NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTMENT
OF PHYSICS

NON-VERBAL COMMUNICATION WITH PHYSIOLOGICAL SENSORS

THE AESTHETIC DOMAIN OF WEARABLES AND NEURAL NETWORKS

WILLIAM RUDDOCK PRIMETT

Master in Creative Computing

DOCTORATE IN BIOMEDICAL ENGINEERING

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Non-verbal Communication with Physiological Sensors

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“Falling is one of the ways of moving.” (Merce Cunningham)

Abstract

Historically, communication implies the transfer of information between bodies, yet this phenomenon is constantly adapting to new technological and cultural standards. In a digital context, it's commonplace to envision systems that revolve around verbal modalities. However, behavioural analysis grounded in psychology research calls attention to the emotional information disclosed by non-verbal social cues, in particular, actions that are involuntary. This notion has circulated heavily into various interdisciplinary computing research fields, from which multiple studies have arisen, correlating non-verbal activity to socio-affective inferences. These are often derived from some form of motion capture and other wearable sensors, measuring the 'invisible' bioelectrical changes that occur from inside the body.

This thesis proposes a motivation and methodology for using physiological sensory data as an expressive resource for technology-mediated interactions. Initialised from a thorough discussion on state-of-the-art technologies and established design principles regarding this topic, then applied to a novel approach alongside a selection of practice works to compliment this. We advocate for aesthetic experience, experimenting with abstract representations. Atypically from prevailing Affective Computing systems, the intention is not to infer or classify emotion but rather to create new opportunities for rich gestural exchange, unconfined to the verbal domain.

Given the preliminary proposition of non-representation, we justify a correspondence with modern Machine Learning and multimedia interaction strategies, applying an iterative, human-centred approach to improve personalisation without the compromising emotional potential of bodily gesture. Where related studies in the past have successfully provoked strong design concepts through innovative fabrications, these are typically limited to simple linear, one-to-one mappings and often neglect multi-user environments; we foresee a vast potential. In our use cases, we adopt neural network architectures to generate highly granular biofeedback from low-dimensional input data.

We present the following proof-of-concepts: Breathing Correspondence, a wearable biofeedback system inspired by Somaesthetic design principles; Latent Steps, a real-time auto-encoder to represent bodily experiences from sensor data, designed for dance performance; and Anti-Social Distancing Ensemble, an installation for public space interventions, analysing physical distance to generate a collective soundscape. Key findings are extracted from the individual reports to formulate an extensive technical and theoretical framework around this topic. The projects first aim to embrace some alternative perspectives already established within Affective Computing research. From here, these concepts evolve deeper, bridging theories from contemporary creative and technical practices with the advancement of biomedical technologies.

Keywords: Wearable Sensors, Non-Verbal Communication, Interaction Design, Aesthetics, Machine Learning.

Resumo

Historicamente, os processos de comunicação implicam a transferência de informação entre organismos, mas este fenómeno está constantemente a adaptar-se a novos padrões tecnológicos e culturais. Num contexto digital, é comum encontrar sistemas que giram em torno de modalidades verbais. Contudo, a análise comportamental fundamentada na investigação psicológica chama a atenção para a informação emocional revelada por sinais sociais não verbais, em particular, acções que são involuntárias. Esta noção circulou fortemente em vários campos interdisciplinares de investigação na área das ciências da computação, dos quais surgiram múltiplos estudos, correlacionando a actividade não-verbal com inferências sócio-afectivas. Estes são frequentemente derivados de alguma forma de captura de movimento e sensores "wearable", medindo as alterações bioeléctricas "invisíveis" que ocorrem no interior do corpo.

Nesta tese, propomos uma motivação e metodologia para a utilização de dados sensoriais fisiológicos como um recurso expressivo para interacções mediadas pela tecnologia. Iniciada a partir de uma discussão aprofundada sobre tecnologias de ponta e princípios de concepção estabelecidos relativamente a este tópico, depois aplicada a uma nova abordagem, juntamente com uma selecção de trabalhos práticos, para complementar esta. Defendemos a experiência estética, experimentando com representações abstractas. Contrariamente aos sistemas de Computação Afectiva predominantes, a intenção não é inferir ou classificar a emoção, mas sim criar novas oportunidades para uma rica troca gestual, não confinada ao domínio verbal.

Dada a proposta preliminar de não representação, justificamos uma correspondência com estratégias modernas de Machine Learning e interacção multimédia, aplicando uma abordagem iterativa e centrada no ser humano para melhorar a personalização sem o potencial emocional comprometedor do gesto corporal. Nos casos em que estudos anteriores demonstraram com sucesso conceitos de design fortes através de fabricações inovadoras, estes limitam-se tipicamente a simples mapeamentos lineares, um-para-um, e muitas vezes negligenciam ambientes multi-utilizadores; com este trabalho, prevemos um potencial alargado. Nos nossos casos de utilização, adoptamos arquitecturas de redes neurais para gerar biofeedback altamente granular a partir de dados de entrada de baixa dimensão.

Apresentamos as seguintes provas de conceitos: Breathing Correspondence, um sistema de biofeedback wearable inspirado nos princípios de design somaestético; Latent Steps, um modelo autoencoder em tempo real para representar experiências corporais a partir de dados de sensores, concebido para desempenho de dança; e Anti-Social Distancing Ensemble, uma instalação para intervenções no espaço público, analisando a distância física para gerar uma paisagem sonora colectiva. Os principais resultados são extraídos dos relatórios individuais, para formular um quadro técnico e teórico alargado para expandir sobre este tópico. Os projectos têm como primeiro objectivo abraçar algumas perspectivas alternativas às que já estão estabelecidas no âmbito da investigação da Computação Afectiva. A partir daqui, estes conceitos evoluem mais profundamente, fazendo a ponte entre as teorias das práticas criativas e técnicas contemporâneas com o avanço das tecnologias biomédicas.

Palavras-chave: Sensores, Comunicação não verbal, Design de Interação, Estética, Inteligência Artificial

Contents

1

Introduction

In the process of any given interaction, humans will naturally reveal a vast arrangement of signals independently from speech. Physical traits such as posture, gait or eye contact come under the social phenomenon known as non-verbal behaviour. Other examples of these cues commonly studied in the literature include facial expressions and tone of voice [83, 87], assuming a kind of social cue that's observable during a conventional human-human exchange when given deliberate attention. However, we should also take into account the changes that take place inside the body, being those not so easily perceived without way of technological intervention.

1.1 Motivation

Affective Computing and specifically the combination of physiological sensing and cognitive frameworks, has been an active field of study for over two decades [345], securing prospects for developing emotionally-informed systems. A significant progression in this field can be conclusive of using state-of-the-art machine learning (and deep learning) methods to interpret large-scale datasets, achieving honourable breakthroughs in view of emotion recognition studies [54]. Such systems tend to operate according to linguistic descriptors of universal emotions, a process known as the informational view [49]. From a communication standpoint, we recognise that these discrete representations become less meaningful when perceived in lack of contextual information. An emerging area of research considers the role of interactive systems for sharing physiological activity between users, enhancing connectedness by way of anatomical transparency [291]. The resulting artefacts tend to utilise raw forms of data representation, disregarding emotional interpretation. Simultaneously, embodied sensor technology has been incorporated into creative practices, commonly as a means to capture emotional qualities of bodily gestures during performance, and then being able to transmit this information to a third-person perspective [144].

In addition, aesthetic representations have been incorporated into a wide range of user-centred technologies, observed by the broader vision of third-wave Human-Computer

Interaction (HCI), through the comprehension that aesthetics are not bound to formal artistic creation but an essential function of sensorial engagement [47]. Building upon these trends, novel systems have been capable of capturing and mediating the emotional experiences that present themselves in everyday life [394].

We identify a motivation and methodology for using wearable sensors as an expressive resource for speechless dialogue, putting aesthetics at the forefront of interaction. Initialised from a thorough discussion on state-of-the-art technologies and established design principles regarding this topic, then applied to a novel approach alongside a selection of practical works to complement this. Given the preliminary proposition of non-representation, the intention is not to infer or classify emotion but rather to create new opportunities for rich gestural exchange, unconfined to the verbal domain. Embracing the right to express oneself from the within, taking the heart, lungs, muscles and motor activity as a basis for maintaining expressive speechless dialogue through the act of being present with the self, others and social environment.

1.2 Core Research Questions

This work focuses on three main research questions: (1) Why should embodied sensor technologies be used to mediate non-verbal dialogue? (2) What mediums are capable of producing emotionally meaningful representations of physiological signals, suitable for social intervention? And (3), by adopting methods from modern Machine Learning and New Media practices, how can aesthetics be incorporated into visuals, sound and haptic mechanisms to articulate and express emotional content? And how does this encourage user empowerment and penalisation for effective intervention? Each of these components are further detailed in the following segment.

1. **Why.** Given the layers of novelty and interdisciplinary nature of our work, weaving between the domains of data science, psychology, artistic performance and interaction design, we commit to delivering a comprehensive review of relevant research actions presented in the state-of-the-art, and validate our appropriation of such technologies and practices.

2. **What.** Part of our research is also devoted to evaluating specific technologies that can be used. Starting from the common wearable sensing modalities, reviewing the interactive affordances of each, along with their corresponding feature extraction methods to retrieve emotionally relevant information. We evaluate methods for producing novel representations and the appropriate mediums for communicating this between users, whether that be through sound, visual or hardware-based interaction, in a way that balances aesthetic and informational qualities.

3. **How.** By adopting user-centred design principles from third-wave HCI research, already demonstrating success in these areas, we aim to push more towards technical

transparency, in that the user is really a part of the design process and consequentially feels a sense of authority over the system. This assumes a level of responsibility towards proactive sense-making, by way of parameter adjustment, personal contributions to datasets, and voluntary participation.

1.3 Collaborations and Affiliations

The works presented have been realised as a result of the collaborations between academic, industry and cultural representatives. The following have sustained the research process in providing the financial, technical and human resources necessary to successfully carry out the user studies. The individual contributions derived from these collaborations will be explicitly noted where applicable throughout the thesis document.

The PhD research was partly funded by the Innovative Training Network “Marie Curie Actions” supported by the H2020 People Programme (GA 722022) entitled **AffecTech**, incentivised towards developing personal health technologies for affective disorders, and bridges expertise from physiology, engineering and interaction design. This interdisciplinary network is responsible for spawning the underlying motivations of the thesis, maintained through various collaborative research activities.

The majority of the PhD was supported under the employment of **PLUX Wireless Biosignals S.A.**, responsible for supplying the foundation of technical materials used in the research outputs, namely the BITalino R-IoT device, along with sensory peripherals that were manufactured and customised in-house. This collaboration was intrinsic to the adoption of the specific materials used to develop our practical works while more generally being symbolic to the use of low-cost solutions for designing sensor-based applications.

A significant portion of the research was achieved in partnership with the Creative Europe initiative, **Moving Digits: Augmented Dance for Engaged Audience**. The team were responsible for coordinating field research in the context of dance performance over the course of two years. The project received local support from Madeira Interactive Technologies Institute (M-ITI) and Sõltumatu Tantsu Lava (STL), responsible for hosting the workshops and research residencies that are detailed in Chapters 6 and 8. The research team was also in charge of acquiring participants with specialist skill criteria to take part in the studies, specifically referring to a group of professional artists working at the intersection of contemporary dance and technology.

The division of Interaction Design at **KTH Royal Institute of Technology** was responsible for hosting a personal research secondment that resulted in the research actions contained in Sections 5 and 7, accompanied by authoring contributions to the thesis publications. While having direct contact with highly acclaimed figures in the Somaesthetic design community [211], these collaborations were immensely influential in our adoption of such principles exemplified in contemporary interaction design.

1.4 Thesis Structure

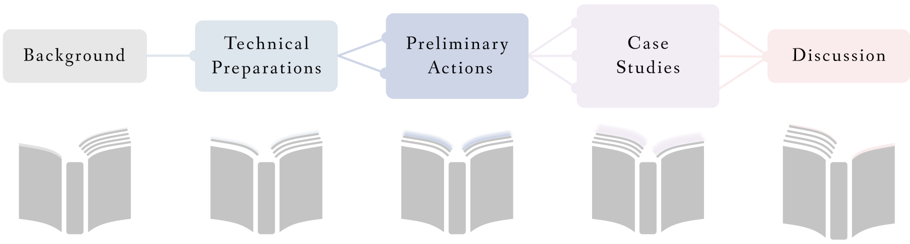

Figure 1.1: Thesis structure divided into five stages.

Chapter 1: Introduction

The current section briefly sets out the underlying motivation and raises the major research questions that run consistently throughout the thesis research.

Chapter 2: Theoretical and Technical Concepts

Chapter 2 provides a background to the technical and theoretical concepts that form the foundation of the thesis based upon four constructs: Non-verbal Communication; Physiological Sensors; The Aesthetic Domain; and Neural Networks. These constructs establish the major themes of the research and introduce conceptual bridges therein. From a technical standpoint, we provide a primer on the different physiological signals commonly used in the corresponding literature, noting their relevance and usability when applied in a given experimental context. We also take the opportunity to introduce some standard practices used in relevant research fields, such as Gesture Analysis, Social Signal Processing and the philosophical underpinning of Somaesthetics. Advancing from various topics grounded in computing and psychology research, we start to uncover a firm basis for aesthetic evaluation in the context of technological intervention as social-affective mediation.

Chapter 3: Literature Review

In Chapter 3, we comment on some relevant literature covering the following key topics of interest, first looking at established research fields, namely, Affective Computing, Social Signal Processing, Interactive Machine Learning, Somaesthetic Design, and Non-Representational Theory. Then, to cover the broad domains of biosignals in creative practice, the appropriation of wearable sensors in creative practice and performance context, the social impact of sharing physiological activity and recognised methods for emotional representation are reviewed. Following an overview of a diverse range of topics and research outcomes, we try to draw out a conceptual narrative, justifying the intersection of these topics and identifying core design principles to be adopted into the research actions that follow, as described throughout the subsequent chapters.

Chapter 4: Technical Preparations

In Chapter 4, we will introduce and examine a set of hardware and software tools developed within the duration of the PhD, and adopted to augment collaborative sensor-based interactions. This will include the design of specialised wearable devices for physiological data sensing in the wild, temperaments for latency estimation, and systems for processing and preparing sensor data for various interactive environments. An underlying aim here is to utilise web-based data transmission protocols to deploy interactive systems in a portable and spontaneous fashion, establishing a basis for studies to take place "in the wild".

Chapters 5 & 6: Preliminary Actions

Our Preliminary Actions (Chapters 5 and 6) are initiated with an individualistic exploration of input-output mediums for physiological representation, forming a broad foundation of aesthetic affordances when testing with our own bodies. Transitioning from an introspective experience, we prepare engagements with a selection of specialist user groups deemed suitable for providing new insights in a series of workshops comprised of focus group, data collection, ideation and evaluation stages. The research outcomes contained in the Preliminary Actions I and II are used to support the proceeding Case Studies I and II (Chapters 7 and 8) respectively.

Chapters 7, 8 & 9: Major Case Studies

Following these research actions, we present a collection of case studies that are realised using the knowledge organised from the prior research actions. In Chapters 7, 8 and 9, we will present a set of experimental systems developed during the PhD, each intended to establish a theoretical framework for designing systems for emotional exchange. Given this experimental methodology, a matured research space should provoke and sustain discussions around the socio-political implications of technological interventions and appropriation in preparation to be deployed in out-of-lab environments, eventually gearing towards pervasive engagement.

Chapter 7: Results and Discussion

Finally, we can reflect on a multi-layered research process (Figure 1.1) and consolidate the overall outcomes rooted in the essential research appeal of the thesis. These are ultimately formulated as aesthetic considerations when designing for sensation, representation and communication in the context of sensory intervention. In Chapter 10, we open up to some of the major limitations present in our work, disclosing the additional paths for investigation, and closing the thesis with a call for future work in the push towards aesthetic engagement with communication technologies.

2

Theoretical and Technical Concepts

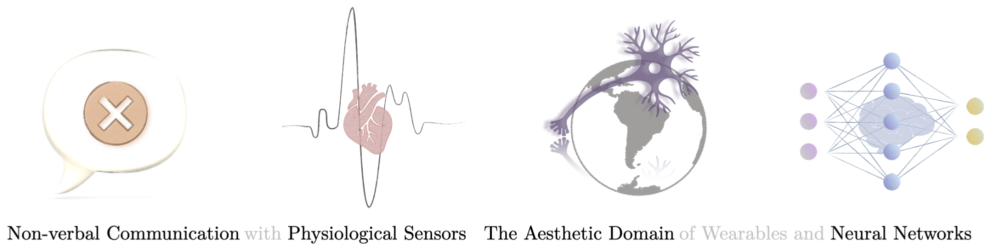

Figure 2.1: Title constructs illustrated.

In the following section, we initiate the theoretical framing directed towards the thesis research goals. We begin by breaking down the thesis title into four constructs that are used to establish the major themes of the research (shown in Figure 2.1), each accompanied by preliminary definitions as well as key references present in the literature. We aim to address some of the commonalities between these that help to unify these concepts into a common research goal. This framework is further supplemented with an overview of key principles taken from other complementary fields, concluding with a proposed criteria for aesthetic evaluation. Herein the title *"Non-verbal Communication with Physiological Sensors: The Aesthetic Domain of Biosignals and Neural Networks"* is distilled into its base constructs and explained.

2.1 Base Constructs

Non-Verbal Communication

Non-verbal communication is an umbrella term used to distinguish modalities of interpersonal exchange that are independent of speech, many of which are unconsciously transmitted during social relations, this encompasses a variety of modalities that convey emotions, feelings, and messages. Behavioural analysis grounded in psychology research calls attention to the emotional information disclosed by non-verbal social cues, in particular, actions that are involuntary. Computing and Physiology researcher Alex Petland frames these as *Honest Signals* to articulate a level of emotional authenticity while complimentary studies note the permitted degree of ambiguity.

"The unconscious quality of particular informative non-verbal behavioural cues grants a level of authenticity." Pentland and Heibeck [341].

Physiological Sensors

Physiological signals provide a measurement of biophysical, biomechanical and bioelectrical changes that occur from within the body. These data streams can be used to validate semantic emotional descriptors based on valence and arousal measurements, linked to the user's involuntary reactions transmitted by the Autonomic Nervous System (ANS) [273, 406]. These are widely used to monitor a plethora of non-verbal social cues, measuring the 'invisible' internal signals that are otherwise not explicitly perceived.

Non-verbal behaviour is commonly associated with "body language", aspects such as posture, gaze and other observable traits. But how about bodily signals that are invisible from a third-person perspective? Signals acquired using physiological sensors (or biosignals) are capable of monitoring these internal changes, that can be associated with an emotional response, typically in accordance with a measure of arousal, that operates on a unidimensional scale.

