

Enaction in adaptive architecture

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Abstract

Our life is becoming increasingly computerised at nearly all scales, a trend evident in terms such as the Smart City, the Smart Home, or the Internet of Things. The introduction of digital technology enables environments to respond to data gathered from many of our behaviours. A growing field of architectural design and research focuses on kinetic responses to inhabitant behaviour. However, the specific modes of interaction as well as the effects of such environmental responses on their inhabitants are currently underexplored. Using a literature-based approach, we argue that because such digitally augmented environments respond to bodily behaviours of their inhabitants, one important dimension of investigation is the embodied relationship between the architectural space and its occupant. One perspective that offers insight into this relationship is the so-called enactive approach to cognition, describing mutual influences between inhabitant and environment, which can create autonomous behaviour dynamics. Understanding the enacted relationship between inhabitants and environment will help architects create kinetically responsive environments that benefit their inhabitants physiologically and psychologically. The paper concludes with an overview of our lab-based research already conducted and current investigations.

Keywords

Adaptive Architecture; Enaction; Embodiment; Human-Building Interaction.

Introduction

Although we are not always aware of it, we have never been more intimately connected to our built environments. The fast increasing infusion of our buildings with sensors enables them to monitor our behaviour. But buildings do not only sense where we are and what we do, an increasing number of buildings also start to respond to our behavioural patterns. This trend manifests itself, for example, in the growing number of home automation devices, such as the *Nest* product range and mobile application frameworks like the Apple iOS *HomeKit* allowing interaction with home automation devices using a mobile phone. Similarly, *HealthKit* enables apps to utilise health-related data sensed by other devices, such as smart watches and wristbands, which sense real-time physiological data from their users, such as their heart rate.

From here, it is a small step to envision the domains of architecture on one hand and personal wellbeing and health on the other to engage each other in a near-future consumer market. Indeed, in experimental and artistic settings, the linking of real-time physiological data and architectural response is already being explored in an increasing number of adaptive environment prototypes. Specifically, these research and exhibition environments use real-time physiological data to respond directly to the bodily behaviours of their occupants. This creates an interaction cycle or loop, which can temporarily couple an architectural environment with the human body. One specific family of such an interaction loop are so-called biofeedback environments, such as *ExoBuilding* (Schnädelbach et al. 2012) (Figure 1). These reflect in real-time the inhabitant's physiological behaviour, such as their heart rate, respiration, or other physiological processes. As a result of the reflection of behaviours, an inhabitant and their adaptive environment form an interaction system similar to that between a person and their mirror image.

This new potential to make the built environment responsive to the behaviours (and emotional states) of the people inhabiting it brings both excitement and trepidation. On the one hand, it may directly contribute to our physiological and psychological wellbeing by allowing us to better relax and become more resilient towards stress. In this sense, it would support Weiser's (1991) vision of calm computing that he saw "*as refreshing as taking a walk in the woods.*" On the other hand, such environments might introduce additional stresses into our lives, potentially inducing 'over-awareness' of physiological processes and revealing very intimate behaviours, such as erratic breathing, to others nearby. Such fears were voiced by some participants in the first formal study with *ExoBuilding* (Schnädelbach et al. 2012).

Thus, understanding the psychological and physiological effects biofeedback architecture in particular and Adaptive Architecture in general have on their inhabitants will help to maximise the as of yet dormant potentials. Such potential effects include relaxation, mindfulness, and thus perhaps increased recovery and resilience. Adaptive environments might even contribute to more harmonic relationships with others if their effects are fully understood and applied in new designs.

Not understanding the effects may bring about detriments, such as the above mentioned 'over-awareness' or even direct harm as the environment may cause some inhabitants to physiologically behave in unnatural and perhaps unhealthy patterns, such as hyperventilation (breathing too quickly, possibly causing dizziness, fainting and seizures in extreme cases) or hypoventilation (breathing too slowly to provide enough gas exchange, potentially leading to suffocation).

Because of the possibilities and potential dangers, it is crucial to study the bodily relationship between inhabitants and the adaptive environments they occupy. One approach to explore such relationships is to investigate aspects of enaction, a sub-domain of embodied cognition, in adaptive architecture.



Figure 1.
ExoBuilding.

Source: Schnädelbach, H. et al., 2012. ExoBuilding: Physiologically Driven Adaptive Architecture. *ACM Transactions on Computer-Human Interaction*, 19(4), pp.1–22.

