how the (stepped) curve of heart rate and respiration (raw data measured by respiration belt) align. Thus, it is possible to indirectly influence or control the variability of heart rate through one's respiration.

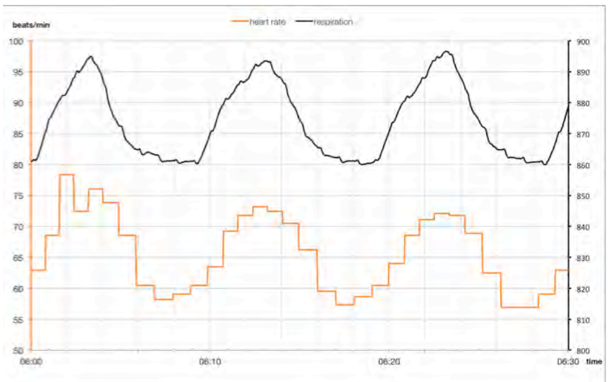

Figure 5: *HRV and RSA - heart rate data (bottom) in relation to raw respiration data (top)*

RSA biofeedback has physiological benefits. It helps to increase heart rate variability amplitude [5], which, for example, has been used to treat post-traumatic stress disorder [15]. It has also been suggested that RSA biofeedback training can have positive influences on state anxiety and stress reactivity of heart rate [13]. Any health benefits are welcome, yet not central to our study. However, we use the physiological phenomena of HRV and RSA and the indirect control mechanism for the purpose of this study.

2. THE PLANNED FORMAL STUDY

Here we describe the goals and setup behind the planned formal study, with which we intend to investigate control in and over adaptive architecture.

2.1 Study goal

We aim to effectively control a participant's respiratory rhythm through the ExoBuilding environment under the condition that the participant is unaware of losing biofeedback control over said environment.

In order to control a participant's physiology, the participant must be unaware of being controlled. As Schnädelbach's formal study has shown, regular motion of ExoBuilding without discernable relation to participant physiology did not cause physiological effects in participants. Hence, we do not reveal the true purpose of the study at first. In addition to being unaware of the real purpose of the study, participants must not be able to perceive any difference between biofeedback control over the environment and being controlled by the environment.

2.2 Taking control

Since the participant is controlling ExoBuilding indirectly, as described above, we expect that this abstraction of control will allow us to more easily and less obviously reverse the power relationship between participant and ExoBuilding. Still, several conditions must be met before control can be transferred unnoticeably.

First, the participant must establish a trusting relationship with the environment. That is, the participant needs to experience control over the environment. Therefore, we allow participants to experience biofeedback control over ExoBuilding. We also (seemingly) duplicate this first biofeedback session, for the participant is likely to feel familiar with the environment and procedure at this stage and will expect ExoBuilding to behave as it did during the first session.

Secondly, the transition between biofeedback control over the environment and being controlled by ExoBuilding must be seamless to the participant. Hence, the second session is split into an initial biofeedback phase and a subsequent phase during which ExoBuilding imperceptibly assumes control and attempts to alter the participant's physiology. During the first phase of this second session, the biofeedback phase, our software tracks the fluctuation of participant heart rate (HRV) and calculates its frequency. The software then uses this information to mimic the participant's HRV in order to disguise the switch in control.

2.3 Driving a participant

With the previously mentioned tactics of switching control in place, we require a measure of success enabling us to tell if ExoBuilding is indeed controlling the participant's respiration frequency. Changing the motion frequency of ExoBuilding was selected to measure whether the participant would follow this frequency and adjust his or her respiration rate accordingly.

We decided that once the transition to ExoBuilding control has occurred, our software would reduce the motion frequency of ExoBuilding by 20 per cent over a predefined period of time. We chose a reduction of the frequency because of the previously explained health benefits of RSA biofeedback. It seemed logical to reduce the frequency rather than to create an environment that attempts to induce stress (i.e. increased respiration rate).

2.4 Anticipated participant behaviour

As explained above, participants indirectly control ExoBuilding's motion through their respiration. We have seen in a previously conducted pilot study that not all participants might be able to make ExoBuilding move regularly and smoothly. Based on this experience and extensive testing of the technical setup with various data sets, we can expect three main participant behaviours or reactions to this kind of environment and experimental design.