"In other words, nonverbal behavioural cues are the physical, machine detectable evidence of affective phenomena not otherwise accessible to experience, an ideal point for technology and human sciences to meet." Vinciarelli and Mohammadi [455].

The Aesthetic Domain

To put forward such a heavily loaded concept, we can reduce aesthetics down to its literal derivative of *aístesis*, which describes the process of perceiving through sensory engagement. Whilst this phenomenon is continually re-evaluated, it can be assumed to operate on a scale of order and complexity. This is essentially how we as humans are able to perceive new kinds of information contained in our surroundings, reducing to a meaningful inference, through a process of learning as a result of personal experiences. From this, we consider ambiguity as an affordance for expressive exchange. In *Two Modernist Approaches to Linking Art and Science*, Eric R. Kandel ties relevance to the art history concept of the beholder's share to the biological understanding of the human mind [242].

"Human emotional life is rich; we can experience a huge number of emotions, possibly a continuum, not just a few for which we have words, like fear, sadness, joy, etc." Perlovsky [343].

Neural Networks

An artificial neural network aims to simulate the core functions of the human brain, used to define complex input-output patterns, using previously learned information to comprehend sensory inputs. Combined with the other constructs, we consider the human-like qualities of Artificial Neural Networks (ANNs) as the technical foundation for emotional engagement with physiological data. Considering that modern data science practices have already validated neural networks as an effective method for associating human-understandable contexts to otherwise ambiguous sensor data [54], we reflect upon human-centred augmentations by which the user is immersed in the learning process.

"Treating embodied knowledge as something that cannot be accessed directly and only through examples of action (treating the learning algorithm as a "black box") is therefore missing a lot." Gillies [176].

2.2 Physiological Signals

Categories

In this document, we will cover a range of physiological signals in the context of potential interaction modalities. Physiological signals can be categorised according to the origin of the activity that is being recorded from the body [133]. The signals we will be assessing and comparing in this work are defined as bioelectrical and biomechanical. Bioelectrical signals provide a measurement of the electric and electromagnetic fields produced by living cells. Examples include Electromyography (EMG), Electrocardiogram (ECG), and Electrodermal activity (EDA) [297]. Biomechanical signals on the other hand measure the physical forces produced by or applied to the cells, tissues and organs. These include respiratory cycles and acceleration of the limbs [189, 336]. The complete list of categories based on anatomical origin is comprised of biomagnetic, biochemical, bioacoustic and biooptical signals. For more detailed information on physiological signals, we may refer the reader to [462].

Controllability

We take into account the controllability a subject has on a given physiological response, depending on the source, which can be classified as *Voluntary*, *Indirect* or *Involuntary*. Through *Voluntary* sources, the user can intentionally manipulate the signal with a high degree of freedom. These include, for example, muscle contractions or displacement of joints, activities that are associated with the somatic nervous system. *Indirect* (or *Mixed*) sources grant the user partial control whereas *Involuntary* sources indicate that there's almost no control over the outcome [410]. *Involuntary* sources are generally assumed to be transmitted from the autonomic nervous system as they occur without conscious control [271].

Movement is normally categorised as a visible and voluntary action in the scope of physiological signals, and understandably so when compared to internal functions receptive to the ANS, such as cardiovascular activity. We aim to support the persuasion that many non-verbal behaviours do in fact materialise as involuntary motor actions [202] or even spontaneous micro-gestures [90], those so subtle that they can be difficult to perceive without any technological intervention, such as body-worn sensors [229].

Applications and Research

Physiological sensing is studied prominently under the interdisciplinary field of biomedical engineering. This prides itself on pulling new perspectives from research fields such as electronics, programming, humanities, culture and psychology, and as such, invites specialists from alternative disciplines to validate insights outside of traditional practices [133]. For example, in affective computing research, the study of human psychology is vital for understanding the detection and regulation of emotions using technology. The term lends itself towards a vast selection of applications and research topics, to an extent that is impressive without doubt, but at the expense of obscurity when trying to determine a meaning that is inclusive. For example, biomedical engineering may be rightfully allocated to the production of prosthetic devices intended for physical rehabilitation [450], while on the other hand, it serves as a relevant label for say, a biofeedback system design for guided meditation [153]. What binds these distinct functions can be owed to the appropriation of biomedical technology and data, which can be divided into two major essential categories:

- **Sensors**: These are the components that are responsible for acquiring physiological signals from the body, purposed to measure the specific bodily processes that occur. Section 5 provides a general overview of the main sensor modalities used in our research, while discussing their aesthetic affordances.
- **Actuators**: This describes some form of output mechanism that is being manipulated by the sensor data; the process in which we perceive this representation of physiological activity describes the foundation of biofeedback (in some design contexts, such actuation systems may be referred to as interactive artefacts)

As we begin to appreciate the value of such collaborations outside of the strictly medical domain, we will present our research efforts to continuously defend the inclusion of aesthetics, primarily in the scope of emotional modelling technology, but also in the broader scope of biomedical science. We foresee a co-benefit between the appropriation of physiologically-centred systems for artistic practices, and enhancing our sensory engagement with technology.

Our three major case studies will address a selection of physiological sensing modalities from those commonly found in the relevant literature. From Chapter 7, we start with respiratory sensing, followed by intertial motion, combined with EMG in Chapter 8, and finally, in Chapter 9, we consider novel ways of sensing interpersonal proximity, captured externally from the body. Though non-exhaustive, are considered relevant for observing a range of introspective and collective behaviours; perceived internally and externally; and performed with varying degrees of control.

2.3 Non-verbal Cues as Social Signals

A fundamental objective of this work is to explore methods of communicating emotional or affective states without a dependency on spoken language. Non-verbal communication is a term that encompasses a variety of modalities such as posture, physical gestures or facial expressions to convey emotions, feelings, and messages beyond the use of words [251, 367]. This can be interpreted to augment meaning alongside the verbal channel during an interaction, or by itself in circumstances where there are only non-verbal channels present.

Non-verbal signals can be described as communicative or informative. A signal is produced consciously in an effort to convey a specific meaning that is communicative. On the other hand, when the user emits signals unconsciously, without an intended meaning, it is informative [455].

The field of Social Signal Processing (SSP) can be tied to the increased importance of emotional sensibility covered in third-wave HCI research [98]. Social Signal Processing revolves around the monitoring of non-verbal behaviour to analyse social interactions. The attention directed towards non-verbal communication can be justified as a method of extracting social signals that are hard-wired in the human brain [454].

2.4 The Embodiment of Expression, A Theoretical Primer

The association between emotions and bodily expression in humans and animals was first described by Darwin [103], which has been followed by numerous studies in social psychology, human development, and more recently HCI [8, 143, 175] to address the communication of emotions from the human body [192]. In this work, we will be working with the existing non-verbal modalities of gesture and posture, which are considered aspects of kinesics. They are both executed from the body and have the capacity to transmit social messages, but can be differentiated by their degree of intentionally and kinematic quality. Gestures are often (though not always) associated with movement and classed as communicative, as they are performed consciously [455]. A subcategory of gestures, known as *adaptors* are performed unconsciously which may indicate changes in arousal or anxiety [199, 328].

Social signals addressed from postures are commonly a result of unconscious behaviour making these amongst the most honest and reliable non-verbal cues according to Richmond and McCroskey [367]. In a seminal work on posture and communication, Scheflen proposes three main social messages to be extracted from an interaction [389], to characterise the posture as inclusive or non-inclusive and to assess the level of engagement and rapport [456]. Rapport can be associated with postural mimicry (or mirroring), which has been linked to smoother interactions and greater empathic understanding [89].

This notion of the felt experience is compatible with various other philosophical theories proposed in the works of Merleau-Ponty [316], James-Lang [77], Dewey's Aesthetics [113], Lakoff & Johnson [263] to name some, each serving deeply profound insights into perception and emotional life. We will refrain from describing individual details, but appreciate the cohering thread that runs among these is that emotions are not constrained to cognitive function alone, but rather taking resources from a corporeal body, responsive to enactive engagements.

2.5 Somaesthetic Design

If we concur with the baseline understanding of aesthetics that was defined in the title constructs (Section 2.1), we can begin to formulate a concise understanding of this phenomenon when we recognise that aesthetic perception is not restricted to our 5 primary sense organs. Shusterman's philosophy expresses the importance of our entire body, and how this has been used not just to perceive, but how one interacts with their surroundings [407]. Through Shusterman's (Somaesthetic) theory, we can assure that aesthetic experiences are not strictly bound to a gallery setting or a formal artistic education, since the body is inherently capable of cultivating aesthetic value in everyday life. This ability is enhanced through performative practices, such as dance [135, 408].

Our approach is informed by the soma design process of Höök [211], which *"requires training your ability to aesthetically appreciate all your senses, but also to imagine through your senses, movements and material encounters"* [215]. According to a soma design process, what takes form *"is not only the digital and physical materials you use to build your interactive artifact with, but also the end-user's somas"*. Somatic practitioners are known to intentionally disrupt habitual actions in order to decouple first and third-person perspectives, that is to comprehend their experiences from the outside-in. This was demonstrated in the "Collaborative Walking" exercise presented as part of the *Move to Be Moved Workshop* [214], which was inspired by Loke and Robertson's method [282]. This process leads us to understand the pinnacle function of technological intervention in contemporary Soma Design theory. Such methods have also been appropriated to support intercorporeal modes of being, *"enhancing second-person perspectives, empathy, communication, and joint acts of perception and action"* [448].

Throughout our research, we will be taking somaesthetic design, a design stance that draws upon the felt body and takes inspiration from experiencing it, and then combine it with the innovative integration of biosensors and actuators. In this context, we present novel research on embodied interaction design couplings, that is, sensing-actuation combinations of aesthetically evocative body input-output modalities that render biodata shareable, body-centered, highly tangible or even able to be experienced collectively.

In the wider scope of body-centric HCI research, we include Somaesthetic design as an individual component amongst literature from other research communities, broadly speaking, studies of Moving Computing (MOCO) [484] and Tanglable Embodied Interfaces (TEI) [276], to nominate some key examples. Soma and Somaesthetic design researchers have sustained a profound voice in pushing Affective Computing away from its traditional frameworks of emotion detection, but instead consider emotional experiences enriched by computer-mediated interaction, cultivating an alternative outlook that is now recognised as The Interactional Approach [210]. A plethora of articles and case studies can be found in the bibliography, with records dating back as far as the early 2000s that demonstrate and assert the relevance of this methodology (see Section 3.4 for more detail).

2.6 Parameters for Aesthetic Quality

In the midst of cultural sensibility that's prevalent across HCI's third wave, we recognise that the Aesthetic Domain is truly a complex and multifaceted phenomenon that does not abide by traditional computational modelling, at least in an obvious way [27, 366]. With aesthetics comes a permitted degree of ambiguity whereby the perceiver is responsible to construct their own emotional understanding of the artefact. This theory of meaning through engagement is discussed in further detail in Section 3.2. We may clarify that ambiguity should not necessitate vagueness or obscurity, these being considered examples of poor communication. Rather, to understand the bridge between aesthetics and ambiguity as inherent components for individual expression by way of embodied metaphor [104, 262].

Complimentary to the core proposition for aesthetic representation as expressive mediation, the discussion of *Aesthetic Emotions* sparks interest around the kinds of feelings that arise when engaging with artistic practices, opening up a rich space for emotional descriptors [150, 390]. A thorough enquiry into aesthetics and digital representation could rightfully be reserved for an entire work in of itself [84] . To overcome an ever-expanding topic, we will begin by establishing a firm criteria based on two perceptual qualities:

Spatial: the distribution and organisation of distinct elements based on their relative position to one another and **Rhythmic:** the temporal presence for which something is produced and perceived, typically observed in regular intervals that are repeated.

Spatial representations may be identified in (a)symmetry, displacement and continuation in accordance with fundamental geometrical terminology [53, 310]. Relating more closely to the anatomical frame, proprioception (or kinesthesia), refers to one's continual awareness to their individual body-parts according to sensory receptors that relay information about our body's spatial position [264]. Taking this resource, the notion of orientational metaphor has been embedded into everyday communication, articulating the intersections that stand between embodied and emotional experiences [185, 486] (e.g. *"My spirit rose"* and *"I'm feeling down"*)

Rhythmic qualities are determined by temporal patterns, examples of which are (a)synchrony, syncopation, entrainment and delay. We also point to the relevance of rhythm in the assessment of physiological regulation. Immediate examples of this are found in automatic functions such as respiratory and cardiac activity [323] which can even be seen working in tandem with one another [398]. Other processes occurring over longer time-frames, such as sleep cycles are also accountable to rhythmic patterns [324]. The role of rhythmic motor activity has also been beneficial in the context of rehabilitation strategies [164].

The spatial and rhythmic attributes described here stand as a very broad feature space, intended to remain generalisable across any kinds of mediums and modalities, as exemplified in the works documented from Chapter 5 onwards. These demonstrate how rhythm and space are incorporated into sonic, visual and haptic forms of bodily representation. We appreciate that generally, there persists an intuitive association that rhythmic qualities are commonly accepted as sonic representation whereas spatial distribution assumes to take on a visual geometric form. Nevertheless, we aim to balance these criteria throughout our investigation of different mediums. Additionally, features such as synchrony and entrainment can be used to characterise aspects of interpersonal behaviour that emerge during social interaction, as shown in previous studies focused on dyadic movement patterns being observed in a performance setting [461] and those induced when listening to music [102, 399].

To better clarify our understanding of the aesthetic domain, it's important to depart from the contingency that aesthetic quality generally refers to something being beautiful or pleasing to the senses, and therefore should not be biased toward positive emotion [150]. During the discussions that arise from our practical investigation, we will examine some of the prevalent themes associated with sensorial satisfaction, namely the convergences that lie between symmetry and asymmetry, as well as synchronous and asynchronous representation. The way in that we experience these sensorial stimuli can be characterised as spatial or temporal qualities respectively.

3

Literature Review

In this chapter, we explore the current state of the art and examine existing research efforts related to non-verbal communication and physiological data. We divide the research topics into the following areas, namely: the social impact of sharing physiological activity in human-human interactions, the appropriation of biosignals in creative practice and performance contexts, and methods for inferring emotional states from physiological data. After presenting a comprehensive collection of studies, we articulate a personal perspective, justifying the intersection of these topics and initiating the design principles that materialise in the research outcomes described throughout this thesis.

3.1 Communication and Connection

In the pursuit of communication with embodied sensors, we can direct our interest to the topic of sharing biosignals or *foreign live biofeedback* to support social interactions, where users are provided real-time feedback on another person's physiological state, as it is described in Ewa Lux et al.'s [291] review article, listing 20 use-cases under this category. This includes a number of studies on sharing physiological signals (predominately heartbeats) between users to enhance remote presence. Such feelings of interpersonal connectedness can be accredited to a kind of anatomical transparency. Beyond that, however, it's not well understood on an emotional level the extent to which this information can be interpreted by a foreign body.

In Slovák, Janssen, and Fitzpatrick's study into sense-making with interpersonal biofeedback for heart rate (HR) sharing, possible interpretations are classed as HR as information and HR as connection [418]. The article compares visual and aural systems for this purpose, showing that auditory feedback of the cardiovascular activity can support HR as connection in a remote setting where greater physical distances actually improved the feeling of connectedness, by which *"participants suggested that less context was better"*. With HR as information, on the other hand, *"participants consistently said that there was a need for context in order for the HR to be informative"*. Regarding this methodology, we note that a crucial dependency of the bonding experience and comfort lies within the pre-existing relationship between users, implying that this manner of HR sharing becomes less viable when situated between strangers. Similar works have considered the willingness of exposing private physiological information such as heart rate (e.g. [459]). Confronting such challenges that come with public space interventions, Howell, Niemeyer, and Ryokai's study into sharing heart sounds explores the convergence between intimacy and anonymity in a way that encourages a co-present affirmation during momentary encounters [217]. Another perspective on this approach can be seen in Lozano-Hemmer's *Pulse Park* artistic light installation, demonstrating the case for a mass shareability of pulse signals when integrated into communal structures [287].

Examples of shared biofeedback have been documented using other input and output modalities, such as skin conductance (EDA) and respiration being combined with light, visuals, and haptic forms of feedback [19, 163, 218]. Among various configurations, these case studies are aligned to an interpersonal awareness of emotional states, without the need to define them literally. While these research outcomes bring affirmation to fostering social connectedness, we take into account use-cases for which subjects are able to convey contextual information from embodied sensor data. For example, inferring emotional traits from visual representations of another user's heart rate when supplemented with the events of a board game [162]. During gameplay, participants associated changes in other players' heart rates with bluffing, being upset, stress and even happiness.

3.2 Aesthetics and Abstract Representation

In Chapter 2, we formed an understanding of the aesthetic domain in the context of the thesis research, pointing towards the acceptability of abstract representations in communication, unbounded by specified linguistic descriptors. This is to accept that if something is cultivated out of a subjects' personal life experiences, it is inherently ambiguous [243]. The overall objective with this is to open up to an individualistic presentation and perception of foreign live biofeedback [291], which in our case are driven by wearable sensors. In light of this, we take note of how abstraction is being routinely practised in the arts, playing a major role in describing established systems of contemporary art. For instance, abstract expressionism implies that personal and emotional structures are isolated and emphasised against ambiguous forms [348].

In Modernism

Kandel ties relevance to the concept of the beholder's share to a biological view of the human mind [242], focusing on a specific period of art history, comparing two approaches presented by Alois Riegl and Sigmund Freud. Where the former is focused more on the artist's developmental psychology [161], the article Kandel highlights the importance of aesthetic reception, suggesting that art is incomplete without the perceptual and emotional involvement of the viewer [368]. This follows into the notion identified as the *beholder's share* (previously named the beholder's involvement), in which the perceiver unconsciously assigns their own meaning to the non-representation in accordance with their previous life experiences, stimulating an emotional dialogue. This understanding of a viewer's perception gives way to the ambiguous nature of individual expression, on the account that *"when an artist produces a powerful image out of his own life experiences, the image is inherently ambiguous"* [242], taking from Kris & Kaplan's work [243].

In Psychology

In [21] the authors compare the mental processes that occur between perceiving artistic images, citing fMRI based studies that show distinctive patterns in the subject's neural activity between representational or abstract forms. More recently, this perceptual comparison has been studied to understand how abstract art can evoke feelings of psychological distance, hypothesised to help withstand situations of interpersonal and social distancing [127], drawing parallels with Riegl's theory of subjective experience. The authors develop a strong case for adopting abstract representations in supporting one's mental well-being in the long term. Essentially stating that, by exposing users to abstract representations, it is possible that they become more accustomed to sensing undefinable feelings in their everyday lives [127].