The remainder of this article first reviews Adaptive Architecture historically and with regard to the emerging digital instances of Adaptive Architecture that respond to human behaviour. The next section focuses on a specific kind of Adaptive Architecture called biofeedback architecture, which responds to its inhabitants' physiology. This leads to the discussion of 'Enaction', a concept of embodied cognition, which we relate to Adaptive Architecture. Concluding this paper, we outline our research on Enaction in Adaptive Architecture to date.

Adaptive Architecture

The central defining feature of Adaptive Architecture is that it has been intentionally designed to adapt to environmental changes or occupant behaviour, as Schnädelbach (2010) explains. Designing for constant adaptation is fundamentally different from common notions of architecture as a static construct. While responding to inhabitants in real-time is of primary importance in our research, we include for completeness that buildings might also adapt to environmental conditions such as temperature, daylight, wind, and seasons (cf. Kontovourkis et al. 2013).

The multitude of approaches and dimensions of adaptive architecture make this a diverse field, which is evident in terms such as *Interactive Architecture* (Fox & Kemp 2009), *Responsive Environments* (Bullivant 2006) or *Digitally-Driven Architecture* (Bier & Knight 2010) among a long list of others. The variety of terms and definitions also illustrates the underlying desire to innovate by exploring new technologies as well as creating more suitable, pleasant, stimulating, relaxing, efficient, or comfortable environments for their occupants.

Digital Adaptivity

Architecture has long offered manual adaptive features, ranging from nomadic tents (Kronenburg 2003) to interior screens in Japanese architecture beginning in *Shinden zukuri* (Paine 1981). More recently, sliding and revolving panels feature in Rietveld's 1924 *Schröder House* (Mulder & Rietveld 1999). Similarly, a pivoting wall corner allows changing the spatial topology in Holl's *Fukuoka Houses* (2003) (Figure 2).

As opposed to traditional, manual adaptations, our research is concerned with adaptive architecture that employs digital technologies to adapt to human behaviour. New technologies, such as wearable sensors and more powerful and versatile actuators now provide the opportunity to adapt the physical settings we occupy either automatically in a pre-defined pattern or in direct, non-prescribed response to our behaviours. The first engagement between architecture and the digital world occurred as the application of cybernetics to the architectural designs of Cedric Price (2003), such as the *Fun Palace* (Figure 3) or the *Generator project*.

While these projects were never built, they appeared to become the starting point for the vision of others, such as Mark Weiser. He developed a vision of ubiquitous computing that saw a close integration of digital technology and architectural environments. Weiser called this vision *calm computing*, which he imagined as computing technologies that completely disappeared into the background of our perception but supported our daily activities, culminating in his statement:

"Machines that fit the human environment instead of forcing humans to enter theirs will make using a computer as refreshing as taking a walk in the woods."

(Weiser 1991)

While mainly focused on screen technologies, Weiser foresaw that humans would interact with digitally augmented architectural spaces well beyond increasing efficiency in the work environment. He saw computers as becoming integral to all aspects of our daily lives, including our relationship to the physical environments we inhabit.