First, the participant is able to quickly get into a regular breathing pattern and maintains this pattern throughout the sessions. After the transition to artificial data has happened in the second session, the participant closely follows the decreased motion frequency of ExoBuilding.

The second plausible course of participant behaviour is that the participant is able to get into a regular breathing pattern, causing ExoBuilding to move regularly. But just before the transition to CG data, either the participant momentarily loses respiratory regularity or the software produces inaccurate data (frequency too high or low). This would create a motion frequency of ExoBuilding that is unrelated to the participant's prior performance and experience. It is likely that this would prevent the participant from following the decreasing motion frequency of ExoBuilding.

The third expected scenario consists of a participant who is unable to produce regular heart rate variability curves resulting in seemingly erratic ExoBuilding motion. To the participant ExoBuilding will appear to be moving independently from the participant's breathing pattern. Such a scenario will make it difficult to control the participant's respiration frequency through ExoBuilding, as the participant might not have been able to establish a 'trusting' biofeedback relationship with the environment. Accordingly, any expectations of the environment's reactions and how to influence these reactions will differ significantly from participants in the previous scenarios.

3. PILOT STUDY NO. 1

3.1 Aims

This pilot study was conducted to test the main procedure for the formal study, as well as participant behaviour, measurements and analysis of the data.

3.2 Participants

The first pilot study consisted of three participants, one female and two male in the age range of 25-35. All three participants were recruited from within the lab but had neither prior experience with ExoBuilding nor exposure to the study procedure.

3.3 Methods and Measurements

3.3.1. Methods

We did not initially reveal the true nature of the study in order to avoid participant expectations or suspicions. We told participants that we were interested in observing differences between first- and second-time exposures to HRV biofeedback through an environment.

The experiment was designed with two experimental sessions of 12 minutes each, occurring consecutively on the same day. To a participant both sessions would appear to consist of biofeedback. The second session, however, was split into two parts: (1) participant control (biofeedback) and (2) computer control.

3.3.2. Measurements

We measured primarily the participant's physiology (i.e. heart rate respiration rate and skin conductance). We also measured the motion of ExoBuilding itself with an accelerometer. This allows us to measure whether participant and ExoBuilding are behaving/moving synchronously. All the mentioned sensors are part of the MindMedia biofeedback sensor kit called NeXus-10.[7]

A demographic survey and multiple pre- and post-session questionnaires were used as statistical co-variates.

We also assessed the participant's experience through an open-question questionnaire as well as a semi-structured interview at the end of the experiment.

A video camera in front of the participant recorded the participant's behaviour during each trial.

3.4 Procedure

Initially, each participant was fitted with electrodes (electrocardiogram, galvanic skin response, and a respiration belt) and experiences two experimental sessions. Prior to the first experimental session, the participant received a short explanation of heart rate variability, its link to respiration, and its mapping to ExoBuilding's motion. Before each session, the participant received minimal instructions to "breathe slowly and regularly and focus on your breathing." The participant filled out pre- and post-session questionnaires for each session. Each participant was also fitted with noise cancelling headphones to prevent the participant from focusing on external sounds, especially from the servomotors, and to help with focusing on breathing.

After the second session, the participant executed a short drawing task of the experience, which is intended to help the participant think about his or her relationship to ExoBuilding. The drawing was then used as an entry topic to a short, semi-structured interview.

3.5 Results

3.5.1. Physiological Data
Pilot study no.1's most intriguing result indicates a change in the participants' breathing behaviour after the transition to artificial data in the second trial. As opposed to our expectation that participants would follow the decreased motion frequency of ExoBuilding with their respiration (i.e. participants would breath more slowly), all three participants' respiration rate increased on average after the transition. It is unclear if this effect is caused by the sequence of trials (the manipulation being always in the second trial) or the duration of exposure to biofeedback through the environment (the manipulation happening after a total of 15 minutes of biofeedback).

3.5.2. Self-report
All three participants reported the experience to be relaxing and overall pleasant. In addition, all three participants independently reported sleepiness after the first trial. None of the participants noticed or suspected a manipulation. However, they did report that the mechanism was not working as well as before. One participant assumed that the environment (after the transition to automated data) was attempting to help to achieve a more regular respiration.