In Design

The expressive utility of abstract representation has been taken fondly by interaction design practices, notably rooted in the seminal writings of Gaver, Beaver, and Benford that describes finite interpretation as a limitation in data-driven digital technologies, leveraging aspects from design practice into HCI [171]. In a subsequent interview based on these ideas, a call for ambiguity in design is firmly articulated by Gaver, given that *"we don't need systems telling us how to live and what to do."*, thus favouring an aesthetic appreciation that allows us to *"find out own ways of leading meaningful lives"* [169]. Ambiguity as a resource has since been embraced as part of several HCI research efforts, serving as a key contribution to a non-reductionist, non-informational view on emotionally-informed technology [218, 382, 425]. These principles are complemented in Gaver et al.'s *ludic design* [172]; while granting openness to interpretation, is also directed towards encouraging curiosity and exploration of an interactive artefact, lending authority to the user to curate their own experience of it. This later made its way into case studies advocating for creative participation, in a variety of contexts, including that of architecture and musical instrument design [201, 312].

Therapeutic Qualities in Artistic Creation

As we consider the function of aesthetics in representing one's physiological activity, we are able to proceed with our underlying research goal of supporting non-verbal communication strategies. Highlight the relevance of non-verbal communication in therapeutic settings, so in addition to performance contexts, we are also interested in arts-therapy practices, which also rely on aesthetic engagement.

In the following article entitled, *"The Aesthetic Turn in Mental Health"*, Samaritter assess the potential benefits music therapy and dance movement therapy can have on one's mental well-being, recognising the sensory-expressive experience of the maker, as opposed to an audience [381]. Five core themes are derived from a literature review and comments taken from experts in the field, which are briefly as follows: requiring embodied presence, to apply the senses kinaesthetically and musically; somatic resources, supporting anatomical, visceral and neuropsychological functioning; articulation and expression of emotional content; sensitivity to non-verbal communication, and enactive empathy; The non-verbal or pre-verbal character of aesthetics to support diversity and cross-cultural interaction.

Amongst these themes, considered harmonious with our research goals, we can interpret that in these scenarios, that collective sense-making can be considered part of the experience. Here, we can make a connection between Gaver et al.'s' Ludic Design principles [172] with the function of *"enactive engagement"*, encouraging participants to experiment freely with new possibilities, cultivating a bond with the system and one another. While it is not explicitly mentioned here, we may suggest that a creative provocation can help foster the intergroup relationships which participants have not already acquainted i.e strangers amongst each other. Related reports have observed children exercising non-verbal forms of communication to maintain group dynamics during dance-movement therapy [477], engaging with foreign communities through common dances, experiencing shared embodiment [216], staying responsive to partnering movements through kinaesthetic listening [476], and how a non-judgemental attitude helps participants to share stories with one other during arts-therapy sessions [240].

The article also establishes the essential role of an experienced somatic practitioner that is given the responsibility of guiding these sessions in a safe and constructive manner. *Somatic connoisseurship* is granted to those that hold a comprehensive training and experience in one or more relevant body-centred practices, which certifies the appropriate facilitation of such activities to somatic laypersons [381].

3.3 Wearable Technology in Creative Practice

The integration of wearable devices in creative practice and artistic performance, in particular, provides motivation to present physiological activity in provocative ways for which an audience can empathise with the performer while they are being exposed to their inner state, as explained by Françoise et al. [158]. Such performer-audience relationships can be seen as a collaborative process on account of the *beholder's involvement*, asserting that the role of the perceiver is to create meaning [241]. In this section, we review some examples that achieve this by utilising the aesthetic value that's extracted from wearable sensor data to convey a sort of emotional meaning.

Within the broad domain of wearable technology for performance environments, Laetitia Sonami stands as a key pioneer in building and performing with new digital instruments since 1991, presenting the *Lady's Glove*, capable of sensing intricate properties of the hand's shape and motion (as described in [51]). Looking toward other wearable sensing strategies, Aly et al. conducted a review of biosensor modalities in the scope of designing biosignal-driven instruments, which explains the affordances of EMG signals to depict significant motor actions that are revealed through internal muscular functions, praising high degrees of expressiveness [16], as represented amongst corresponding artistic actions and case-studies (e.g. [78, 134, 157, 230]). The cited studies ([134] especially) discuss the use of non-visible aspects of motion observed as internal anatomical mechanisms, performed through one's learned intuition over deliberate consciousness. In a similar vein, Tanaka describes the EMG signal as the performer's intention to make a gesture before it's percieved [437]. Much of this work is recognised under the NIME research community (see [148], as an example), where the given systems can be compared to traditional musical instruments, granting virtuous control through attentive practice developed over time [471]. Knowing this, we also point to works that incorporate wearable sensors alongside traditional forms of musical performance, such as Terminalbeach's *Heart Chamber Orchestra* [457] or Lyon's *Biomuse Trio* [292].

A recent review by Giomi, provides insights into somatic sonification approaches. While continuing to work with sound-based interactions, these are more suitable for dance performances, whereby the user is performing with their body on stage, and the system is used to better communicate their experience, though motor actions can also be influenced by sound. "Écouter/Toucher" details non-conscious and involuntary motor responses to pairing movements while muscle activity is mapped to sound feedback [179]. As part of Latulipe et al.'s "Bodies/Antibodies" performance, for example, wearable accelerometers are used to interactively control 'secret representations' of abstract forms, alongside pre-made animations [269].

Different types of inputs can be used to obtain the respective dance data sets. Alaoui and colleagues [144] distinguish among: (i) positional data retrieved by employing motion capture systems; (ii) movement dynamics (such as acceleration/deceleration), recorded by means of inertial sensors; and (iii) physiological information, obtained from biosignal sensor technologies. Correspondingly, authors created a methodology that combines multimodal capture with recognition of Laban Effort qualities [144]; this is used to assign mappings between gestures and sonic parameters, directing attention away from task-oriented interactions. Similarly, this has also been done to develop visualisation systems that are informative of performed movement qualities [7, 222, 228]. Rostami et al. [378]

created five design concepts for interactive performance adopting bio-sensing and bodily tracking technologies.

Given that it can be unintuitive to hard-code the detection and analysis of performative gestures, machine learning can be utilised to allow the system to associate features of the sensor data with gestures after being trained on a set of examples. This approach has shown promising results regarding the exposure of expressive traits within the subject's movement [78]. This echoes early research achievements such as Wekinator [148] and puts forth recent progress such as that exhibited by the Teachable Machine [81]. Interactive machine learning [138]. By means of tools like Wekinator or Teachable Machine-like paradigms, it is possible to define actions, visual material, movements or gestures according to example data curated by the responsible user. To summarise these motives, we can assume a mutual view by which the output of the machine learning system is considered to play a role in communication, which can be achieved through audiovisual augmentation that compliments the movement [157], or even more literally in the form of an artificial agent that performs on stage [36].

3.4 Inferring Emotional States from Physiological Data

Background

Generally speaking, studies in this field are expected to measure the emotional responses that are elicited whilst perceiving an overt stimuli, comprised of predetermined emotional triggers [54]. For this purpose, there are already several datasets of scientifically validated elicitation material organised according to a set of affective categories (e.g. [56, 252, 474]); a collection of relevant studies can be found in a recent survey [383]. Among these, the informational outlook adopted in some of these examples has since been contrasted with an interactional approach that's used to emphasise the social aspects of emotions. We may assume its origin from Boehner et al.'s enquiry into affective measurement short after the field came into fruition, calling for technology that support *"people to understand and experience their own emotions"* [48, 49]. We find the interactional approach work in compliment with the non-classical view of emotion derived from Lisa Feldman Barrett's writings [29], highlighting the role of the perceiver to induce meaningful inference, moving away from discrete categorisation models of emotion. Or, as Höök et al. puts it, *"An interactional perspective on design will not aim to detect a singular account of the "right" or "true" emotion of the user and tell them about it as in a prototypical affective computing application, but rather make emotional experiences available for reflection . Such a system creates a representation that incorporates people's everyday experiences that they can reflect on. Users' own, richer interpretation guarantees that it will be a more "true" account of what they are experiencing."* [212].

Emotional Interaction

While the use of structured elicitation material allows for statistical evaluations and successfully determines a numerical accuracy of emotional inference [54], interactional studies are implicitly more dependent on qualitative analysis (e.g. [214, 217]). We may suggest also that in lack of stimuli, an interactional approach relies upon its users and surroundings to stimulate expressive dialogue [182]. From this, we'd like to express how shifting from the informational view provides an appropriate base when taking sensory interactions out of controlled lab environments, hence being more adaptive to the unpredictable nuances that present themselves in everyday life [63, 296, 428].

To summarise, we consider that the interactional view supports the theoretical grounds for communication strategies with wearable sensors by welcoming aesthetic representation and henceforth, ambiguity. This leads us to broaden the proposed affective loop framework proposed in [210], by engaging multiple subjects simultaneously, inclusive of third-person perspectives, supporting empathy, communication, and joint acts of perception to transpire [158, 448].

Measuring Affect in Social Contexts

In face-to-face interactions, subjects make use of "*Body Language*" as a form of non-verbal communication, assuming actions such as gaze, gestures, posture and navigation of interpersonal space [121]. Psychology literature admits to the limited ability we have as humans to interpret non-verbal behaviours during social interactions [235]. However, by recognising the coordination with emotions and physiological changes [306], we can consider sensory interventions as a means to help convey and interpret social cues emitted from other people.

In the interest of bridging two prominent topics that are aligned with our research goals, we give attention to an article by Chanel and Mühl [87] which surveys the use of physiological data to facilitate affective non-verbal communication, combining concepts from Affective Computing and Social Signal Processing. The authors acknowledge the case for traditional emotion recognition tasks and explain that physiological activity can also be related to several social processes, such as empathy [272]. It's also explained how activity from the central nervous system correlates to affective and cognitive states during social interaction, where social emotions include shame, embarrassment, gratitude and admiration. These physiological changes are considered for the most part involuntary and therefore hold little to no bias.

Despite knowing that there's a strong correlation between physiological data with affect, authors identify a lack of studies directed towards social interaction, and the most studied non-verbal modalities are in fact facial expressions and tone of voice. This can be partially justified given that in conventional social situations, these internal signals aren't so easily perceived [456]. In this persuasion, two research directions are proposed, the first is to display social cues to foreign users through physiological data, and the second involves analysing physiological activity among multiple users to facilitate collective interaction. The latter approach compliments Slovák, Janssen, and Fitzpatrick's proposal for *composite signals* for HR as information (i.e., combining physiological signals from different people together) [418].

3.5 The Embodiment of Expression, Self-Report Strategies

Self-reports are often considered a necessary resource in studies of psychology and mental well-being, suitably transferable to Affective Computing also. Generally speaking, this serves as an assessment of the subject's cognition, emotion, motivation, behaviour, or physical state, accepted as a personal judgement. Such reports can emerge in many different forms; questionnaires and interview transcripts are commonplace, but not inclusive [400]. Taking the understanding of embodied emotions described in Section 2.4, we highlight existing methods of reporting that comply with non-verbal modes of expression, specifically those linked to bodily attributes.

The Self-Assessment Manikin

The Self-Assessment Manikin (SAM) has proven to be a successful method of mapping emotional responses to a set of pictorial representations, pre-arranged to visualise 5-point scales of valence, arousal and dominance, thus considered highly compatible within the scope of Affective Computing research [61, 74]. The method was introduced as a way of overcoming the semantic dependencies in traditional self-reporting, which carry major limitations related to the tedious data organisation required and being poorly adaptable between different languages [74]. However, where the SAM provides an effective way of capturing emotional states related to a specific object or event, there remains lacking feasibility for representing traits relating to one´s habitual patterns of emotion.

Body Maps

The term 'body mapping' is defined as the process of creating human body images *"to visually represent aspects of people's lives, their bodies and the world they live in"* [166]. This term has been used for health contexts (e.g. HIV/AIDS) in the last two decades, as well as in the context of occupational health and safety for almost 50 years [166]. De Jager et al. conducted a systematic review of body mapping, identifying several attributes, such as social justice, community development tool, planning and psychological assessment [108]. The body maps Gastaldo et al. [166] presented in their research are free-form and unconstrained; there is no predefined structure (such as a preexisting body outline) and include contextual elements such as annotations. A more constrained body map, with an outline of the human body, is used by Windlin et al. [465], to reflect on experiences through drawings and notes: *"these maps became a rich source of data for first-person perspectives of bodily experiences and sensations"*. For the body maps, the authors adapted an earlier body outline from Loke et al. [281]. A similar body map has been used in related soma design research, for example by Höök et al. [215] and Tsaknaki et al. [447].

We would like to suggest here, that these representations become more difficult to interpret from one person to another as they are used to document more abstract sensations in the body. When considering that, for instance, two persons may be highlighting the same areas, producing illustrations that look very much alike while trying to describe an experience that is entirely different from one another (and visa versa). Unlike the SAM, there is no definitive emotional inference to be made from an individual bodily drawing, this is formed by a process of interpretation when presented alongside supplementary information. Body maps may be presented as first-person descriptions, visual annotations [465], video recordings (explored in Section 6), or taken together with additional body maps, revealing generalisable patterns amongst them. Nummenmaa et al. conducted a study where over 700 participants we asked to colour body map regions according to various emotional stimuli [332]. By layering these visual impressions, it was possible to observe *"net sensations"*, this being the collective agreement towards the bodily regions being activated when subjected to a particular emotional cue. For example, "anger" in the hands or the whole body in "happiness" [105]. Taking inspiration from this, Schino et al. exemplifies how body mapping exercises enabled participants to report complex emotions that were elicited by new media artworks [391].

Recent literature on soma design has aimed to overcome the temporal limitations of body maps, as *"they exist as a snapshot or state representation"* [441]. To solve this limitation, Tennent et al. propose the concept of *"soma trajectories"*, i.e *"how a user feels through an interaction, both in body and mind"* [441]. In Chapter 8, we further detail what we perceive as major limitations of body mapping strategies and investigate new ways of overcoming them.

Tangible Artefacts

The visual self-reports described above are assumed to be viewed on paper or digital display. As an alternative, we can make a note of efforts into physical self-reporting mediums. Núñez-Pacheco proposed *"the use of tangible materials as a way to articulate experience from the inner self"*, employing the structure of body maps [333]. Further, Isbister et al. examines the tactile visual qualities of physical objects that can be mapped to emotional imagery, with an interest to overcome the inter-cultural limitations of measuring affect [225]. More recently, developments into tangible mechanisms for logging affect, specifically designed for older adults have shown their potential to support emotional reflection and well-being [183].

Physiological Responses

A recent survey describes how affective physiological measures alone can subside the use of traditional self-reporting procedures [400]. However, much of this work is geared towards consumer appeal and advertising, settling for basic uni-dimensional forms of emotional measure. Ciuk, Troy, and Jones explicitly opens up such limitations given the context of gauging political attitudes, where physiological measures fall short in comparison to self-reports when accounting for emotional nuances [91]. To our knowledge, studies that combine physiological data with visual self-reporting are hard to come by. One example that successfully correlates these two forms of assessment was carried out by Jung et al. seeks to understand how emotional states can be influenced by one's awareness to their internal bodily states (e.g. heart rate) [237].

Concluding from all of this, we are far more interested in adopting a multimodal approach where sensor data is rather used to organise and navigate between user-reported states, not acting as the inference itself.

3.6 Summary

In this work, we aim to develop and evaluate methods of sharing physiological activity, in an approach that is abstracted from raw signals and without explicit associations to linguistic descriptors. Through visual, auditory and tactile feedback, we intend to generate new representations of the subject's inner state inferred from analysing physiological signals, which can then be transmitted to foreign users as a means of communication. In reflection of the studies referenced above, we embrace non-representations and aesthetics that can engage the brain in new ways, developing new cognitive and emotional associations.

In Figure 3.1, we show a simplified plot of how physiological activity can be presented either before or after inference. The leftmost end of the spectrum leans towards the ideas discussed in Section 3.1, where live biofeedback depicts the low-level features of the signal. The rightmost end of the spectrum describes what is achieved in cognitive-based emotion recognition systems, where the data is computationally analysed to produce emotional inferences for the user, manifested as high-level descriptors (e.g. fear, joy, surprise, etc...). We intend to demonstrate a middle-ground, for which it's not necessary to determine a particular socio-affective inference, nor intended to display. To achieve this, we take inspiration from performative uses of embodied sensor data, introduced in Section 3.3, enabling features of the signal to generate abstract representation, to be perceived by a foreign body.

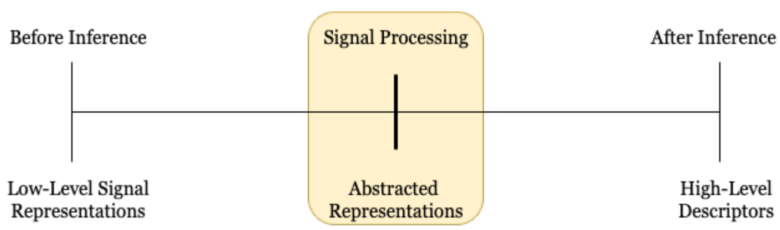

Figure 3.1: Types of outputs for representing physiological activity.

Extending previous work surveyed in this section, herein we delve into the affordances of contemporary machine learning techniques as a means of generating new representations of biosensor data. We consider this initiative to be a novel contribution to the field given the impression that machine learning systems are commonly purposed to derive high-level emotional descriptions for emotion recognition tasks. To stay persistent with the thesis objectives, these generative representations should align with the interactional perspective in regards to the non-reductionist principles summarized in Section 3.2. The aim is not to detect a singular "right" or "true" emotion, but rather, to inspire expressive dialogue and emotional reflection [210]. Our incentive for adopting non-representational machine learning solutions in this context is to exhaust the output possibilities when mapping decoded sensor data of relatively low dimensionality and embracing high-granularity results that can expose expressive nuances that may not be so salient in the raw data alone.

In summary, we offer the following design principles that will be adopted into practical assessment: (i) Communication mediums should not infer emotional states that hold a predetermined meaning; (ii) Physiological sensor data elicits feedback, however, the content of which should not directly mirror the raw biological functions that correspond; (iii) Users are granted the responsibility to explore the affordances of a system according to their bodies and interpret the representations that are produced in that process; (iv) Sensor data alone is not a sufficient means of expression, rather considered a way of navigating the aesthetic functions informed by the user and their surroundings.

4

Technical Preparation

4.1 BITalino R-IoT: Overview and Assessment

We begin this section by introducing the BITalino R-IoT, serving as a technical cornerstone for the wearable sensor applications developed as part of the thesis research outcomes. We then review some of the key technical affordances that are deemed necessary in the scope of our work, namely in regards to real-time feature extraction, web-based communication protocols, along with the possibility to acquire data from many sources.