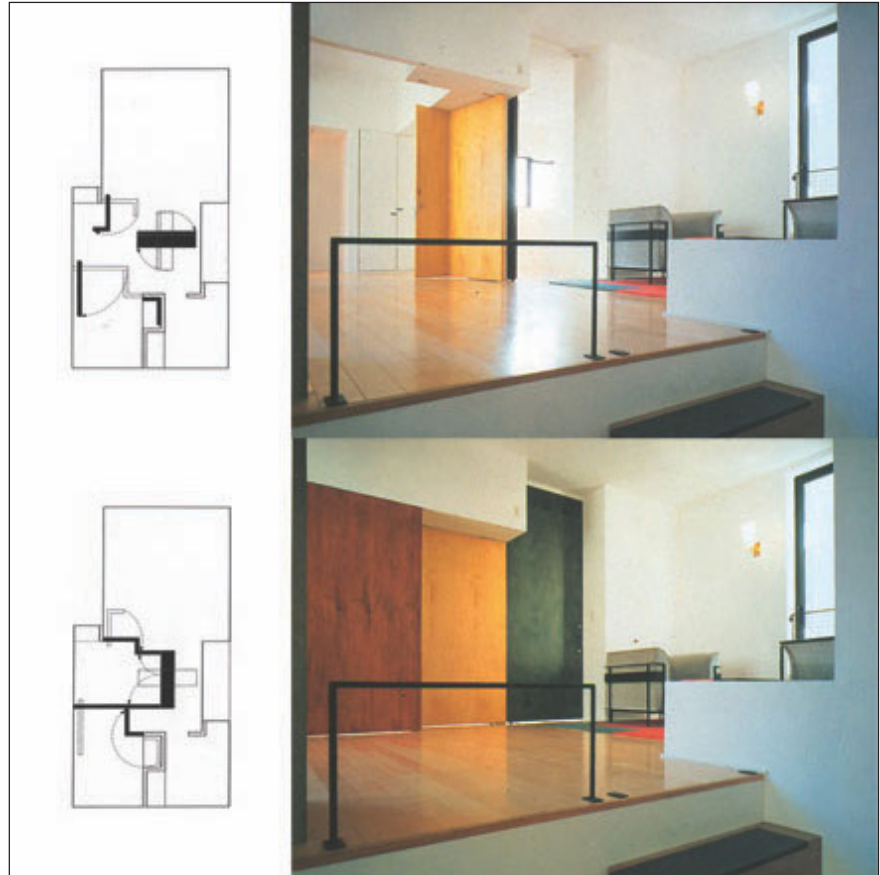


Figure 2.
 Fukuoka Houses, interior view.
 Source:
 Holl, S., Fukuoka Houses,
El Croquis N. 78,
 Steven Holl 1986-1996.

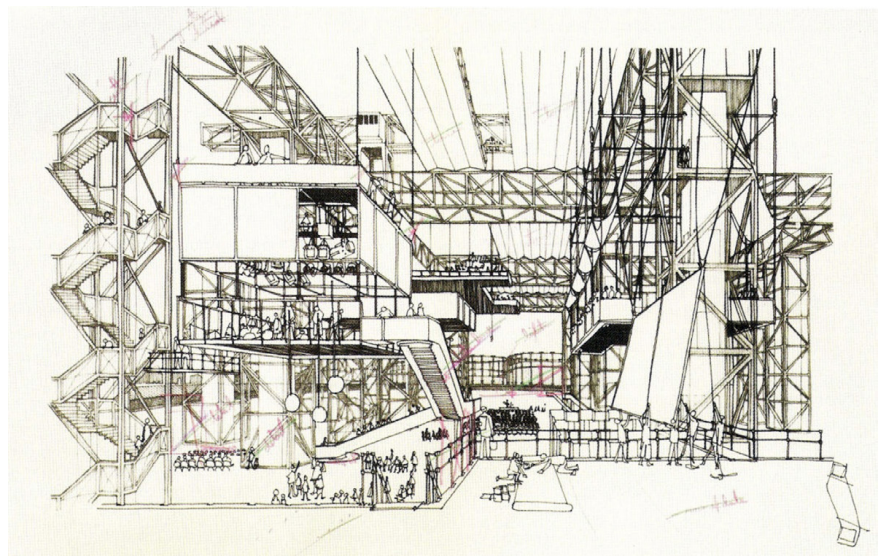


Figure 3.
 Fun Palace.
 Source:
 Price, Cedric. 2003.
Cedric Price: The Square Book.
 London: Academy Editions

One manifestation of Weiser's idea of ubiquitous computing are *Smart Homes*, which typically take the form of conventional homes augmented with technology to automate processes, such as heating, lighting, and air conditioning, provide increased inhabitant comfort, energy efficiency, time-saving or security but generally without kinetic features. They have been described and discussed in detail by others (Chan et al. 2008).

Physiological Interactions with Adaptive Architecture

More closely keeping to Weiser's vision of environments that offer experiences as refreshing and stimulating as walking in the woods, artistic and research prototypes illustrate the currently possible degree of linkage between inhabitant and environment. A common approach to adapting to the inhabitant body is a response to presence, which projects such as *ADA* (Eng et al. 2003) or the *Muscle Projects* (Oosterhuis & Biloría 2008) among numerous others illustrate (see Figure 4 and Figure 5). Much more intimate relationships between environment and occupant emerge when the environment responds to physiological behaviours, such as heart rate or respiration. As one example, *Breathe* (Jacobs & Findley n.d.) reflects (and records) the current inhabitant's breathing by swaying ceiling-hung strings (Figure 6) of one colour. Simultaneously, it replays the breathing pattern of the previous inhabitant using different coloured strings, allowing time-shifted inhabitant interaction.