3.5.3.Technical aspects
Pilot study no. 1 revealed a delay in the responsiveness of ExoBuilding to physiological data that was not previously detected. For all three data sets, the delay seemed to vary, with one data set being significantly different (longer delay) from the other two. This phenomenon is currently under investigation. We intend to remove delay of responsiveness as much as possible while simultaneously maintaining the ability of transitioning between physiological and artificial data unnoticeably.

3.6 Reflection

The results of this first pilot study prompt questions regarding potential order effects, experimental procedure, and trial length, which need to be addressed before proceeding with the formal study.

We currently investigate two options regarding order effects: one option is to incorporate counterbalancing in the formal study, while another option is to run a subsequent study to confirm the manipulation's effect independent of its timing.

Regarding experimental procedure, the formal study will include tasks before each trial designed to raise participant alertness. Such tasks might consist of physical or cognitive exercises. The issues of order effects and trial length seem to overlap and are partially being addressed in an additional (already conducted) pilot study (no. 2), which is described in the section "Pilot Study No. 2".

It is unclear if the effect of changed respiration behaviour in participants is caused by the experimental manipulation (switching control) or due to the length of exposure to a biofeedback environment. We, hence, designed a second pilot study to investigate the effects of extended exposure to a biofeedback environment on inhabitants.

4. PILOT STUDY NO.2

4.1 Aims

In response to pilot study no. 1, the goal of this study was to investigate how extended exposure to a biofeedback environment affects participants. The findings should help establishing parameters for optimal trial length in the formal study.

4.2 Participants

We recruited eight participants from within the lab, of whom three were female and five male. The age distribution was as follows: 18-21 (1), 22-25 (1), 26-30 (3), 31:40 (1), 41-50 (2).

4.3 Methods and Measurements

4.3.1. Methods
The experiment was designed with one experimental trial of 30 minutes HRV biofeedback inside ExoBuilding.

4.3.2. Measurements
The measurements were identical to pilot study no.1.

4.4 Procedure

The procedure was very similar to the procedure of pilot study no. 1. The main difference is that there was only one trial of 30 minutes. Fitting of electrodes, explanation of heart rate variability, surveys and questionnaires, breathing instructions, use of headphones, drawing task and interview were identical to the first pilot study.

4.5 Results

We visually analysed respiratory behaviour regarding regular respiration and respiration rates. Resting respiration frequencies range between 12 and 15 cycles per minute (cpm). [1] The ability to stay below 12cpm for an extended period of time indicates both the understanding and following of the instructions given and the understanding of how to manipulate the mechanism. The video recordings were analysed for first signs of discomfort (shifting of the torso). Preliminary visual analysis of the physiological data was done to observe the participant's ability or failure to maintain regular respiration and consistent respiration rates below 12 breaths per minute.

4.5.1. Physiological data
Early visual analysis of the physiological data of this study suggests that the eight participants fall into three groups of respiratory behaviour. Two participants were able to breath consistently at low frequencies (repeated periods of several minutes below 12 breaths per minute) with few deviations (faster respiration) from this pattern. Four participants seem to have been able to maintain respiration rates regularly below 12cpm in the beginning of the experiment ranging from about 2.5 to about 7 minutes. However, they subsequently started to deviate from a regular and slow breathing pattern. The third group consists of two participants who seem to have been generally unable to fall into regular and slow breathing patterns. This will need further analysis to substantiate these preliminary results.

4.5.2. Video data
Preliminary analysis of the first 15 minutes of video data (frontal view of the participant during the trial) indicates that participants start to move their torso (indicating discomfort with their seating position) for the first time on average after about eight and a half minutes (8m27s). However, the times vary between not moving within the first 15 minutes and moving after only 2 minutes and 13 seconds. However, six participants moved after seven minutes.

4.5.3 Self-report
Seven participants reported the experience to be generally relaxing. One participant said that the experience would be relaxing under certain circumstances, such as not being overly stressed, which this participant reported to have been at the time of the experiment.

Two participants reported that they felt to have lost control over ExoBuilding during the trial. Both these participants were aware of our research in the previous pilot (but were not participants of pilot no. 1) and had apparently projected this knowledge onto pilot no.2.