Technical Specification

The BITalino R-IoT module is the 7th generation of IRCAM's wireless sensor digitising unit [45], an essential tool linking motion sensing, gestural recognition and Live Performance Arts. Since 2001, IRCAM aimed to provide a low latency, high data-rate & resolution and stage compatible devices, capable of streaming gestural information to the computer from multiple performers. The BITalino R-IoT embeds a 9-axis digital IMU sensor (LSM9DS1) featuring a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer, allowing for instance the onboard computation of the absolute orientation of the module [305].

Wireless Communication Methods

Out of the box, the R-IoT is programmed to transmit data over Wi-Fi through the Open Sound Control (OSC)[1] protocol. With the default configuration, each device will send an array of 21 float values every 5 milliseconds. This array includes motion data from the 9-axis IMU, as well as the analog inputs when are coupled with an OSC message address that includes the ID number of the device. We can assign individual ID numbers to each device in the network to separate the incoming data within the host computer.

Open Sound Control (OSC) has been implemented into a plethora of multimedia environments. Its use is supported by many common programming languages as well

[1] Open Sound Control: http://opensoundcontrol.org/

as a variety of hardware devices. More recently, it has been integrated into high-level software such as VST synthesisers and is becoming an increasingly popular option for designing New Interfaces for Musical Expression (a.k.a NIME); this can be justified by the integration of timestamps and forward synchronisation [395]. Whilst OSC was developed to support research programs that focus on music and technology [159], it's also proven to be a compelling choice for supporting other interaction modalities.

In a prototyping scenario, OSC benefits from operating on top of the UDP transport layer protocol, allowing new clients to be freely added or removed on the fly while the system continues to operate as normal. This method is favourable when considering the frequent interchange of sensor modalities, placements and users that comes as a necessary part of our research. Where alternative protocols, such as TCP, would require a handshaking process to authorise the messages being received, UDP will continuously emit data to the send address regardless. Additionally, compared to Bluetooth, this configuration bypasses the need for the individual devices to be paired each time they are being activated.

4.2 Latency Assessments when Using Multiple Acquisition Sources

Motivation and Objective

When using the R-IoT in our work, a crucial feature we want to evaluate is the ability to acquire and process data from multiple devices simultaneously. This can be configured to monitor the activity of many users or even to place sensors on additional body parts (to track movement from different limbs, for example). To benchmark the hardware capabilities of the device in experimental environments, we carry out tests to evaluate performance, outlining the absolute and relative latency in different conditions. These tests consider the effect of including additional devices to the network and differences in wireless range of data transmission.

Preliminary Results

In our tests, we calculate the time taken for the host computer to receive a response to a stimulus which changes in the analog input on the R-IoT device, which continuously sends data back to the host computer over a shared Wi-Fi network using the Open Sound Control (OSC) protocol. The stimulus signal is distributed to multiple devices which are included in the network to see the effect this has on latency. In addition, tests are performed to evaluate the impact of increasing the wireless communication distance from 1 metre to 5 metres. The test is run for a duration of several minutes to assess how the latency deviates over time. Results show that as a base-latency, using one device at a placed a metre away from the wireless receiver, we calculated a mean latency of 8.9

milliseconds (ms). This increased to 10.7ms as the distance increased to 5 metres. When we included 4 devices, we saw a 1.1ms average increase in latency at 1 metre and 1.3ms at 5 metres. The average difference in latency among the devices was calculated as 3.2ms and 5.9ms respectively. The latency measurements were deemed stable over the time period of the test with no observable trend.

We found a slight increase in latency when using more devices on one network and as we increased the distance. Whilst this should be taken account for data synchronisation tasks, we would consider the BITalino R-IoT to be a suitable device for studies collecting physiological data from multiple sources. Our tests also support the use of the OSC protocol for this purpose.

Experimental Protocol

In our tests, we calculate the time taken for the host computer to receive a response to a stimulus which changes in the analog input on the R-IoT device. The stimulus signal is distributed to multiple devices which are included in the network to see the effect this has on latency. The test is run for a duration of several minutes to assess how the latency deviates over time.

Reference Signal and Timestamps

The stimulus signal is originally triggered from the host computer, which sends single byte messages to a Teensy 3.2 board[2] via USB serial. Upon receiving a message from the host computer, the Teensy board will output either 3.3 or 0 volts that is put through a voltage divider before reaching the analog input of the R-IoT device. The R-IoT then sends OSC packets (containing the analog input value) back to the host computer via a TP-Link MR3020 Wi-Fi router. The stimulus is set to switch every second, resulting in an oscillation of 0.5 Hz (Figure 4.1).

A timestamp is logged at t_0, the moment the trigger message is sent from the host computer. Another is logged at t_1, when the change is received in the incoming OSC message. From here, we define the latency as $t_1 - t_0$ for each instance of a trigger message. This approach is partially inspired by the closed-loop latency tests performed by Sebastian Madgwick for the x-OSC device [294], where a square wave is fed into the analog input of the device and outputted into a frequency counter to measure latency. We acknowledge that this method is not as accurate due to the small latency that occurs between the host computer and the Teensy, addressed in Section 4.2. However, we consider this a low-cost solution that can be more easily replicated for the user's specific conditions and environment.

[2]Teensy 3.2: https://www.pjrc.com/store/teensy32.html

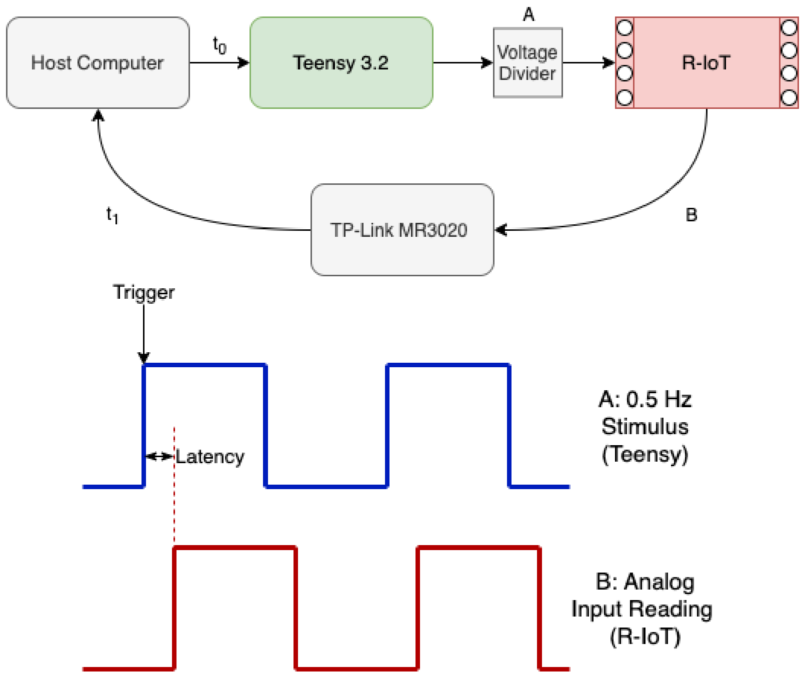

Figure 4.1: Experimental protocol for latency tests.

Multiple Device Setup

To test multiple devices simultaneously, we feed the same reference signal from the Teensy to multiple R-IoTs, as shown in Figure 4.2. The devices are configured to stream data through the same Wi-Fi router, where the data is addressed by the ID number of each device.

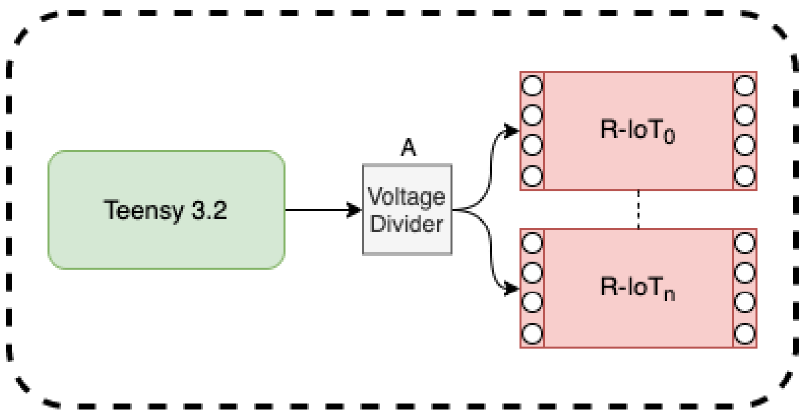

Figure 4.2: Feeding reference signal to multiple R-IoTs.

Device Firmware

Each device is flashed with the default firmware, which implements algorithms to compute the absolute orientation of the device from the raw IMU data, providing quaternions and Euler angles every time a data packet is transmitted. For this reason, our tests can be considered to account for the latency that occurs when retrieving motion data.

Results & Discussion

Conditions

For these tests, the device(s) were first placed less than 1 metre away from the router which was connected to the host via an ethernet connection. From the test, we extracted 248 triggers form a total duration of approximately 8 minutes and 15 seconds. We then repeated the tests with the device(s) placed 5 metres away from the router.

Single Device

For the duration of the test, we accumulate the latencies for every trigger and calculate a minimum, maximum and mean average latency. The results are given in Table 4.1a, ranging between 6 to 11 milliseconds. When we repeat the test at greater distance, we see a greater range of values and a higher average, as shown in Table 4.1b and Figure 4.3. Over the duration of the acquisitions, we could not observe any increasing/decreasing trend in the results.

Device ID	Maximum Latency (ms)	Minimum Latency (ms)	Mean Latency (ms)
0	11.019	6.605	8.859

(a) Latency at 1 metre.

Device ID	Maximum Latency (ms)	Minimum Latency (ms)	Mean Latency (ms)
0	20.603	7.077	10.702

(b) Latency at 5 metres.

Table 4.1: Latency measurements for one device.

Multiple Devices

For the following, we report our results when using 4 devices simultaneously. To test multiple devices, we pair each R-IoT to the same router and separate the incoming data according to the ID number of the device. All devices are sending data to the same port number. Other conditions are kept the same as the previous test.

Absolute Latency

The minimum, maximum and mean latency measures for the individual devices are shown in Table 4.2a and 4.3a. We can see the maximum and mean latency has increased

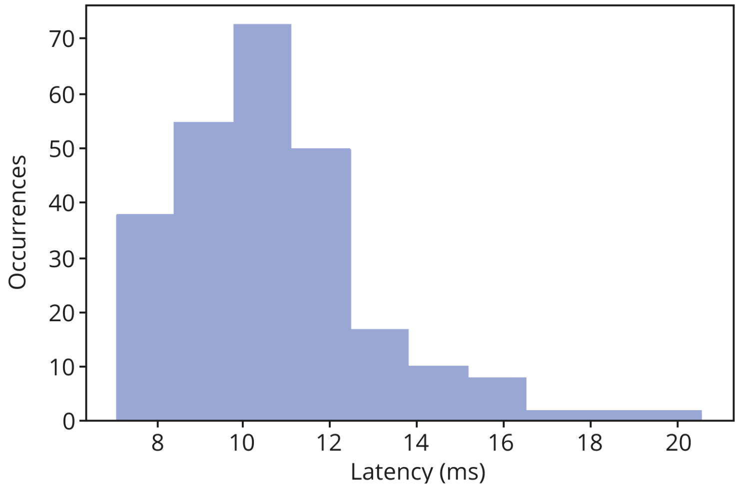

Figure 4.3: Latency results for one device (1 metre).

in all instances when more devices are added to the network. The results are fairly consistent between each device aside from device ID 2, which doesn't reach as high of a maximum. From all 992 triggers, the latency durations ranged from 6.55 to 17.31 milliseconds, and the mean average was calculated as 10.03 milliseconds. We present these results as a histogram in Figure 4.4 and Figure 4.5. When we repeat the test at 5 metres, we identified a small increase in the average latency and a higher maximum amongst all the devices.

Device ID	**Maximum Latency (ms)**	**Minimum Latency (ms)**	**Mean Latency (ms)**
0	16.243	6.705	10.011
1	17.201	6.657	10.007
2	14.877	6.550	9.998
3	17.305	6.868	10.130

(a) Latency at 1 metre.

Table 4.2: Latency measurements for four devices.

Relative Latency

As well as the response time between each individual device and the host computer, we are also interested in the difference in latency of the received message between all the devices in the network. This is important to enable data synchronisation between sources. For each trigger, we calculate the difference between the first and the last response out of the 4 devices. From our first acquisition, the mean average latency difference was calculated as 3.22 milliseconds with a maximum 8.96. In Figure 4.6 and 4.7 the data is plotted as a histogram to assess the likelihood of these latency differences occurring.

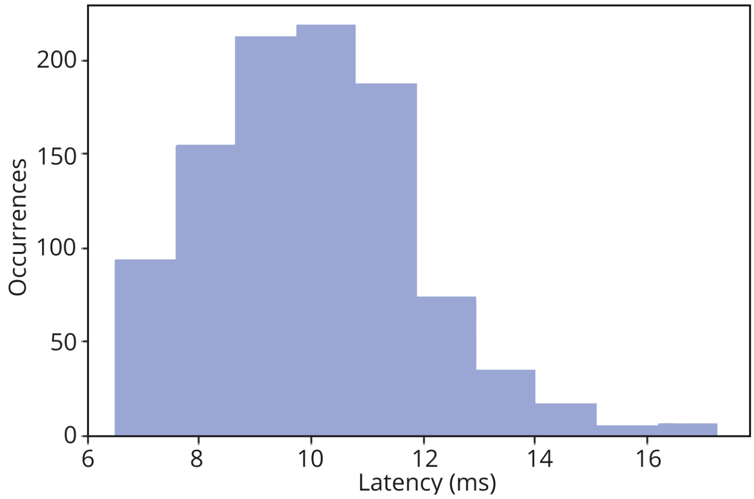

Figure 4.4: Latency results for one device (1 metre).

Device ID	Maximum Latency (ms)	Minimum Latency (ms)	Mean Latency (ms)
0	27.992	6.720	11.023
1	27.559	7.248	11.916
2	27.990	6.857	11.263
3	26.346	6.837	10.830

(a) Latency at 5 metres.

Table 4.3: Latency measurements for four devices.

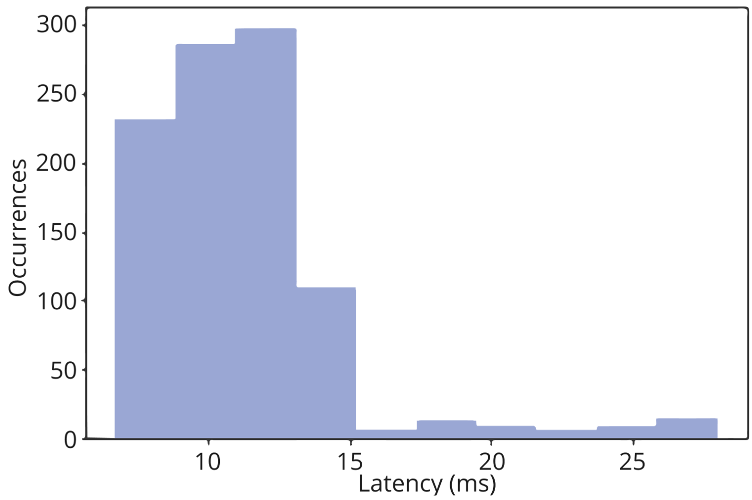

Figure 4.5: Latency results for one device (1 metre).

When we increase the distance, we find the maximum relative latency goes up to 20.148 milliseconds, and we calculate an increased average of 5.925 milliseconds.

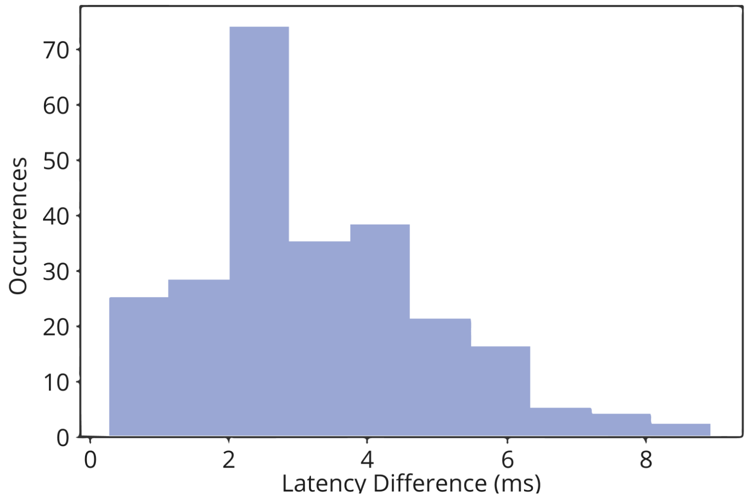

Figure 4.6: Latency results for one device (1 metre).

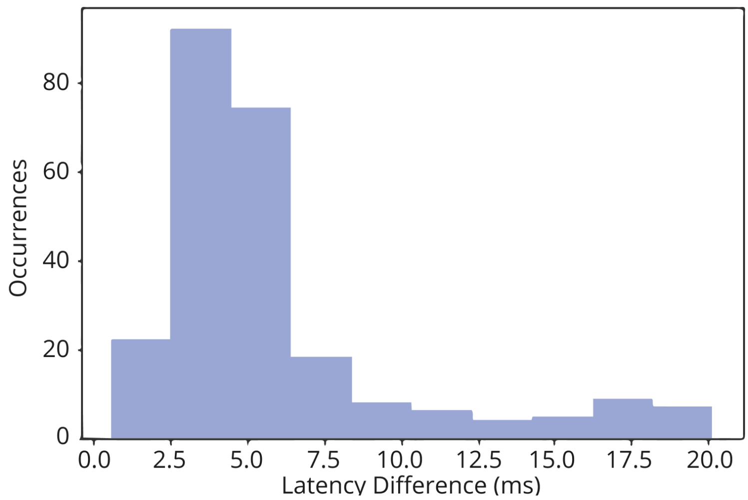

Figure 4.7: Latency results for one device (1 metre).

Summary

Limitations

There are a couple of factors regarding wireless configuration that are worth noting. First is that all the devices were sending data to the same port number (8888). We did this for convenience and ease of programming. However, we acknowledge that separating ports for each device may have an effect of performance, as advised in the official documentation [45]. Secondly, we set a WPA-2 password on the network which uses more bandwidth. Another factor that is briefly addressed in the document is the added latency between the host computer and the Teensy 3.2, connected by USB. As the communication was dependent on single byte messages, we assume that this is negligible to the final results[3].

Latency Assessment

From the results, we conclude the following factors to have an impact on the latency between the R-IoT and the host computer. Having more devices in the network will increase the average latency and maximum latency. Additionally, increasing the distance between the R-IoT(s) and the Wi-Fi router will also increase the average latency. When we tested four devices at 5 metres, we observed a few instances of the latency being much higher than the average, compared to when we tested at a short distance. We also found that the distance would affect the difference in latency between devices, which would have an impact on data synchronization.