More visceral experiences, compared to watching strings sway are provided by *Sonic Cradle* (Vidyarthi et al. 2012) and *ExoBuilding* (Schnädelbach et al. 2012). The former (Figure 7), a dark chamber in which the user sits, creates an adaptive soundscape in real-time response to inhabitant respiration. The latter (Figure 1) translates inhaling and exhaling in real-time into upward and downward movement of a tent-like fabric inside which an inhabitant sits. Both environments have been empirically studied and evaluated.

Biofeedback Architecture

Environments like *Sonic Cradle* and *ExoBuilding* that sense and reflect physiological behaviour of their inhabitants are called *Biofeedback Architecture*. Reflecting the inhabitant's physiological behaviour back to the inhabitant is based on the principle of biofeedback (cf. Schwartz & Andrasik 2003), which refers to the electronic monitoring and visual representation of physiological processes, such as heart rate, respiration, or electrodermal activity, in order to train a person to influence these processes voluntarily. Common goals of biofeedback are to reduce stress and build resilience.

The mechanism on which biofeedback depends is our ability to perceive actions (some form of feedback) and respond to them with new actions (adjusted behaviour), a so-called *perception-action* loop. This has also been described as a form of "dynamical attunement of organism to environment" (Gallagher & Bower 2014, pp.241/242). Being able to sense and respond to inhabitants in real-time provides buildings with such a *perception-action* system. In other words, real-time bodily communication between building and inhabitant becomes possible because of sensors and actuators. As Haque (2015) explains "We no longer think of architecture as static and immutable; instead we see it as dynamic, responsive, and *conversant*." [author's emphasis]

In biofeedback environments, the physiological behaviour of the inhabitant becomes expressed through the very fabric of the physical environment. This can also be seen as the architecture embodying its own inhabitant (cf. Jäger et al. 2014). This bodily coupling is already observable in a very small number of presently existing prototypes, such as *ExoBuilding* (Schnädelbach et al. 2012). However, this observation requires an understanding of the interactive bodily relationship between inhabitant and environment, which we introduce below.



Figure 4.
ADA.

Source:
 Bullivant, Lucy. 2005. 'ADA:
 The Intelligent Room.'
Architectural Design 75 (1).
 Academy Press: 1–5.



Figure 5.

Muscle Tower

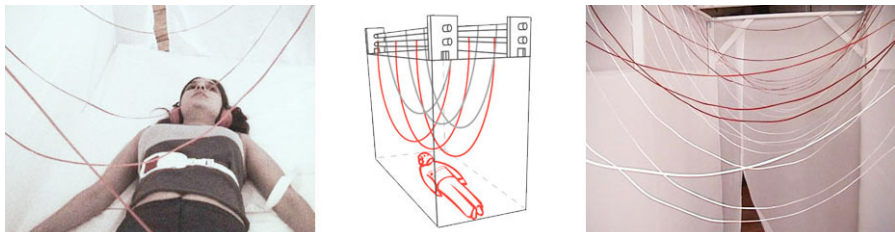
Source:
 Hyperbody, TU Delft
<http://www.interactivearchitecture.org/wp-content/imagebank/muscle-tower.jpg>



Figure 6.

Breathe

Source:
 Findley & Jacobs
<http://www.sonicribbon.com/sonicribbon/wp-content/uploads/2011/10/jessica-findley-art-breathe1.jpg>



Enaction

Enaction is a form of embodiment that emphasises the interactive nature of making sense of the world. This interaction bias, a continuous process, differentiates enaction from other common concepts of embodied cognition, such as embodiment, extension, and embeddedness. Together, these four concepts (embodied, extended, embedded, enacted) form the so-called *4E approach* to embodied cognition (Menary 2010), which we now briefly explain to provide context.

The 4E Approach to Cognition

Embodiment refers to a type of cognition that rejects the separation of mind and body as proposed by Descartes. While there is some disagreement of the importance of individual aspects of embodiment theories (Menary 2010), all approaches to Embodiment seem to agree upon most if not all concepts of the 4E approach. This approach is a synthesis of embodiment concepts that promises to comprehensively explain embodied interactions with our world. It describes embodiment through four interdependent concepts: *embodied*, *extended*, *embedded*, and *enacted*.

These four terms describe cognition as depending on the body and even occurring in its physicality, which is called *embodied*. For example, having two eyes for stereoscopic vision allows humans to see and interact with three-dimensional objects because of the specific distance they have to each other, enabling the judgment of size and distance of objects in relation to us (Rowlands 2010). Thus, *embodied* describes the specific physical setup that enables us to engage with the world.