4.6 Reflection

The preliminary results of pilot study no. 2 suggest that participants on average remain comfortable for about 8.5 minutes. Additionally, a majority of participants seems capable of achieving and maintaining regular respiratory patterns for several minutes. More detailed analysis of the data will be necessary to establish the optimal timing for experimental manipulation, in this case the transitioning from participant control to computer control.

Although most participants reported a relaxed experience, analysis of the video data revealed that some of these participants started to move their torso (shifting weight and making posture adjustments) after only a few minutes inside the structure. We interpret this behaviour as restlessness or discomfort. Accordingly, a contradiction between self-report and behavioural observation seems to exist, which will need to be investigated further.

The results also suggest ensuring careful recruitment of participants for the formal study to avoid biased data.

5. FORMAL STUDY

Results of both pilot studies appear to suggest that the formal study can be undertaken once all previously raised issues have been addressed. We describe the adjustments for the formal study in the following.

5.1 Participants

Most participants of pilot study no. 2 had knowledge of our general research interest in adaptive architecture and responsive environments. In particular, the finding that participants might enter experiments with specific expectations, such as being manipulated, shows the importance of, recruiting from outside of the lab. This will help to avoid expectations or anticipation of any manipulation. Therefore, participants will be recruited campus-wide through email distribution and posters. Participants will be screened for severe heart or respiratory conditions, as well as claustrophobia. All participants will receive financial compensation. We anticipate recruiting twenty or more participants.

5.2 Methods and Measurements

5.2.1. Methods
The methods remain the same as described for pilot no. 1.

5.2.2. Measurements
Measurements also remain the same as described for pilot no.1 To measure physiological effects and alignment between participants ExoBuilding, we will compare correlation coefficients between accelerometer data (movement of ExoBuilding) and participant heart rate (variability) data and respiration data (raw). We will analyse two time windows per session, before and after the point of transitioning from 100 per cent to 80 per cent of the participant's respiration rate.

We will analyse questionnaires and demographic survey as covariates.

Video analysis seems capable of revealing possible contradictions between self-report and behavioural observations and will again be part of our measurements.

5.3 Procedure

The procedure of pilot no. 1 will remain generally intact with two trials, one of which will contain the manipulation. A decision on counter-balancing within this study will be made after careful consideration.

We will add a task before each trial. As mentioned above, such a task might be physical or cognitive but will be intense enough to ensure the same baseline of alertness for both trials.

Based on the results from pilot study no.2, it seems feasible to reduce the time for both trials to about 9 minutes, as participants seem comfortable for roughly 8.5 minutes on average. The best possible timing of the transitioning of control still requires further analysis of the physiological data of both pilot studies.

5.4 Anticipated results

Based on the results of the two pilot studies, we expect a majority of participants to be able to sustain regular and slow respiration for several minutes. Hence, we anticipate that the manipulation of transitioning control from participant to ExoBuilding and the simultaneous deceleration of motion frequency will have an effect on most participants. The pilot study seems to suggest that at least some participants will increase their respiration rate instead of decreasing it. This phenomenon still requires investigation but might be related to physiological, demographic, or personality reasons.

Should a significant number of participants indeed reduce their respiration in correlation to ExoBuilding's motion frequency, this would support the argument that environments, under specific conditions, might be able to control parts of the human physiology. The implications both for research in computer-human interaction as well as architectural research and design applications would be significant.

6. DISCUSSION

As Ratti and Haw have pointed out buildings are increasingly becoming sentient and active in their participation in daily life. They argue similar to Merleau-Ponty [6] (although not directly involving the human body) that architecture is becoming "self-aware digital systems inseparable from the flesh of life itself." [9] In the case of the introduced study, the level of embedded computing in the case of ExoBuilding goes beyond Ratti and Haw's description of the built environment. Not only does the digital system become part of the physical structure but it also becomes part of human physiology. In turn, human physiology becomes an integral part of the software by providing the data that is used to actuate the environment.

The ability to control a person's physiology through an environment, however, raises ethical questions as well as initiating a discussion about agency in the environment.

The ethical issues are manifold. As mentioned by Schnädelbach [10-12] the use and storage of personal data and its public availability needs to be carefully considered. Additionally, there are personal preferences regarding potential physiological integration with the built environment. Some participants have reported that the intimate physiological linkage to an environment is not pleasant.