[3] Serial Latency: http://neophob.com/2011/04/serial-latency-teensy-vs-arduino/

4.3 ServerBIT: Abstracting from Hardware Specificities through Network-driven Middlewares

This section describes a middleware framework that facilitates rapid application development by abstracting hardware specificities. With this framework, users can easily bridge hardware devices with state-of-the-art network protocols, making it possible to stream data packets to their custom applications. As a result, the physiological sensor data can be integrated into their code base without needing a dedicated API or language-specific library.

The source code for ServerBIT (r)evolution is available from: https://github.com/BITalinoWorld/revolution-python-serverbit

Overview

Real-time streaming of embodied sensor data has enabled artists, designers, hobbyists and researchers to prototype new interaction modalities with systems that respond to the user's physiological activity. Furthermore, integrating new biofeedback devices further supports exploration when developing rich interactive experiences. This chapter introduces the ServerBIT framework, a software tool for rapid and accessible sensor-based application development. This middleware allows users to connect sensory devices through wireless protocols, process incoming signals and stream data packets to new applications. These may include machine learning tools, real-time data visualisation, gesture-controlled games, software instruments, and even foreseeing the control of other hardware devices. Becoming familiar with such multifaceted workflows is complex, often requiring extensive support to overcome the persistent technical barriers of sensor-based development. ServerBIT intends to address these issues by providing an abstraction layer and promoting the distribution of example applications and tutorials that can be run locally, on the web, and even on mobile devices without needing additional software. By utilising globally compatible communication protocols, these software packages may be supplemented with user-specific configuration files to bypass tedious networking tasks, facilitating more effective remote support.

Physiological sensor data has become an increasingly growing field of interest in prototyping new interaction modalities. However, a significant limitation still exists in the ability to rapidly produce end-user applications[15]. We foresee this hindrance being a result of the limited resources, abstract from the hardware layer, available to those who are not technically proficient in these fields. In addition, implementing more complex aspects of the software layer, such as time-critical operations and multithreading, introduce concepts that are likely to be non-trivial to novice programmers. Non-modular solutions that require a user to build everything from scratch can be highly time-consuming and unsupportive of spontaneous design choices.

Our framework builds upon previous work from the thesis supervisor, Silva et al.

[411, 412] and extends a previous version of ServerBIT, which presents a bare-bones service to bridge the connection of a BITalino device to the user's web browser, where the sensor data can be handled in real-time. Our approach generalises this concept to enable interfacing with other hardware devices and network communication protocols.

Background and Motivation

The software package described in this text adapts itself from a preexisting version of ServerBIT[4], which provides a bare-bones service that would bridge the connection of a BITalino device to the user's web browser, where the data can be handled in real-time. The framework emulates the software architecture of the high-level application, *OpenSignals*, purposed for data visualisation and analysis. As both versions remain available, we identify this rendition of the software as, *ServerBIT (r)evolution*. Amongst the features documented in this chapter, the software is designed to support the BITalino R-IoT device (see Section 4.3), enabling spontaneous data transmission over Wi-Fi with many clients simultaneously, which comes essential later in our practice works.

Other Services for Sensor-Based Application Development

High-level software tools such as Maxuino[2] and the Arduino Cloud[3] platform present a graphical interface to assist users in connecting their hardware devices and streaming sensory data in real-time; certain features assist the user to troubleshoot common connectivity issues and validate their input. We observe these services as supportive within rapid prototyping environments when compared to command-line interfaces.

Code templates such as the BITalino OSC bridge[4] call upon functions given in existing frameworks to stream sensor data to other applications. When confronting this *"quick and dirty hack"*, there remains a reasonable technical barrier as some programming experience is necessary to develop and operate a complete system. On the other hand, MyoMapper [123] represents a more comprehensive software toolkit for prototyping biosignal-based interactions. From the diverse range of research projects realised using this toolkit [64, 69, 114], this can be recognised as a highly effective approach for the intended purpose. However, this software is only compatible with the Thalmic's Myo armband[5]. Whilst this is a convenient solution for those who wish to use a prefabricated product, viable interaction modalities are constrained to the built-in sensors and a limitation of bodily placements imposed by the armband's construction.

[4] http://github.com/BITalinoWorld/python-serverbit

[2] http://www.maxuino.org/about

[3] http://www.arduino.cc/en/IoT/HomePage

[4] http://gitlab.doc.gold.ac.uk/mick/bitalino-OF

[5] https://www.myo.com/

Supported Hardware

A technical constraint apparent in the previous versions of ServerBIT was the hardware-specific architecture, only permitting the use of a BITalino board[6] as an input device. In order to overcome this issue, it was necessary to propose a homogeneous workflow between different sensory hardware devices. In Section 4.3, we describe how ServerBIT works with the BITalino R-IoT[7] which communicates over WiFi. These devices are directly compatible with a host of analogue and digital inputs for monitoring physiological activity e.g. electrocardiography and electromyography sensors. With this technical flexibility in place, we aim to develop an adaptable prototyping tool that can be utilised throughout our research.

Data Transmission Through Web-Based Protocols

The fundamental reasoning behind ServerBIT is to continuously stream sensor data from the R-IoT to third-party applications in real-time. ServerBIT opts for network-based communication protocols, allowing data transmission to a wide range of applications without needing a dedicated API. Given a basic use case where the sensor data only needs to reach one host computer, ServerBIT can be used to run a server assigned to a local address. However, for more advanced use cases, such as those concerning collaborative interaction or sophisticated biofeedback systems, it is also possible to send data to a static IP address associated with another computer, mobile device or microcontroller.

WebSocket

The Websocket protocol is a recent advancement in web technologies [284], introduced to address the growing demand for applications that require a full-duplex connection between the web interface and server-side processes. ServerBIT supports communication to a web browser environment via a WebSocket connection. Here, users are able to mock up interfaces easily, making use of native HTML elements and even taking advantage of the many open-source, well-documented data visualisation libraries available. Furthermore, it's highly convenient to distribute applications developed using this method, particularly when used in conjunction with a cloud-based coding platform such as CodeCircle [147].

Building upon the WebSocket-based software architecture, in our approach data, is sent between a server and client within JSON formatted strings. This format is independent of any programming language, and the data structure consists of key/value pairs making the result more human-readable with associative descriptors [299]. When a new JSON string is generated by ServerBIT, text labels are applied to the channels that the device acquires data from. Users are granted the option to alter these labels depending on the arrangement of the sensors so when the data is accessed on the client-side, the

[6] https://bitalino.com/datasheets/REVOLUTION_BITalino_Board_Kit_Datasheet.pdf
[7] https://bitalino.com/en/r-iot-kit

structure of the code is more coherent in regards to the specific use case. This would be appropriate, for example, in a workshop or tutorial scenario where participants are expected to apply specific sensor inputs into a preexisting code template.

Open Sound Control

In Section 4.1, we explain how Open Sound Control (OSC) has been integrated with the R-IoT to data transmit over WiFi in a way that is highly versitile amongst various proptyping environemnts. In addition to this, OSC may also be used to transfer messages locally between softwares. Comparable with the WebSockets approach, each 'frame' of data is sent as a single bundle, containing sub-messages for each channel defined by a human-readable label. As a result, each input in the bundle can be processed simultaneously by the client, lending support to multi-modal solutions. The functionality given to the naming scheme makes it highly suitable for multiple device management. Where each message is specified by a numerical device ID and channel name, pattern matching language can be used to nominate multiple elements within the bundle. For example, if the user wants to pick out all the data from a specific device, they can listen for messages addressed as **/deviceID/***. Similarly, data from the first two analogue channels from any device in the network would accumulate under the address **/*/A1, A2**.

System Overview

Physical Interaction Environment

This defines the space where physiological sensors are interfaced with the end-users interacting with the application. Many of these sensors must be in direct contact with the skin; common solutions for this involve using gelled electrodes and wearable hardware components. These sensors are connected to a microcontroller, which forwards sensor data to ServerBIT wirelessly over Bluetooth or WiFi. With regards to the technical provisions in our work, we are primiarly focused on WiFi communication using the R-IoT.

ServerBIT (r)evolution

This part of the system, running on a host computer, can be split into two sub-layers. One is a graphical interface for configuration, where the designer establishes one or more hardware connections and defines how the sensor data will reach the software application. From here, incoming data and control messages are re-formatted according to the desired communication protocol: WebSockets or OSC. This sub-layer runs continuously in the background, where the technical processes are abstracted from the user.

Software Application

The outcome of the system is dictated by the software receiving the data from ServerBIT; this defines the artefacts the end-user(s) will be interacting with, and what modalities will be utilised to do so. As a bidirectional protocol, this layer also handles any biofeedback mechanisms that are implemented in the physical interaction environment.

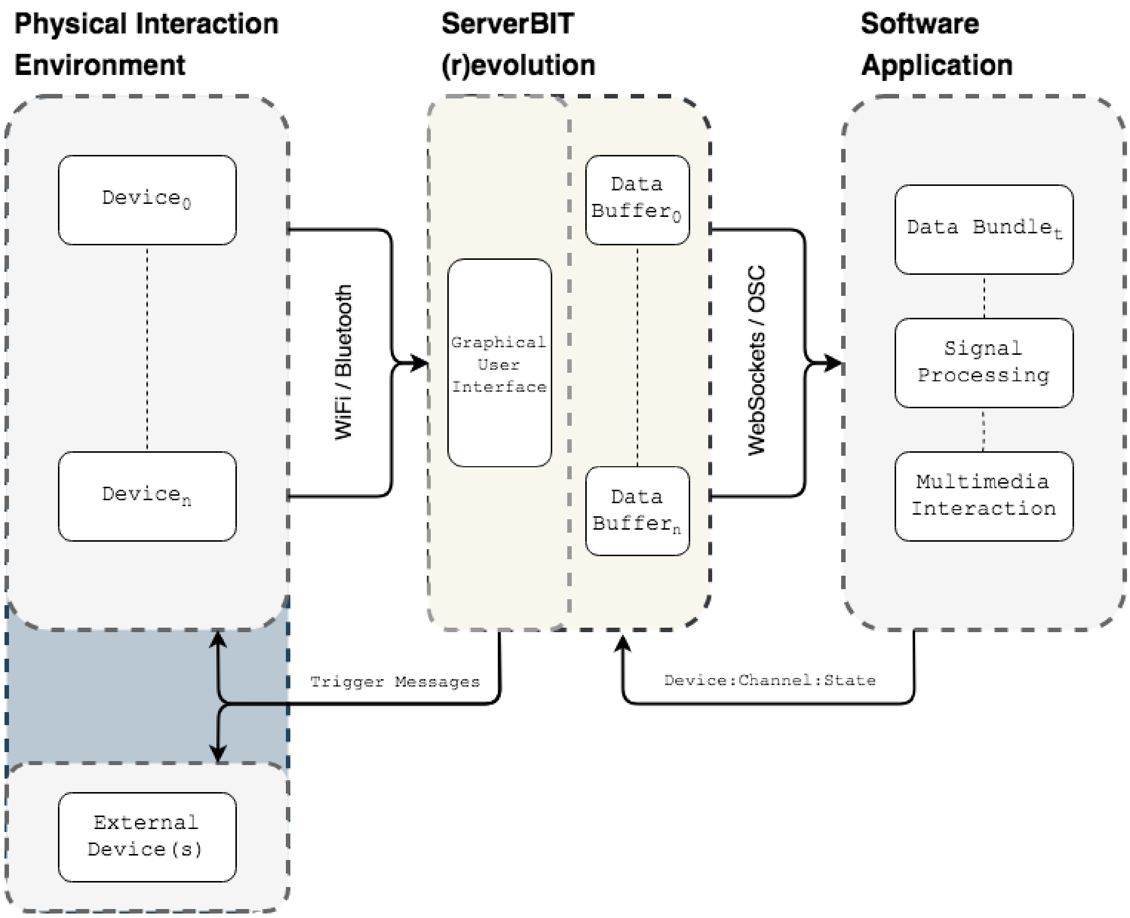

Figure 4.8: Overview of the ServerBIT architecture.

Design Principles

Sequential Data Format

Data buffers provide information regarding how a signal behaves over a given time period. Sensor data is received as a bundle containing an array of contiguous float values for each channel, where the most recent reading is given at the head of the buffer. The proposed ServerBIT development pipeline provides a convenient format for data visualisation and digital signal processing by granting users access to the entire frame buffer.

Open Source

Users should acknowledge that they can make full use of the provided examples without needing to access the ServerBIT source code. Nonetheless, if a user intends to re-purpose the software to satisfy their specific project, it may be necessary to alter certain components of the script. Some reasons for this might include: adding support for additional hardware devices, pre-processing signals before forwarding to external applications or integrating functionality from additional libraries. With this considered, the source code is openly available to the public, including instructions on compiling and running the application from the user's command line.

Automatic Device Connection and Re-connection Handling

When new users try to incorporate sensor-based interaction, a considerable technical barrier has their application successfully recognise the device connection. In a rapid prototyping environment, users are susceptible to more issues as they wish to experiment with different device configurations. Matters can worsen when using multiple devices, particularly when each relies on different communication technologies. For example, the BITalino requires either standard Bluetooth or BLE, whereas the R-IoT device communicates over WiFi. When a connection drops, the application as a whole may fail to operate and troubleshooting the specific issue can be onerous to those unfamiliar with the hardware.

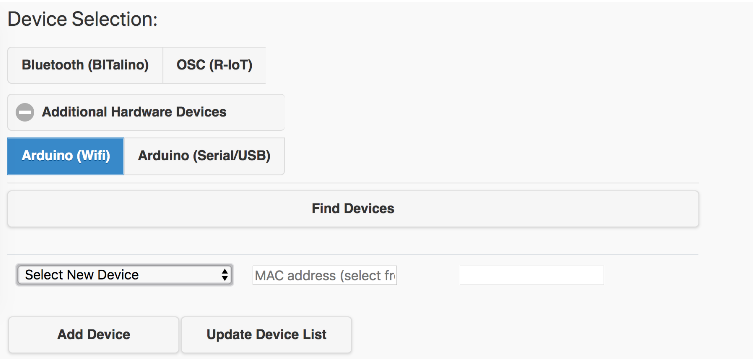

Figure 4.9: ServerBIT configuration page.

On the configuration page presented in Figure 4.9, users can use the device finder menu, which searches for available serial, Bluetooth and Wi-Fi connections nearby. From here, users are presented with an accumulation of device addresses, which can be added to ServerBIT's device list. When the configuration is successfully updated, ServerBIT will automatically attempt to establish a new connection with each device in the list.

Physiological Data Transmission Over Wi-Fi

ServerBIT is designed to be compatible with BITalino R-IoT devices, which transmit multiple data channels over a local Wi-Fi network. This alternative to Bluetooth-based communication holds several advantages. However, it necessitates for the user to set the IPv4 address of their computer to a specific static IP address (see Annex I. For users unfamiliar with this process, this will likely increase the burden of pairing new devices, thus interrupting application development. Before searching for new devices, ServerBIT will detect the current network configuration and generate a shell or bash command according to the operating system. The command can be validated and executed with the graphical interface. Upon execution, ServerBIT matches the computer's IPv4 address accordingly with the module's destination address.

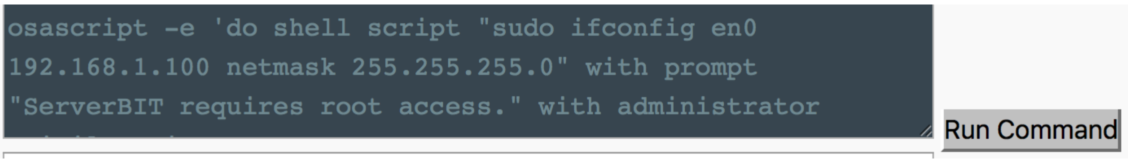

Figure 4.10: Network command generated and displayed in the browser (MacOS).

Uninterrupted Hardware Connections During Development

A trigger handler is automatically established and initiated for each device added to the network. The trigger handler runs in the background and listens for OSC messages addressed in the following format /**"deviceID/output"**. These messages authorise control of the separate digital and analog outputs on individual or multiple devices. This bidirectional communication intends to support interactive systems design where biofeedback mechanisms respond to physiological input in real-time. This approach can also be used to send commands to WiFi-enabled devices, bypassing the labour of bridging the devices over a wired serial connection.

Biofeedback Control Using OSC

For each device added to the network, a trigger handler is automatically established and initiated. The trigger handler runs in the background and listens for OSC messages addressed in the following format *"/**deviceID**/output"*. These messages authorise control of the separate digital and analog outputs on individual or multiple devices. This bidirectional communication intends to support the design of interactive systems where biofeedback mechanisms respond to physiological input in real-time. This approach can also be used to send commands to WiFi-enabled devices, bypassing the labour of bridging the devices over a wired serial connection.

Running A "Hello World" Example

Pairing a New Device

In the case of BITalino, every device has a unique hardware address that must be declared within ServerBIT. On the configuration page (Figure 4.9), users are presented with a list of device addresses that have already been paired with the host computer. One or more devices can be selected from the list and, upon submission, ServerBIT will begin to read sensor data from each module respectively.

Data Acquisition

Once a device has been paired, the user can determine which channels will be acquired and modify the format in which they will be transmitted. In order to run this first example, the user does not need to make any changes here, as the default configuration is already set up to read and stream data from the first analogue input labelled **'A1'**.

Network Settings

At the bottom of the configuration page, the user can specify the network protocol for communicating with the interactive application layer. By default, ServerBIT is set to stream sensor data to a local server (*127.0.0.1* or *localhost*) over the WebSocket protocol using the port number 8000; this configuration can be used with the web-based examples provided in the software package.

ClientBIT Example

Provided within the ServerBIT package is a basic example that can be used to test the connection to a BITalino device and visualise an incoming signal on the browser. *ClientBIT.html* is an example HTML/JS test client which prompts the back end to initialise a connection to a specified BITalino device. Once a connection is established from host to client, sensor data is acquired from channel **'A1'** and plotted in real-time. The HTML file can be found in the ServerBIT directory, located inside the user's home folder, which also includes the *jquery* library files required to run the example.

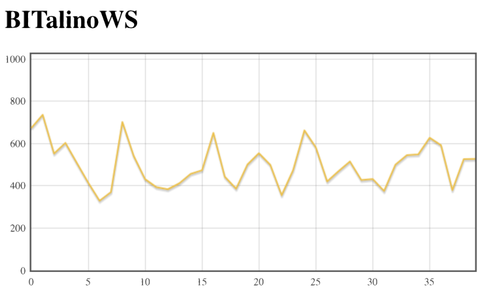

Figure 4.11: ClientBIT.html displaying an EMG signal in the browser.

Exporting and Sharing Applications

Portable Configurations

When attempting to distribute example applications to new users, we often perceive difficulties where additional configuration tasks are required to run the application. This process can be inefficient when involving many participants or even remote scenarios, particularly when dealing with users unfamiliar with the specific technologies and software libraries.