The body also reaches out into the world, which means it is *extended*. Through our senses (haptic, gustatory, olfactory, visual, and audial) our body reaches out and extends itself into the surrounding physical world. Thus, *extended* contributes the notion that the body interacts with the environment with the aim of actively extracting useful information from objects that these contain in a “dormant” fashion (Rowlands 2010). This is distinct from *embodied* as it adds activity to the pure physicality of the body’s senses. Clark (2004) explains in detail how he thinks the extension of the body also applies in the context of computing in particular and digital technology in general.

The body is also situated in its environment—or it is *embedded*. Being surrounded by the world enables the human body to access specific parts of the environment in order to reduce mental load on the brain. How the location of the body within an environment helps the brain to make a cognitive task less demanding, is for example explained by Haselager and colleagues (2008). This differs from *extended* in terms of the perspective: *extended* sees the body as probing the environment for information, while *embedded* sees the body as being situated or immersed in a specific context.

The three previous concepts enable the body to experience the world and access information in it. They contribute to the *enacted* concept, which refers to the body acting on the world. This acting is an exploration of the world’s physical elements, which Rowlands (2010) describes primarily as exploration with the ‘visual modality.’ However, despite its recent emergence as a well-defined concept, a large number of publications on enaction, especially by De Jaegher and Di Paolo (see my discussion of their work below), argue that enacted cognition crucially consists of multi-sensory explorations of the world. They emphasise the coupling between agents and the environment and their *continuous* embodied interaction.

This definition, we argue, allows an interpretation of the *4E approach* in terms of space and time. While embodied, extended, and embedded relate the body to space, the interaction component, which is the pivotal argument of the enacted thesis, in our view, adds the dimension of time to the other three concepts (Figure 8) by focusing on the body constantly acting in, exploring, and, thus, making sense of the world.



Figure 7.

Sonic Cradle

Source:

Vidyarthi, J., Riecke, B.E.
& Gromala, D.,
(2012)