Also, the duration of such environmental interactions and interventions can become challenging. As was revealed in the unpublished study by Schnädelbach, the effect of respiratory biofeedback on respiration rate decreased significantly after about 6 minutes. Consonantly, one of the participants in the recently conducted pilot study of HRV biofeedback liked the experience in general but suggested that this might be best used as an "after work" relaxation rather than inhabiting a constantly moving structure. This suggests biofeedback environments or controlling environments to be temporally visited or temporarily enabled rather than persistent features of the built environment.

Accordingly, similar to a sauna or floatation tank, one can easily imagine a temporarily visited environment that supports relaxation, healthier sleep patterns, or recovery from illness through specific actuations. On the other hand, it seems not implausible to imagine misappropriation of such technology. Examples of which might be to never let people fully rest as part of torture or simply to have employees constantly engaged or "on edge" as opposed to letting them fall into afternoon sleepiness.

Another set of questions involves the notion of agency in the environment. Here, one of the interests lies in the distinction between using the environment as a tool in influencing human behaviour and affording the environment with agency of its own. Particularly intriguing seems to be the case of an environment actively intervening in a person's health through actuations. It seems reasonable to assume that this kind of "enmeshedness" and embeddedness with the environment and subsequent embodiment of the environment would fundamentally challenge our attitudes towards both the built and natural environments. It is at this intersection between physical and digital world where the contribution of our research lies. As part of the formal study's data analysis and discussion, we intend to engage with actor-network-theory as well as further investigations of embodiment theories.

7. REFERENCES

[1] Cacioppo, J.T., Tassinary, L.G. and Berntson, G.G. 2007. *Handbook of psychophysiology*. Cambridge University Press.

[2] Dovey, K. 1999. *Framing places: mediating power in built form*. Routledge.

[3] Greenhalgh, C. 2005. Equator Component Toolkit, Nottingham, UK.

[4] Hirsch, J.A. and Bishop, B. 1981. Respiratory sinus arrhythmia in humans: how breathing pattern modulates heart rate. *American Journal of Physiology - Heart and Circulatory Physiology 241*, H620-H629.

[5] Lehrer, P.M., Vaschillo, E. and Vaschillo, B. 2000. Resonant Frequency Biofeedback Training to Increase Cardiac Variability: Rationale and Manual for Training. *Applied Psychophysiology and Biofeedback 25*, 177-191.

[6] Merleau-Ponty, M. and Edie, J.M. 1964. Eye and Mind. In *The primacy of perception: and other essays on phenomenological psychology, the philosophy of art, history and politics*, J.M. Edie Ed. Northwestern University Press, 159-190.

[7] Mindmedia 2012. MindMedia.

[8] Newman, O. 1972. *Defensible space; crime prevention through urban design*. Macmillan.

[9] Ratti, C. and Haw, A. 2012. Living Bits and Bricks. In *Architectural Review* EMAP, London.

[10] Schnädelbach, H. 2010. Adaptive Architecture: A Conceptual Framework. In *MediaCity*, Weimar, Germany.

[11] Schnädelbach, H. 2011. Physiological Data in Adaptive Architecture. In *International Adaptive Architecture Conference*, London, 1-15.

[12] Schnädelbach, H., Glover, K. and Irune, A.A. 2010. ExoBuilding: breathing life into architecture. In *Proceedings of the Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, Reykjavik, Iceland2010 ACM, 1868965, 442-451.

[13] Sherlin, L., Gevirtz, R., Wyckoff, S. and Muench, F. 2009. Effects of Respiratory Sinus Arrhythmia Biofeedback Versus Passive Biofeedback Control. *International Journal of Stress Management 16*, 233-248.

[14] Song, H.-S. and Lehrer, P.M. 2003. The Effects of Specific Respiratory Rates on Heart Rate and Heart Rate Variability. *Applied Psychophysiology and Biofeedback 28*, 13-23.

[15] Zucker, T., Samuelson, K., Muench, F., Greenberg, M. and Gevirtz, R. 2009. The Effects of Respiratory Sinus Arrhythmia Biofeedback on Heart Rate Variability and Posttraumatic Stress Disorder Symptoms: A Pilot Study. *Applied Psychophysiology and Biofeedback 34*, 135-143.