A major goal of ServerBIT was to improve the portability of sensor-based applications. For this to be satisfied, it should be possible for new users to receive a software package that can be executed on their machine without the need to make changes to the source code. At a minimum, such a software package should include (1) the ServerBIT executable, (2) the source code for the application that handles the incoming data, and (3) a preset configuration file that can be imported with the ServerBIT GUI.

Saving a Preset

The ServerBIT configuration page is accessible from a web browser. When accessing the page for the first time, the user is presented with the default settings. In order to interact with the software, the user must select and pair at least one new device (see Section 4.3). When completed, clicking **"Submit"** at the bottom of the form will save the current configuration into the ServerBIT home directory as *config.json*.

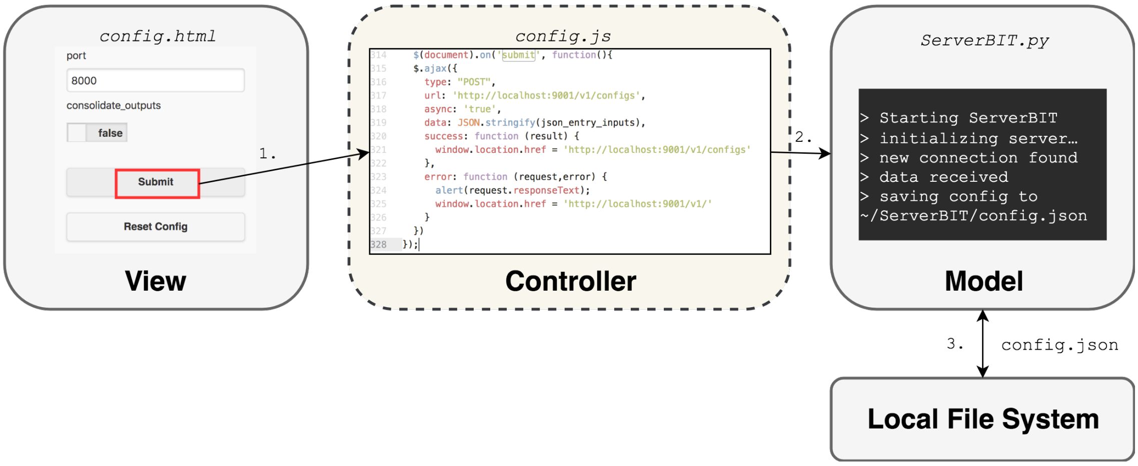

Figure 4.12: Workflow of the configuration saving process.

This micro-framework was designed under a Model-View-Controller (MVC) architecture. A Python WebSocket server communicates between the presentation layer and the processing and persistency layers [412]. The unified process can be separated into three interdependent modules, as shown in Figure 4.12, authorising access to network properties and low-level hardware specificities from a visual interface.

Loading an Existing Configuration File

From the browser interface, users can import an existing configuration file in ServerBIT's JSON format. The new settings, such as device addresses and channel labels, will be displayed as form entries; these can be altered accordingly and saved by re-submitting the form.

Users should note that for the sensor data to reach a new OSC or WebSocket listener, the port number and host IP address must match what's assigned to the ServerBIT configuration. If these parameters are changed from their defaults, they should be saved to the configuration file so the sensor data can stream to the server upon launching without issues.

Summary

In this chapter, we presented ServerBIT (r)evolution, a software toolkit serving to complete the interaction loop between sensory hardware devices and multimedia applications, including those that can be run on a web browser. We provide a brief overview of existing utilities, which deliver a comparable service of abstracting hardware-specific configurations within a rapid-prototyping scenario. From this, we formulate criteria for a set of software requirements based on the common issues developers experience when prototyping new interaction modalities with physiological sensors; this is used to justify our design choices which are subsequently described throughout the report. Proposed future work will consider the evaluation of the toolkit as an educational tool, with ambitions to introduce sensor-based applications to new communities that specialise in other technical domains. Such field-work opportunities will advocate for the assessment of user feedback to discover in what scenarios this approach is potentially advantageous and later warrant new adaptations of the toolkit in forthcoming iterations.

5

Preliminary Actions I: Biosensing and Actuation Couplings

Our first research actions were lab-based, first-person experimentations with biofeedback. From this, we developed a strong understanding of the expressive affordances of physiological modalities. Here, we report our initial findings as a series of conceptual use-cases in context of a review article that was delivered during the doctorate programme, including personal contributions as respective co-authors.

M. Alfaras, W. Primett, M. Umair, C. Windlin, P. Karpashevich, N. Chalabianloo, D. Bowie, C. Sas, P. Sanches, K. Höök, C. Ersoy, and H. Gamboa. "Biosensing and Actuation—Platforms Coupling Body Input-Output Modalities for Affective Technologies". en. In: *Sensors* 20.21 (Jan. 2020). Number: 21 Publisher: Multidisciplinary Digital Publishing Institute, p. 5968. DOI: 10.3390/s20215968. URL: https://www.mdpi.com/1424-8220/20/21/5968 (visited on 12/22/2020)

5.1 Introduction

In this Section, we present an overview of biosignals that have become standard in low-cost physiological monitoring and show how these can be matched with interaction design concepts for facilitating *bodily engagement* and *aesthetic experiences*. First-person soma design lets researchers look afresh at biosignals that, when experienced through the body, are called to reshape affective technologies with novel ways to interpret biodata, feel it, understand it and reflect upon our bodies. Taking both strands of work together offers unprecedented design opportunities that inspire further research. Through first-person design, an approach that draws upon the designer's felt experience and puts the sentient body at the forefront, we outline a comprehensive work for the creation of novel interactions in the form of couplings that combine biosensing and body feedback modalities of relevance to affective health. These couplings lie within the creation of design toolkits that have the potential to render rich embodied interactions to the designer and user alike. As a result we introduce the concept of "orchestration". By orchestration, we refer to the design of the overall interaction: coupling sensors to actuation of relevance to the affective experience; initiating and closing the interaction; habituating; helping improve on the users' body awareness and engagement with emotional experiences; soothing, calming, or energising, depending on the emotional and social context and the intentions of the designer. The findings of these explorations are moralised as a set of experimental sensor-actuation couplings to gain a broader perspective on designing embodied systems.

5.2 Sensing Strategies

Physiological signals are time representations of changes in energy produced in the body (see Section 2.1). These changes correspond to energy variations of different nature, such as electrical, chemical, mechanical, and thermal [401]. Through digitization, these serve as a somatic input of an interactive artefact, processing new data while it is running, thus enabling a unique and continual engagment with its aesthetic parameters [84]. Here, we present a selection of wearable sensors that can be incorporated into the creation of novel communication systems. In particular, we will focus on a subset of sensing modalities compatible with the R-IoT module (described in Section 4.1), offering a brief description of the physiological process, common feature extraction methods, suitable placement on the body and assess some of the challenges of signal artefacts that arise during movement.

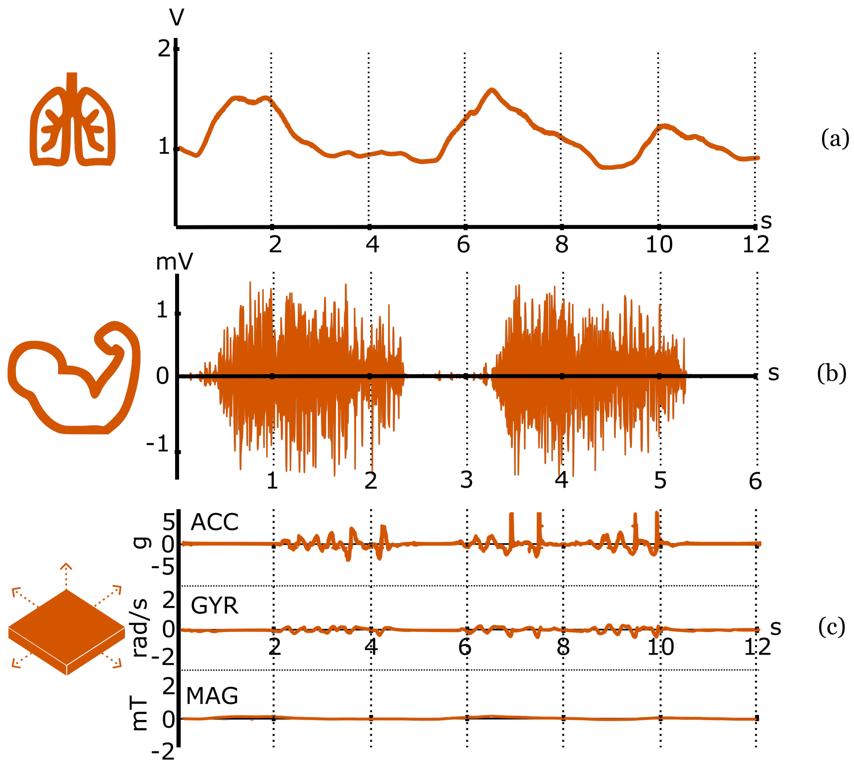

Figure 5.1: Visual representation of different physiological signals: (a) Respiration, (b) Electromyography (EMG) and (c) Inertial Measurement Unit (IMU)

Respiratory Sensing

Respiration sensors monitor the inhalation-exhalation cycles of breathing, i.e. the process to facilitate the gas exchange that takes place in the lungs. In every breathing cycle, the air is moved into and out of the lungs. A breathing sensor uses either piezoelectric effects on bendable wearable bands or accessories (one of the most predominantly used technologies), respiratory inductance plethysmography on wired respiration bands around the thorax, microphones on the nose/mouth airflow, plethysmographs (measuring air inflow) or radiofrequency, image and ultrasonic approaches. A review on breathing monitoring mechanisms is found at [302]. For piezoelectric breathing sensors, thoracic or abdominal displacements produced in breathing cycles bend a contact surface that converts ressistive changes to continuous electrical signals (see Figure 5.1a).

A piezoelectric breathing sensor is usually located on the thoracic cavity or the belly, using a wearable elastic band. With adjustable strap and fastening mechanisms, the sensor can be placed slightly on one side where bending is most relevant, optimizing the use of the sensor range. These kinds of sensors, allow both the study of thoracic and abdominal breathing. With the development of conductive fabric, breathing sensors are making its way into the smart garment market in the form of T-shirts and underwear bands. Breathing is a relatively slow biosignal, with breathing rates often below 20 inhale/exhales per minute. A sampling rate frequency as low as 50Hz is sufficient to capture the dynamics of respiration.

A breathing signal informs the respiration dynamics of the subject, i.e. the dynamics of the process mediating gas exchange in the lungs. The monitoring of an innate breathing action brings in the assessment of breathing cycles and rates which can be used to handle problems involving breathing interruptions, oxygen intake, metabolism of physical activity, as well as emotional stressors. In terms of analysis, breathing cycles are studied using breathing rates, the maximum relative amplitude of the cycle, inhale-exhale volume estimation, inhale-exhale duration, and inspiration depth, that allow the characterisation of several breathing patterns.

While piezoelectric breathing sensors are prominent given the low cost and form factor advantages of wearable sensor platforms, deviations in placement have an effect in the relative range of the response signal. Movement artefacts, most relevant when physical activity is present, are a common source of problems. Respiration sensing techniques like the respiratory inductance plethysmography, compensate the highly localised piezoelectric approach with a sensor capturing the general displacement of the whole thoracic cavity, yielding a signal less prone to movement artefacts. The monitoring of breathing cycles is usually accurate, although the exploration of effects to be used as voluntary inputs in interactions, such as holding the breath, are not easily captured.

Electromyography (EMG)

The recording of the electrical activity produced by skeletal muscles receives the name of electromyography (EMG). Human muscles are made up of groups of muscle units that, when stimulated electrically by a neural signal, produce a contraction. The recording of the electrical activity of the muscles (voltage along time), traditionally relying on intrusive needle electrodes (intramuscular), is easily accessible nowadays by means of surface electrodes that capture the potentials of the fibers they lay upon. The result of this measurement is a complex surface electromyography signal (sEMG) that reveals data about movement and biomechanics of the contracted muscles. (see figure 5.1b).

Electromyography signals inform about the contraction of specific muscles and parts of the body. The EMG signal consists in the time representation of rapid voltage oscillations. Its amplitude range is approximately 5mV. The EMG signal grants an assessment of several aspects of a physical activitys such as muscle contraction duration, the specific timing at which movements or contractions are activated, the presence of muscular tension or fatigue, and the extent to which different fibers (area) are contracted. The analysis is conducted through noise filtering, together with feature extraction that yields contraction onset detection, the estimation of signal envelopes, and the computation of average frequencies.This lets subjects deepen their understanding of movement strategies, very relevant for embodied art and sports performance, improve muscle coordination, or even reveal existing movement patterns that they are unaware of.

Having become the standard in EMG monitoring, bipolar surface electrodes consist of three electrodes. Two of them (+/-) must be placed close to each other, on the skin that lies on top of the muscle under study, along the fibers' direction, while the third one is placed in a bony area where no muscular activity is present. This allows the measurement of electrical potential differences with respect to a common reference, yielding a unique signal that represents the muscular activity of the area. Given the fast muscle-neural activation nature of EMG signals and the presence of different active muscles contributing to the same signal, muscle activity must be acquired at sampling rates no lower than 200Hz frequencies. Working at 500Hz is desirable, while a sampling rate of 1000Hz guarantees the tracking of all the relevant events at a muscular level.

Surface EMGs are intrinsically limited to the access to superficial muscles. This is compromised by the depth of the subcutaneous tissue at the site of the recording which depends on the weight of the subject, and cannot unequivocally discriminate between the discharges of adjacent muscles. Proper grounding (reference electrode attached to a bony inactive muscular region) is paramount to obtain reliable measurements. Motion artifacts and muscular crosstalk compromise the assessment of the muscle activity under study. In this context, interference from cardiovascular activity is not uncommon, particularly in areas such as chest and abdomen. The presence of power supplies and mains (powerline) in the vicinity poses the risk of 50Hz-60Hz interference.

Inertial Measurement Unit (IMU) signals

An inertial measurement unit (IMU) combines accelerometers, gyroscope, and magnetometer sensors to measure acceleration, rotation, and magnetic field in the three spatial directions. Used as a body sensor, it informs about its movement. Built upon microelectromechanical systems (MEMS), accelerometers use the displacement of a tiny mass surrounded by capacitors to measure proper acceleration. Gyroscopes, use the Coriolis displacement of two opposite oscillating masses to measure the rate of rotation (or rotation speed). Magnetometers are capable of measuring the surrounding magnetic field by means of magnetoresistance changes, informing about the orientation. Hence, IMU signals depict voltage variations corresponding to acceleration changes measured by accelerometry (ACC), rotational speed changes measured through gyroscopes (GYR) and magnetic field fluctuations measured by magnetometers (MAG), throughout a given dimension in space (see Figure 5.1c).

IMU signals inform about the properties of the movement of the body which they are attached to, such as orientation and changes in speed. The measurement of accelerations and rotations, together with orientation, helps the researchers assess the existing movement patterns. Characteristics such as tilt (orientation), changes of direction, or number of repetitions in a given movement pattern (e.g. steps) are usually addressed. This makes possible the understanding of gait, posture, the dynamics of specific gestures or movements, as well as the detection of undesired movement patterns. Moreover, the measurement of movement properties is crucial in areas like ergonomics research and in estimating the metabolic equivalent of tasks addressed in physical effort studies.

The use of IMUs is very extended in monitoring navigation systems, present in many vehicles, and the devices are nowadays part of the set of sensors that mobile phones are equipped with. IMUs used as the body movement tracking systems work through the different sensors placed on the body part that is subject to study. This is typically the case of limbs and joints, shoulders, hips, or head, among others [330]. Just like in the case of mobile phones, the wide use of IMUs has fostered the appearance of gadgets and wearables equipped with this monitoring technology (e.g. helmets, head-mounted displays, handles, controllers, footwear) that can monitor movement properties without necessarily having to attach sensors on the body.

5.3 Actuation Mechanisms

The mechanisms to provide actuation in a form of feedback to the human take an important role in creating a complete interaction from sensing body properties to making the subject aware of them. Our research aims at linking biosensing to body actuation. Actuation is generally provided by mechanical elements that move and respond to input signals in order to either control or inform about a system. We stretch this definition to include feedback mechanisms such as screen-based visuals, although no mobile mechanical element is necessarily implied. In this section, we focus on actuation mechanisms that can be easily controlled and coupled to our body. We take a similar approach to the structure used to describe the biosignals, providing a technical overview while also explaining the actuator limitations and usage precautions for a selected list of actuators. The range of actuation mechanisms presented draws upon our research on affective technologies and interaction design, as well as inspirational works present interaction design research, but it should be seen as a non-exhaustive list of possibilities.

Visual Feedback

Visual biofeedback is the representation of bodily signals over time, capable of informing physiological changes, initiated from within the body. Examples of this could be ECG feedback, respiration feedback, or movement tracking, usually employed in health metrics or sports performance research. Screen-based systems for biosensor feedback are standard practice in clinical settings and hospitals, purposed as a means to assess the dynamics of the aforementioned changes, helping to gain understanding and tracking the inner state of a given subject. Biofeedback use has for instance been adopted in psychotherapy, as research suggests that the technique provides a mechanism to self-regulate the emotions.

Screen-based visual biofeedback can be projected from a 2D graphical a display, either a computer screen or a designated sensing platform display. This modality benefits from direct control over light, colours, strokes, and visual styles to represent a changing signal that evolves with time. Signal peaks and troughs appear in an axis showing the measurement magnitude in a given range, so that rapid and slow dynamics can be seen as the representation moves along the time axis when updated.

To facilitate a live convergence between the input and feedback, it is important that the represented signals are updated in real-time. Doing otherwise, although possible using delays or technology limitations, would compromise the ability of the actuation to convey the tracking meaning attributed to the practice of biofeedback. When sensing requirements pose concerns on the technical ability to render a smooth representation through time, approaches such as averaging or undersampled representations are used.

Screen-based visual biofeedback connects easily with the mathematical properties that underlie the signals under study. However, signal processing procedures such as filtering, scaling or normalisation are crucial in achieving a smooth and flowing representation. These come, of course, tightly dependent on the available resources in computational power. There are situations in which feedback users report finding difficulties or experiencing anxiety when engaging in the assessment of body rhythms. Moreover, visual information tends to remarkably capture the attention of the user, thus needing special care when used as an element of broader interaction (movement, performance, exercise) that could render a poorer experience quality or present a deviation from the aimed activity.

Sound Feedback

Sound feedback, when applied to biosignals, is the audio representation of body signals that uses sound properties to inform about body changes happening along time. Its goal is to exploit our sophisticated trained sense of hearing to convey meanings linked to body signal features, leading to the understanding and tracking of a given subject's biosignal dynamics.