<http://tinyurl.com/jr5lsb4>



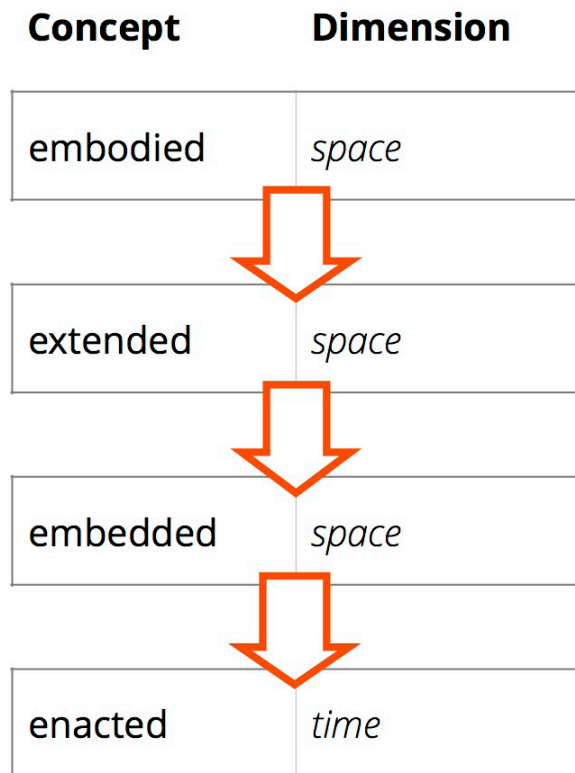


Figure 8.
Sequence and interdependence of 4E concepts

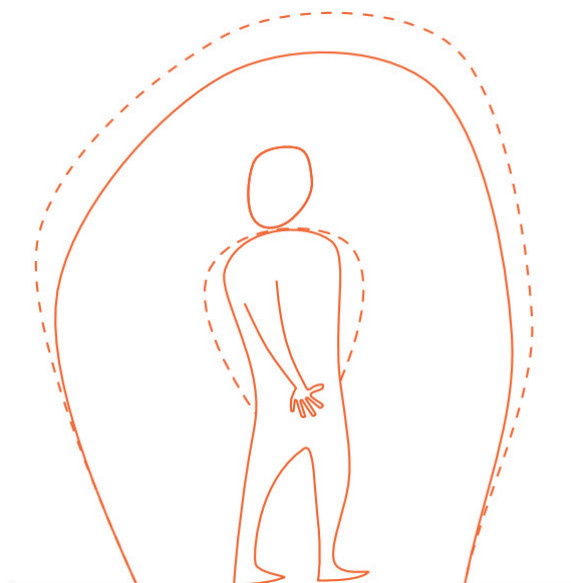


Figure 9.
Illustration of 'Embodiment' concept

McGann and colleagues (2013) argue that the core of enaction is “*the dynamic interaction between the agent and the environment.*” It is important to understand that when enaction researchers refer to ‘environment’ they typically include other humans in it. McGann et al. go on to say that out of this interaction emerges the mind of the individual—rather than the mind being an individual entity that joins into an interaction. This thesis is supported by Gallagher (2011) who argues that the interaction between two agents does more than merely adding the contributions of each agent. Instead, Gallagher explains, the interaction contributes ‘surplus value’ to both agents, as in the formula: $1 + 1 > 2$. How such surplus value emerges out of enaction in the context of Adaptive Architecture follows below.

Building blocks of Enaction

According to Di Paolo, Rohde, and De Jaegher (2010), five concepts build the nucleus of the enactive approach, consisting of: *embodiment, autonomy, emergence, experience, and sense-making.*

Embodiment

For the enactive approach, the crucial interpretation of embodiment is that of “*bodily-mediated cognition*” (Di Paolo et al. 2010) or that cognition quite literally (but without the intent of trivialising it) depends on the body. The activities in which the body engages allow us to be autonomous agents who actively make sense of their interactions with the environment, including other agents.

As an interactive system, Adaptive Architecture relies on the inhabitant to interact with it by using the body. Sensing and actuation technology allows for mutual embodiment to occur in which inhabitant and the environment embody each other. The environment translates behavioural data emanating from the inhabitant into its own action potential. The inhabitant, on the other hand, embodies the environment by means of their own perception-action loop. Sensing and reacting to the actions of the environment enables the inhabitant to incorporate environmental behaviour into their perception of their own body as if they were looking into a mirror. McGann and colleagues (2013) explain:

“By coordinating its activities with the world around it the agent effectively incorporates the environment into its own on-going behaviour.” (p. 206)

Autonomy

Autonomy is the ability of agents to “*follow laws set up by their own activity*” (Di Paolo et al. 2010). Agents do not passively react to external stimuli. Instead, they actively control how to interact with their environment.

For the interaction between an adaptive environment and its inhabitant, autonomy relates mostly to the human inhabitant rather than the environment. The inhabitant acts of their own volition and can create their own rules of interaction. In the case of biofeedback architecture responding to breathing, the inhabitant might adjust their breathing amplitude or frequency or both in order to modulate their interaction with the environment.

Emergence

Di Paolo and colleagues (2010) explain *emergence* as the creation of a completely new entity (process or property) out of the interaction of agents. This new entity itself is autonomous (see above). One might think of synchronous behaviour that sustains itself until one of the agents actively breaks the synchrony.

In general terms, what emerges from the interaction between inhabitant and adaptive environment is an experience for the inhabitant. In environments that respond to breathing,

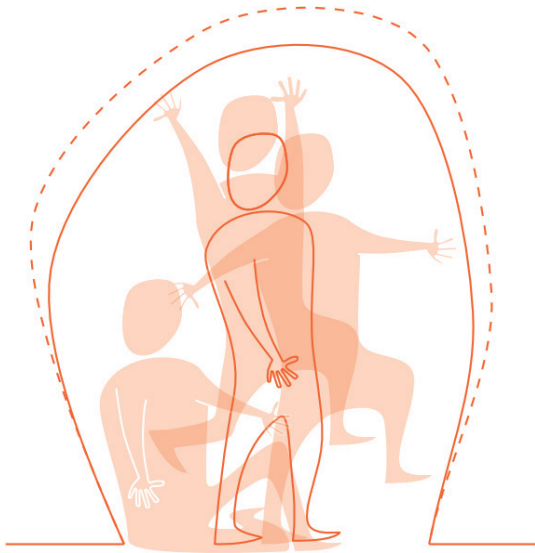


Figure 10.
Illustration of 'Autonomy' concept

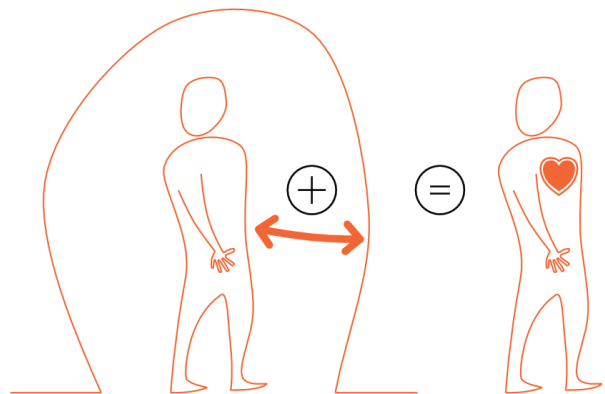


Figure 11.
Illustration of 'Emergence' concept

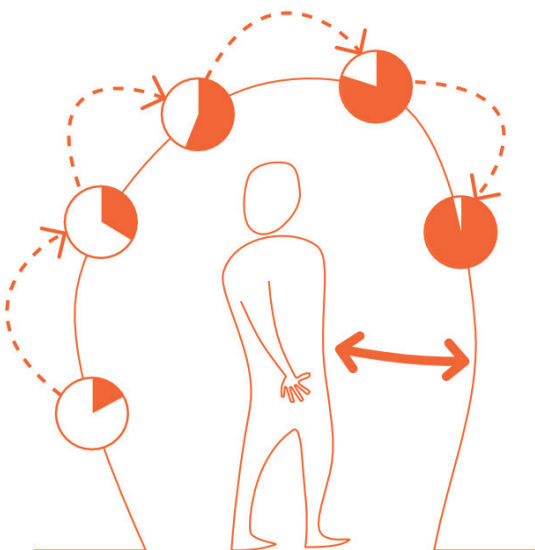


Figure 12.
Illustration of 'Experience' concept

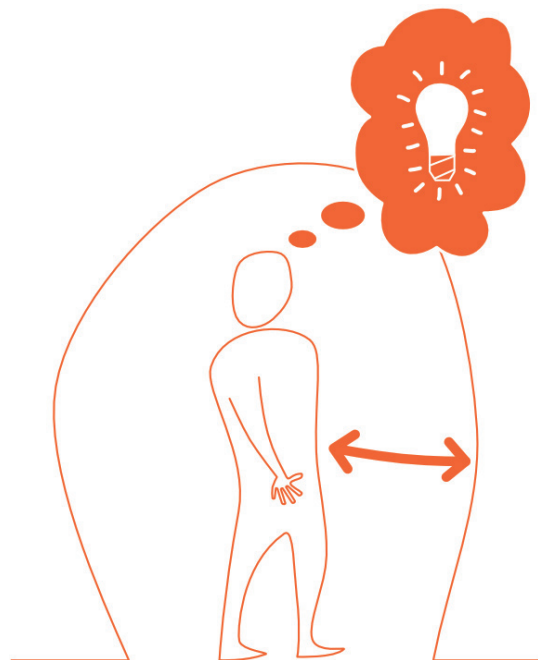


Figure 13.
Illustration of 'Sense-making' concept

the experience might be an increased self-awareness of one's own respiration and potential health benefits. Through repeated interactions with the environment, their health may improve (e.g., lower respiration rates, lower stress levels, increased resilience).

Experience

Di Paolo et al interpret experience as *"intertwined with being alive and immersed in a world of significance."* (2010, p.43) They argue that experience and embodiment are closely interwoven, stating *"we find a lawful relation of bodily and experience transformations."* For example, skills are acquired in a process of improving performance through practice: as we improve, the task becomes easier, and we can focus on, performing it faster, more beautifully, or using less energy.

Adaptive Architecture, especially biofeedback architecture, relates to experience regarding its close relation to embodiment. As the interaction between inhabitant and environment progresses, either within the same session or across multiple sessions, the inhabitant becomes more practiced and more skilled in this interaction.

Sense-making

Finally, *sense-making* is a process closely connected to autonomy. Since autonomous agents interact with their environments and gain experience/skills by adjusting the manner in which they interact, they extract meaning from the interactions (Di Paolo et al. 2010). De Jaegher and Di Paolo (2007) point out that sense-making is an actively pursued process that, at least socially, occurs with other agents in a mutual interaction, making it a participatory process. Agents do not access *"their world in order to build accurate pictures of it. They directly participate in the generation of meaning by their action; they enact a world"* (Di Paolo et al. 2010, p.39).

While interacting with Adaptive Architecture inhabitants create meaning by dynamically interacting with their environment. When interacting physiologically with an environment like Sonic Cradle or ExoBuilding, inhabitants may seek relaxation or mindfulness. The pursuit of this goal is an act of sense-making in which the environment participates by providing feedback, which allows inhabitants to achieve their goal.