Sound feedback uses the properties of sound, i.e. volume, pitch or frequency (note), rhythm, harmony, timbre, and transients (attack, sustain, etc.) among others, to represent a signal (or its features) that changes over time. Its generation, often using speakers or headphones, is linked to properties of the signal. Alternative approaches draw upon several transducing paradigms, i.e. different ways to convert electrical signals into sound (electromechanical as in the case of speakers, piezoelectric or others), often more limited such as buzzers or beepers made of basic vibrating elements that produce sound.

Sound can be produced by speakers when amplifying electrical pulses to audible vibrations, allowing users to listen to the feedback without the need for additional equipment. Headphones, working by the same principle, can be used for the same purpose but only providing feedback to the person wearing them. The human hearing range typically comprises frequencies between 20Hz and 20000Hz. The oscillating frequency of the sound wave that is created is what gives it a particular tone (what we call a note). The different times at which sound waves are generated is what creates the meaning of rhythm and articulation.

Audio generation and processing techniques are complex. Whilst high-level hardware and software tools can be exploited to make a complete system more accessible, there certainly remains a relevant learning-curve. The scenario in which audio feedback is deployed conditions a lot the effect achieved, given the fact that materials surrounding the sound generating system at use impose effects like reverberation, echoes, or absorption. Exposure to sound feedback for a prolonged period of time has some drawbacks. Excessive volumes can be harmful one´s auditory system, to the point of irreversible hearing impairment. Sound elements that lack textural richness (e.g. a pure sine-wave) may limit long-term engagement from users or potentially cause irritation.

Vibrotactile Actuation

Vibrotactile actuation uses motors to stimulate communication utilizing touch sensitivity, and more precisely tactile vibrations. When linked to physiological sensory, the vibration feedback can be used used to convey features of the biosignal being tracked. This mechanism is built upon motors, which can mostly be categorised under two types: Eccentric rotating mass vibration motor (ERM), and Linear resonant actuator (LRA). These actuators usually enclosed within a small capsule with simple positive and negative (+/−)

terminals to be driven. The typical power requirements for these components normally range between 1 Volts and 5 Volts.

With weights below 1g, the small form factor of these actuators makes them suitable for body explorations, often relying on patches, elastic bands, or holders. Typical uses include also vibrotactile-equipped wristbands or smartwatches. Besides the traditional game/remote controllers including vibrotactile feedback and actuating on the hands, the currently ubiquitous role of mobile phones has spread the use of vibration feedback and patterns for notification, alarms and other communication examples anywhere a phone can be placed or hold. Small vibrotactile motors feature fast startup and breaking times and can actuate taking rotations up to 11000 revolutions per minute (RPM), in the case of ERMs, and oscillations of the order of few hundreds of Hertz.

Vibration comes often with undesired noises or sounds. While this is mitigated by rubber-made absorbing structures often integrated in the motors, use cases need to consider this aspect. While vibrotactile actuation offers the opportunity to explore a particular type of haptic feedback, the use of small motors limits the generated effects, in terms of amplitude, duration, and intensity perceived. To create vibration sequences, several motors are needed, provided integration software and hardware development efforts are carried out. The actuators often require extra drivers to widen the operating regime possibilities while maintaining electrical safety standards. As generally advised in the case of feedback modalities applied to the body, haptic feedback actuation has to go hand in hand with user experience studies, since prolonged exposure and certain placements can lead to discomfort.

Shape-changing Actuation

Shape-changing actuation uses interfaces that exhibit changes in size, shape, or texture in order to exploit the human visual and tactile perception to convey meanings and information content. When linked to feedback, these shape-changing mechanisms convey meanings intrinsic in the dynamics of the information that they are linked to, such as rapid changes, stability, increase, decrease, and steady growth. Such interfaces, despite the parallelisms found in visual screen-based explorations done in visual computing, are emerging as an alternative, physical, and tangible way of interacting with technological devices [9]. Three of the most widely used examples of shape-changing actuation elements are Shape-memory wire ("muscle wire", nitinol, flexinol), Linear actuator and Inflatable shapes.

In order for the technology to best benefit from the focus on visual and tactile perception, shape-changing actuation implementations must remain under reach (sight or touch) to convey the meanings embedded in the changes of shape. This can entail direct contact with the body, with the potential to increase the felt shape meaning when in contact with a large body area, or where touch sensations are more developed, or within the field of vision of the user.

The wide range of shape-changing actuation possibilities comes with different actuation timings in it. While it is possible to work with shape-memory wires that are rapidly heated or compressed gas or pumps that quickly fill up a given inflatable, the time affordances of this kind of actuation do not generalize. Linear actuators, for instance, usually require a system of pistons and damping mechanisms that have an impact on the dynamics of the actuation while it unfolds over time. Moreover, it is often the case that the behavior of shape-changing interfaces is not symmetrical, for example, although an inflatable can be rapidly fed air by a pump or a reservoir, deflation valves have their own rules.

Memory wires, although visually appealing, imply the utilization of high temperatures which challenges the use of haptic shape-changing feedback based on them. In turn, the strains achieved (or pulling forces) are generally weak, often leading to implementations that use several wires. In the case of linear shape-changing actuators, movement is often accompanied by undesired noise and relatively slow dynamics. The actuators themselves, made of rigid moving elements, impose a certain rigidity to the overall actuation. Moreover, multiple units are often needed to create appealing effects. Shape-changing inflatables often present problems of fluid leaks, as well as different asymmetric behaviors for inflation and deflation. These can be tuned by further developments on valves and compartments but requires significant work. Besides, the type of pump poses specific fluid requirements and usually exhibits noise that interferes with the actuation designed.

Aesthetic Characteristics of Actuation Modalities

Taking the aesthetic criteria set out in Section 7.4, we briefly describe some of the spatial and rhythmic qualities of interaction that are complimentary to the actuation modalities listed above. To begin, we propose that visual feedback is well attuned to spatial aesthetic qualities, where pixel-based displays are capable of projecting highly granular representations that take upon aesthetically engaging features, such as symmetric (and asymmetric) structures. Li provide a comprehensive review of cognitive processes that occur when perceiving low-level visual features [275]. In Chapter 8, visual feedback is utilised to articulate internal sensations such as muscular activation and balance while a physical gesture is performed and presented to an audience, developed from the guidelines for visualisation set out in Chapter 6.

Sound feedback can conveniently be associated with rhythmic qualities when a regular "pulse" is clearly present [102]. In the following Section 5.4, we demonstrate how shared sound feedback can foster physiological entrainment between two users, sustaining synchronous inhale-exhale rhythms. Sound can indeed be used to provoke qualities of space, a clear example of this being the use of particular reverb effects to mimic the feeling of being situated in a particular space, such as a large hall. This feature is still constrained within the singular dimension of time, however. In order to achieve a sense of localisation that's authentic to three-dimensional space, the binaural arrangement of conventional listening mediums can be limited here [88]. Studies into ambisonic configurations provide a promising research path, however these still retain a high barrier to use when considering cost, learning-curve and portability [221]. Our Case Study III, Chapter 9 showcases an interactive framework to engage many users with one another by leveraging both rhythm and localisation with several mobile speakers.

Tactile forms of feedback, be it from vibration or shape-changing mechanisms, impose feedback directly onto the body, which can be arranged to target specific limbs, muscles, bones and organs. In terms of spatial aesthetics, these tools are resourceful for harnessing one's sense of proprioception, raising awareness to their bodily functions. Moreover, by applying shape changes that unfold over time, the actuation dynamics are brought forth letting the user be able to play with concepts such as time (increasingly/decreasingly fast, slow, abrupt) and volume or size to depict the desired information. In Chapter 7, Section 7.4, we go into detail of the aesthetic affordances that arise while engaging with shape-changing materials over prolonged assessment period. In this case, we study how symmetry, synchrony and bodily alignment can influence one's habitual respiratory rhythm and posture.

Orchestration

By orchestration, we refer to the design of the overall interaction: coupling sensors to actuation of relevance to the interaction space; initiating and closing the interaction; habituating; helping improve on the users' body awareness and articulation of emotion. Such mechanisms try to achieve the overarching goal of linking body measurements to meaningful representation through actuation that addresses various modalities that act on our bodily senses, be it visual, hearing, touch or otherwise. To achieve this facilitation it is crucial to be able to combine and nicely coordinate the relationship between input (sensors) and output (actuators). In this scope, the term orchestration defines the process of:

- Creating couplings, that is, combining biosensors and actuators in place Coordinating the technology-mediated body interactions
- Working on the sequence in which different modalities are addressed via the sensors and actuators. Deciding which one goes first
- Understanding the design possibilities, acknowledging affordances, limitations and roles of the involved technologies that involved in these interactions
- Consolidate the process of introducing a new user to the experience, defining a balance between explicit interaction or open exploration
- Retrieving meaning information from the input data, potentially laying out machine learning, feature extraction, smart event recognition, or signal processing tools that can be applied to render the interactions more intuitive

5.4 Breathing in Synchrony: From Physiological Synchrony to Audio Feedback

Taking the orchestration principles described above, we present a preliminary coupling. This example draws upon the psychology concept of therapeutic alliance [253], takes respiration data from two users in the same physical space, each equipped with personal wearable devices that stream data wirelessly to a host computer. In this example, two users participate in a timed breathing exercise together whilst their individual respiratory patterns are being measured with piezoelectric (PZT) bands placed around the diaphragm (see Figure 5.2). The data is aggregated on the host computer, executing a script that measures the collective breathing activity. From here, we apply shared biofeedback in the form of sound to stimulate synchrony awareness and physiological dialogue between users over time.

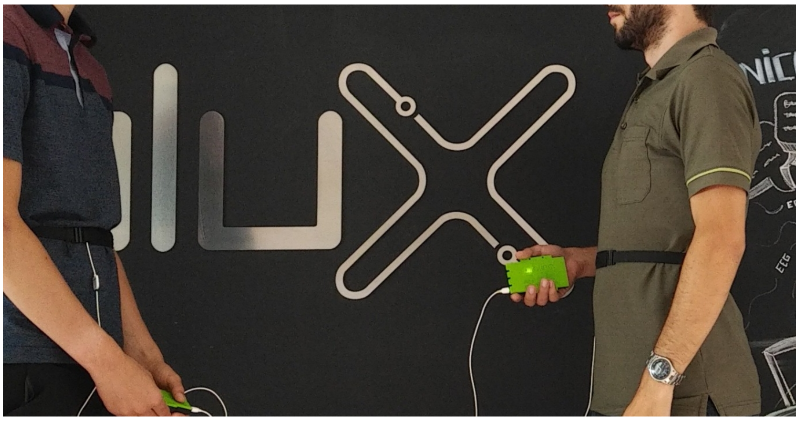

Figure 5.2: Breathing synchrony-audio experiment, based on the analysis of two piezoelectric abdominal respiration signals

Respiration as an Expressive Indicator

While searching for practices beneficial for affective well-being, breathing exercises were also considered. Recent research indicates that many of the detrimental effects of negative emotional states and sympathetic dominance of the autonomous nervous system can by counteracted by different forms of meditation, relaxation, and breathing techniques. In fact, meditation and breathing techniques can reduce stress, anxiety, depression, and other negative emotional states [65, 111, 232]. Moreover, body-centred practices, such as dance or martial arts, require coordinating breathing patterns not only with our own movements but also the person we are moving with [93].

Sensory Input and Processing Strategies

The exploration followed a stage of preliminary research on physiological synchrony features drawn from published research drawing upon statistical measurements, potentially generalise to signals other than breathing [480]. We implemented the computation of linear regression coefficients, cosine similarity and correlations between filtered signal and derivatives. The process for mapping the user's activity audio output can be split into two main components. First, the sensory data is transmitted to a data processing server, which is used to perform statistical analysis on the incoming signals, calculating a "magnitude of synchrony" using the features listed above. After a fifteen second warm-up period, the system accumulates a sufficient amount of data to determine mutual behaviour, and the resulting values are encoded into Open Sound Control (OSC) messages that are continuously streamed to a local address, enabling the designer to map the data to appropriate parameters for sound feedback. With this generic protocol in place, we aim to embrace modularity, and advocate for the experimentation of sonic associations. In our tests, we used Cecilia's [6] built-in granular synthesis engine; this manipulates the playback of a pre-recorded soundscape divided into independent samples of 10 to 50 milliseconds [373].

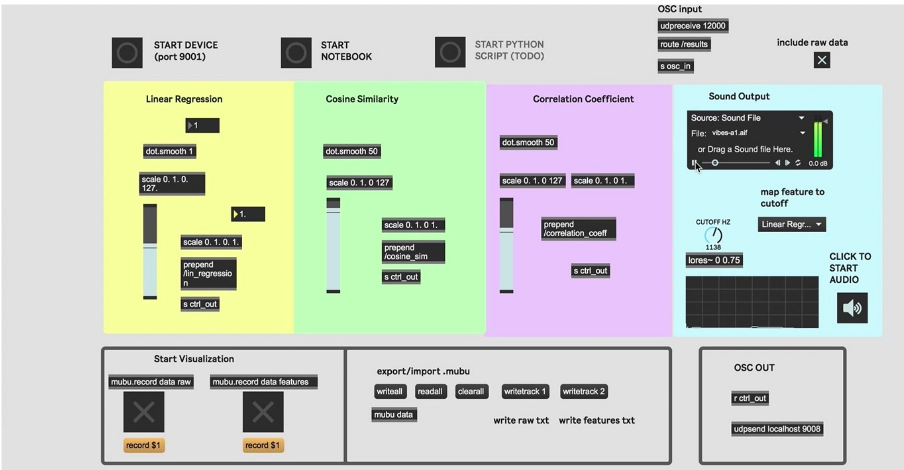

Figure 5.3: Feature extraction GUI for synchrony metrics.

Adjustment and Tweakability for User Empowerment

We describe how embodied sensor technologies react differently in accordance with the unique biological characteristics of the body. Similarly, the perceived impact of a given actuation mechanism—as those described in Section 4—largely depends on the sensitivity to a given stimulus, as well as the natural bodily variations between different users. With this considered, we recognise the necessity to attune the system's parameters in order to produce mappings that facilitate meaningful interactions that are not overly obtrusive. While auto-calibration mechanisms have been implemented in the previous examples, which typically define and minimum/maximum parameter ranges, we foresee an extended benefit in adopting Interactive Machine Learning (IML) [17, 138] frameworks as means to foster perspectives respecting body pluralism. Furthermore, we set out explore the use of Interactive Machine Learning to develop novel coupling relationships that go beyond linear mappings, as well as intuitive mappings between multimodal inputs and multi-dimensional outputs. In our sound-based examples, visual programming environments heavily assisted the orchestration process. In both cases, the systems enabled users to visualise a continuous stream of mappable data in real-time, clearly exposing any unexpected behaviour that may occur (for example, with the displacement of sensor electrodes). The node-based functionality of the frameworks allowed for a coherent representation of the dataflow and signal processing steps in order of execution, less abstract compared to a code-based script. During the process of developing the system, a user interface is generated in parallel on-the-fly as each node presents a GUI element that grants the designer access to parameters such as scaling and smoothing coefficients. This workflow can be beneficial for rapid experimentation with a variety of parameters and signal processing techniques that influence the interactive experience. It also presents a convenient solution for fine-tuning a complete system according to the user's experience.

5.5 Summary

In this chapter, we approached the design of sensing-actuation experiences intended for rich embodied interactions. To achieve this, we adopted first-person soma design to integrate biosignals that are commonly used in ubiquitous low-cost personal sensing together with actuation mechanisms studied in HCI. Our design exploration, giving special attention to the sentient body and acknowledging alternative ways to address affect within interaction, culminated with a coupling example, in which we demonstrate data mapping strategies between respiration and sound feedback in the context of interpersonal bodily awareness. Taking this into a broader perspective, we introduce the concept of orchestration, defining the ways in which body input-output systems and meanings are put in place, the range of mappings and how they unfold. These resources mark as a theoretical and technical foundation for much of the work presented in Chapter 7.

6

Preliminary Actions II: How Do Dancers Want to Use Interactive Technology?

In this final phase of preparation, we carry out a focus group to establish design guidelines that are incorporated into Case Study II, presented in Chapter 8. This takes place during a two-day participatory workshop, that initiates the multistage co-design process described in Section 8.11. Here we will report on the outcomes contained in the following publication that was delivered during the doctorate programme, including personal contributions as respective co-authors:

R. Masu, N. N. Correia, S. Jurgens, I. Druzetic, and W. Primett. “How do Dancers Want to Use Interactive Technology?: Appropriation and Layers of Meaning Beyond Traditional Movement Mapping”. en. In: *Proceedings of the 9th International Conference on Digital and Interactive Arts*. Braga Portugal: ACM, Oct. 2019, pp. 1–9. ISBN: 9781450372503. DOI: 10.1145/3359852.3359869. URL: https://dl.acm.org/doi/10.1145/3359852.3359869 (visited on 05/05/2022)

6.1 Appropriation and Layers of Meaning Beyond Traditional Movement Mapping

There has been an increased interest in HCI research regarding the possibilities of interactive technology applied to the field of dance performance, particularly contemporary dance. This has produced numerous strategies to capture data from the dancers’ bodies and to map that data into different types of display formats. In this paper, we look at the role of interactive technology in dance from a broader perspective, aiming at understanding the needs of dancers and their relation with the audience. To this end, we ran a focus group with ten dancers with expertise in technology, which we analysed using thematic analysis. We discuss the implications for design of our results by framing the role of technology in dance, proposing design guidelines and analysing appropriation and ambiguity in this context.

6.2 Introduction

In the last decades, interactive digital artefacts have become ubiquitous, and their applications have gradually switched from workplace to everyday lives and culture. This has been identified as third-wave HCI [47]. With this tendency, user experience has become central in HCI discourse [469]. It has also emerged that users tend to appropriate digital artefacts in different ways [125]. Consequently, the use and meaning of artefacts might become ambiguous, and potentially open to many interpretations [170]. In general, understanding the needs of the user has became a fundamental design activity [24], and users started to be involved in the design process using User Centered Design (UCD).

Among the variety of contexts touched by the spread of application areas in HCI, dance has gained an increased attention, (e.g. [144][76], and for contemporary dance see [120]). From an HCI perspective, technology for dance can be viewed as a system including input and outputs, as discussed in Chapter 5).

Contemporary dance performance represents a complex scenario of use of interactive technology. To begin with, it is composed by two main activities: the preparation of the performance, and the performance itself; the preparation of performance is itself a development process where “choreographic material” is generated [238]. Moreover, different categories of users (dance artists: choreographers and dancers) are involved in contemporary dance performance. As depicted in the framework proposed by Butterworth, these two main categories might play different roles [42]. Therefore, we argue that designing interactive system for dance performance requires a multifaceted approach from HCI, which takes into account the different roles of the technology in creating meaning in the overall dance performance, as well as the different needs of users.