To summarise, interactions with Adaptive Architecture cannot occur without the body of the inhabitant (*embodiment*). Each inhabitant can individually affect and define the interaction (*autonomy*). From the interaction with the adaptive environment may, for example, emerge increased wellbeing or improved relationships with other agents. Over time inhabitants gain *experience* in their environmental interaction, they acquire and improve a skill. This skill enables them to better *make sense* of the world, such as how to interact with the adaptive environment to feel more relaxed or mindful or be in tune with it. Thus, inhabitant and adaptive environment engage in a special relationship that binds them temporarily together. It couples them.

Coupling with the (Adaptive) Environment

Enactive researchers specifically investigate the coupling between "cognisers" and their environment. McGann and colleagues (2013) elaborate:

"In trying to understand coupling, enactive researchers examine the perception-action loop as involving the coupling (and hence dynamical modulation) between brain, body, tools, objects, other people, and context in general." (p.204)

It is possible to identify the perception-action loop not only in an inhabitant but now also in an adaptive environment (sensors and actuators). Because the environment has, technically speaking, sensorimotor skills, it can reciprocate behaviour. A biofeedback

environment by definition reciprocates behaviour because it reflects or mirrors its inhabitant's physiology. Thus, the environment and its inhabitant are both equipped to coordinate their behaviour and partake as agents in the same interaction. Consequently, *Enacted Adaptive Architecture* is a collective of interacting agents constituted of humans and architecture specifically designed to adapt.

A Research Agenda for Enacted Adaptive Architecture

Each of the five building blocks of enaction is an interesting area to investigate with regard to Adaptive Architecture. De Jaegher and Di Paolo (2007) suggest to also empirically study *coordination dynamics*, and *movement analysis* in the context of enaction, stating that “*experimental approaches that minimise and control sensorimotor coupling [...] are likely to yield the most interesting results.*” They further suggest “*a disciplined approach to the experience of interaction, including experiences such as connectedness.*”

Researching Enaction in Adaptive Architecture

In our research, we have so far investigated the sensorimotor control relationship between inhabitant and adaptive environment as well as physiological synchrony (similar to coordination dynamics and connectedness) between two inhabitants mediated by a newly designed multi-user adaptive environment.

A paper on the control relationship between inhabitant and adaptive architecture is under review. This empirical, lab-based work suggests that adaptive environments can make use of the biofeedback loop to initiate different behaviours of their own. Such environment-initiated behaviours, for example aiming to directly influence respiratory frequencies of inhabitants, can then guide inhabitants to new and potentially optimised (healthier) behaviours.

Another submitted paper illustrates the research-based design of the multi-user adaptive environment called WABI. This paper discusses the challenges of meaningfully mapping real-time data streams emanating from two colocated inhabitants to various parts of the surrounding architectural space. The paper further speculates on the operability, interactions, and application of data mappings to architectural space when the environment accommodates a multitude of inhabitants.

A paper currently in preparation introduces a lab-based, qualitative study investigating dual inhabitant interactions within WABI. This and the above research on control suggest that inhabitants and adaptive environment are closely tied into an enactive relationship in which they mutually and constantly affect each other. Out of this enactive relationship emerges the particularly positive effect for inhabitants of behavioural synchrony in the form of synchronised breathing between them. Benefits of behavioural synchrony, as shown by others, include but are not limited to improved interpersonal relationships, cooperation, memory, pro-social attitudes, and an elevated pain threshold.

Moving our research from lab-based investigations into the real-world, we recently deployed a respiration-responsive multi-user biofeedback environment in an elderly care setting. This deployment explores the effects of the enactive relationship between adaptive environment and inhabitants in the context of residential elderly care. Furthermore, we investigate the limitations as well as the acceptance of this technology in this context. This will deepen our understanding of the applicability of the enactive design approach as well as exploring a real-world application for behaviour-responsive Adaptive Architecture.

Conclusion

Due to the increasing impact new technology has on the built environment, it is vital to investigate the physiological and psychological effects of such augmentations. When these technologies enable environments to become kinetically adaptive to inhabitant behaviour, questions regarding the emerging enacted relationships need to be addressed. In the future, we intend to investigate additional aspects of enaction in relation to Adaptive Architecture, which will include further explorations of real-world applications, such as leisure, work, and health.

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