In this study, we address these aspects by using early-stage co-design activity. Namely, a focus group is presented with ten dancers and proposes design guidelines based on the analysis of the respective results. The main objective of the focus group was to inquiring dance artists (dancers - choreographers) about a general research question: *What is the role of digital systems in dance performance, in particular, interactive technology and visualization?* A secondary objective of the workshop is to understand how that role influences the dancers’ communication with the audience. By this, we mean the communication from the performers to the audience, and the audience’s understanding of that communication.

Our results suggest that dancers want to stimulate the audience without imposing one explicit meaning and using technology as a co-creator of the performance, that imposes a certain level of initial conditioning of the very logic of the works, that dancers/choreographer need to appropriate to adapt (using different strategies) to create the performance. Moreover, our participants stated that most of interactive technology is too illustrative and diminishes the multilayered complexity of performances, an issue that can be overcome using different interaction strategies.

Figure 6.1: The setting of the focus group.

6.3 Study Overview

To address our research question about the role of interactive technology in dance, and how dancers aim to communicate to the audience, we organised a two-day workshop with dancers, composed of a series of design exercises, including a focus group[1].

The participants were selected using an open call, disseminated through mailing lists related to contemporary dance. Ninety-two dancers applied to the call (73 female, 19 male). Each candidate was independently evaluated by six members of our team, according to: (i) their Curriculum Vitae as dancers; (ii) previous experience with technology in dance; and (iii) motivation and expectations regarding the workshop. Finally, the scores were discussed and moderated. Ten dancers were selected (nine female, one male, from eight countries) and all of them participated in the study. We covered travel expenses and paid a fee for each dancer. Due to the competitive selection, all ten participants had considerable experience in contemporary dance as performers, some of them also as choreographers. In particular, all the participants had previous experience as professional dance artists in projects that involved technology. In most cases, our participants had experience both as dancers and as choreographers. The type of technology that our participants have used in previous works ranges from VR, 3D modelling, streams of social media, different types of hardware (including Kinect and Arduino), and software (Max/MSP, openFrameworks, Processing). Referring to the different roles the dancers and choreographers have in the creative process of producing a dance piece, our participants reflect those scenarios where there is a choreographer leading the decisions.

The objective of the focus group was to gather data about the role of technology in dance, aiming to identify needs and requirements of dance practitioners. We were also interested in the role technology might have as mediator between dance artists and

[1] Documentation for the workshops, residency and performance can be found in the Appendix B

their audience. Therefore, we structured the focus group around the following four main topics, which align with our research objectives: communication to the audience in dance performance; the role of technology in dance performance; the role of interactive technology; and the role of visuals. The purpose of this focus group was to frame the initial requirements for a future prototyping process. In this way, we followed a UCD perspective, informed by previous studies [2, 25, 384]: we started by questioning the users about their needs. The users (in this case, the dance artists) were involved from an early stage to identify needs and requirements regarding interactive and visualisation technology in dance, which will be the basis for future a in the co-design process. The focus group took place at the cultural and performance space, Sõltumatu Tantsu Lava (STL) in Tallinn, lasted for approximately two hours and was audio/video recorded.

Results

We recorded audio and video and took hand-written notes during the focus-group. It was analysed independently by two researchers using thematic analysis [57], then the analysis were cross-checked and harmonised. The analysis produced six themes, each with multiple codes. We transcribed and anonymised the interview data and refer to participants as P.1-P.10.

Theme 1: Audience characteristics

The first theme concerns the characteristics of the audience. Our participants generally consider the audience intelligent, but also unpredictable.

- **Audience is intelligent.** The audience is intelligent (P.8) – participants aim to make a performance for the most intelligent person in the audience (P.9).
- **Audience is unpredictable.** There is uncertainty about the audience: you really never know who's sitting in this audience (P.2), also the audience members may have an unexpected response (P.7).
- **Audience as a close human.** Finally, there is also a level of closeness with the audience - like creating this human moment of sharing something common, of human to human (P.8).

Theme 2: Communicate with the audience

Several aspects concerning the communication with the audience emerged. In general, the artists agree that meaning of the experience should not be imposed to the audience.

- **Not impose one specific meaning to the audience.** Relying on the fact that the audience is intelligent, the performance should not impose one specific and didactic (P.2) or prescriptive (P.3) perspective, rather create multi-layers of meaning (P.5) and information (P.9). Dancers aim at not being didactic and at not controlling the audience, even promoting provocative strategies such as deliberately causing confusion (un-focusing P.6). Dancers also do not feel the need to teach (P.2), but prefer to articulate the performance and balance the clarity, without overexposing an idea (P.3).

- **Shared experience with the audience.** Relying also on the notion of closeness, our participants aim at creating a sense of togetherness (P.9) with the audience. The moment of the performance has been described as a shared intimate (P.9) experience between artists and audience, together [...] and in synchrony (P.6) with the audience.
- **Create safe environments for the audience.** Our participants aim to create safe environments (P.5), spaces of intellectual freedom where the audience can come with their own knowledge and their own understanding (P.6).
- **Considering the audience during the creation process.** In order to check the clarity of my idea (P.3) some of our participants invite audience during the rehearsal asking for feedback. Our participants stressed the need of ensure clear articulation .(P .3) in providing the information to the audience

Theme 3: Technology as co-shaper of the performance

Technology has specific characteristics, which enables the dancers to reflect on them during the creative process. In this sense, technology becomes co-shaper of the creation process:

- **The creative technology. The technology is creative:** it's like creative dancers, there is also creative technology (P.3). This creative technology can generate creative ideas (P.2). Therefore, technology may already have a dramaturgy (P.5). There is an awareness of the duality in technological creativity: Is it a dramaturgy in the technology itself or is the choreographer that tries to use technology as a dramaturgical tool? (P.1).
- **Movements fostered by the technology.** A technological artifact has an impact on the movements, it imposes physical limitation (P.3) and proposes new types of technological gestures (P.2).
- **The problem of excessive focus on technology.** The technology should never be the focus of a performance (P.9). It should be subtle or invisible (P.9). Technology can mesmerise and fascinate (P.6) the audience, but it should not be used in this manner: there is a shared need to express something with it (P.3).
- **Integration of the technology in the logic of the work.** The technology should be reflected (P.3) and integrated (P.9) in the logic of the performance.
- **Hacking.** Our participants describe the process of using the technology as hacking the system (P.3), in a figurative sense: dancers are not using the technology the way that the technology designers meant (P.3).

Theme 4: The problem of redundancy of information

One of the main problems that our participants identified is that technology it is often diminishing the layers of meaning in the performance.

- **Technology is illustrative.** *Technology is too illustrative, [...]and too connected to what you are doing with movement* (P.6), for this reason it risks to merely duplicate the body (P.4).
- **Illustration and meaning.** The visual output is too graphic, it's diminishing the multi-layered meaning (P.5). and risks to simply replicate the information (P.6).

Theme 5: Strategies for Interaction

From an interaction design perspective, some good practices emerged.

- **Complex mappings.** Unclear, divergent, or independent mappings from input to output technologies could be used to create counterpoint (P.9) between the dancers and the technology, avoiding more obvious mappings (P.6).
- **Interaction loop.** Technology could create a complex mirror that challenges the movement of the body (P.9), a sort of feedback loop (P.3) that affects the choices of the dancer.

Theme 6: Strategies for visuals/output: adding layers

This last theme clusters suggestions related to the output of the digital artefact.

- **Visualise the structure**. Expose the score before (P.9) or during (P.6) a performance might contribute to adding layers of meaning as it is a commentary on your own work and it's self-reflexive and it's interesting (P.6).
- **Play with time-related elements.** This might include displaying what things that happened in the past and [...] resonate [...] in a performance (P.9), or traces and the resonance of the movement (P.1).
- **Alternative sensorial strategies.** Our participants also suggested to rely on other sensorial channels, such us kinetic illustration (P.5) and sound that might be used to trigger sensation (P.10). Moreover, sound is multi-dimensional in space, and these characteristics makes sound more similar to movement as compared to visuals (P.5).
- **Capture the intelligence.** Several aspects of the intelligence of a body could be captured and revealed: e.g. *what's happening in the brain before the movement* (P.6), record the thinking process of someone doing something incredibly complex (P.2)

Design Guidelines

The design guidelines are organised around three high-level aspects of interactive technology for dancers:

1. **Communication with the audience (from Theme 2)**
   a) Technology should not impose one single perspective to the audience
   b) Technology should contribute to create multiple layers of meaning
2. **The role of the technology in the creation of the piece (from Theme 3)**
   a) Technology should provide space for appropriation, enabling the dancer to give their own use and meaning - facilitate customization might be a possible strategy.
   b) Technology should be easily included in the dramaturgy of the performance - make it meaningful for the performance.
3. **Input and output strategies (From Themes 4, 5, and 6)**
   a) Technology should not repeat the information that the dancer is already giving with their movement (avoid overly clear mappings).
   b) Technology should have a complex input-output mapping, which might be used to create a loop between technology and dancers.
   c) Technology should facilitate adding information contributing to multiple meanings of the performance (Theme 6). Examples that emerged in the analyses of focus group include: (i) showing non visible elements (either inner elements of the dancers or micromovements), (ii) shifting the temporal dimension of the performance (e.g. showing, in time lapses, residuals aspects of movement), (iii) showing the structure (score) of the performance.

6.4 Discussion

The results of the focus group allow us to address our research question. In addition, we discuss this in light of the concepts of appropriation and ambiguity and propose guidelines. These taken forward into the subsequent works presented in Chapter 8, in particular, Section 8.8.

What is the role of technology in contemporary dance, in particular, interactive technology and visualisation?

Technology plays a crucial role as co-creator of performances, but it should not be the focus. A piece of technology already has its own preexisting dramaturgy, it imposes specific problems or limitations to the choreographer, which need to be incorporated in the ideas and meanings of the performance (Theme 3). In order to use technology in a meaningful way that is harmonised with the overall performance, dancers need to appropriate the technology and give it a new meaning that is aligned with the dance piece. A performance should be composed of multiple layers of meaning (Theme 2), and technology should contribute to this multifaceted structure (Theme 4, 5, 6). In Theme 4, it emerged that our participants have had issues with technology when it adopts overly clear mappings, since in this case it repeats the same information of the body creating a redundancy issue.

Appropriation and ambiguity in interaction design for dance

Our participants' need for reflecting and integrating technology in the performance reverberates with the design concept of appropriation. Similarly, the need for adding layers of meaning and not imposing one single meaning in a performance resonates in the design concept of ambiguity. In Theme 3, it emerges that the dancers' use of interactive technology implies a second creative process, whose outcome is a performance. During this process, the dancers need to appropriate the technology [117]. Moreover, the idea of layering the information is also similar to the idea of designing for appropriation proposed by Dourish: supporting multiple perspectives on information [125]. In this sense, there are two faces of appropriation: dancers appropriate the technology to create multiple layers of meaning in the performance, and the layers of meaning supports the audience to appropriate the content of the performance.

We argue that an interactive digital artefact designed for dance performance should take into account these aspects, and not impose one restricted meaning or use, nor of meaning. On the contrary, it should support dancers to appropriate it, to embed it in the performance and contribute to the multiple layers of meaning. To this end, the artefact should already have ambiguous characteristics that facilitate the appropriation process, as advocated by Gaver's seminal work [171], rather than impose one pre-determined usage. In Theme 4, 5, and partially 6 it emerged that ambiguity can be used to build the multi-layered meaning of the performance. Therefore, adding ambiguous elements in the technology (e.g. in the rich and complex mapping possibilities from input/interaction to output/display) could enable dance artists to create those multiple layers of meaning. Based on the discussion above, we highlight two different types of ambiguity that facilitate appropriation:

1. *Ambiguity of use* of the artefact, that facilitate the choreographer to appropriate the technology and use it in the process of creating the performance integrating it in the creative process.
2. *Ambiguity of mapping and meaning* of the artefact, that facilitate the audience to appropriate the meaning of the performance.

7

Case Study I: Breathing Correspondence

The following sections will report on the outcomes contained in the publication that was delivered during the doctorate programme, including personal contributions as respective co-authors:

A. Jung, M. Alfaras, P. Karpashevich, W. Primett, and K. Höök. "Exploring Awareness of Breathing through Deep Touch Pressure". en. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Yokohama Japan: ACM, May 2021, pp. 1–15. ISBN: 9781450380966. DOI: 10.1145/3411764.3445533. URL: https://dl.acm.org/doi/10.1145/3411764.3445533 (visited on 05/08/2022)

We present the outcomes of a collaborative research effort between ourselves at PLUX Wireless Biosignals (M. Alfaras and W. Primett) and KTH Royal Institute of Technology (A. Jung, P. Karpashevich and K. Höök) merging resources from industry and academia

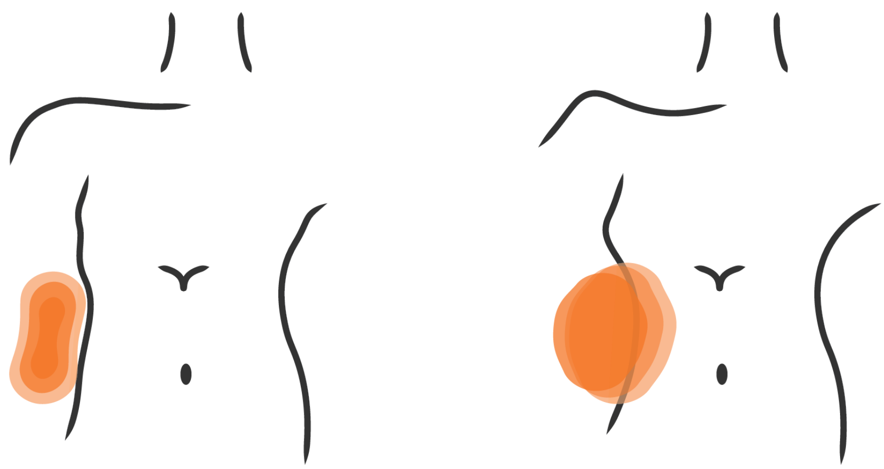

Figure 7.1: Deep pressure, pressing onto the torso, first using weak (left) and then strong pressure (right).

representatives. The other authors will be mentioned by name to specify the responsibility of specific research actions, where appropriate.

This effort was observed over three guest research periods involving M. Alfaras, W. Primett, A. Jung each being hosted by the partnering institutions respectively for 1 to 2 months between. The hosting of A. Jung was partially interrupted in March 2020 due to the first COVID-19 pandemic. The resulting article encompasses a detailed view of the fabrication and technical composition of the actuation wearable produced. In the scope of this thesis, we will take this opportunity to highlight the core insights taken from the user study, and use this to establish an aesthetic framework that holds relevance throughout the comprehensive research goals.

7.1 Breathing Correspondence: Shape-changing Actuation for Breathing Awareness

This study follows our explorations towards biofeedback systems for breathing and shape changing actuation that was initiated in the preliminary actions (Chapter 5) in addition to the work contained in the publications efforts that proceeded [12, 382]. These modalities have been given attention by interaction design researchers, showcasing examples of breathing feedback as visual or aural representation, with other cases using haptic feedback with various tangible media, such as shape-changing materials [317, 354]. We also note the technical progressions towards new shape-changing materials that have complimented this research [94], however, there still remains a call for understanding their aesthetic potential of these systems from the perspective of the user [10, 360].

Deep Touch Pressure (DTP) is used in sensory integration therapy used for treating deficits in tactile stimuli [71], making use of weighted garments and blankets, swaddling, or firm hugs to provide a firm pressure sensation to the body. Its calming effect seems to be due to stimulation of the parasympathetic nervous system, which plays a significant role in anxiety management [219]. In therapy practice, DTP has been applied to increase attention [146] and reduce anxiety symptoms [254], particularly for children and students with autism spectrum disorders (ASD) [13, 266]. So far, DTP is relatively unexplored in interaction design research (with some notable exceptions [110, 129, 153, 154]). We take deep touch pressure as a starting point for aesthetic qualities of coupling shape-changing pads with respiratory sensing, enabling the actuation materials to exert pressure on different locations on the torso of the breathing body.

The design process involved a series of collaborative design sessions engaging with couplings of breathing and pressure, construction of an experiential artefact [433] to explore the affordances of the socio-digital material, as well as long-term first-person explorations of the impact of shape-changing deep pressure feedback coupled with conscious breathing practices. This was done in different teams formed by the authors of the corresponding publication [236].

Through a process of material experimentation, we uncover potential for a number of novel interaction qualities that we will report on here: perceptual differences of applying deep pressure *symmetrically and asymmetrically* on the torso and how these may help to increase breathing awareness; opportunities for *directing attention* to different parts of the breathing apparatus, such as the bone structures or muscles involved, and thereby supporting learning a richer breathing repertory; the effects of providing feedback *synchronously and asynchronously* in harmony with, contrary to, or even out of sync with the user's breathing rhythm leading to a deeper aesthetic appreciation of one's breathing; as well as exploring the balance point between letting the system subtly *lead or influence* breathing patterns versus solely *following* the rhythm of the user's breathing in the interactions – an experience we will refer to as *breathing correspondence*. These explorations contribute to opening up the design space around shape-changing interfaces by characterising potential experiential qualities and affordances based on felt bodily experiences of deep pressure for breathing awareness.

7.2 Background

Breathing Awareness

A growing body of research in HCI focuses on designing interactive systems to extend breathing awareness. Prpa and colleagues [354] provide an overview of the underlying theoretical frameworks and design strategies used in breathing-based interactions. While some aim to trigger physiological responses related to alleviating stress and anxiety by slowing the breathing rate [70, 338, 377], others utilise breathing patterns to promote mindfulness [346, 404] or to support communication between people through synchronization of breathing [112, 249]. The somaesthetic design approach [211], which informed our work, utilises breathing as gentle guidance to develop sustained attention towards bodily sensations and learn to appreciate all the nuances of the felt experience of breathing [353, 426]. By cultivating bodily and breathing awareness, users can come to better understand the connections between their physical and emotional experiences, thereby finding novel paths to regulate emotion and develop a higher sense of trust of their own body [52].

Many of these systems capture breathing data and translate it into sensory stimuli to externalise breathing, making it visually or tangibly accessible to users, creating immersive virtual and physical environments for engaging with breathing practices from mindfulness, yoga, Feldenkrais [320, 339, 404, 426, 453] and other body practices. While most interactions address auditory or visual modalities, there have been a few tangible designs which mirror or guide users' breathing processes, such as fidget spinners with added visual feedback [278], shape-changing airbags [478] or stuffed animals [20]. Other haptic systems mainly use vibration feedback [70, 115, 317], while other forms of immediate haptic feedback on the torso have so far rarely been explored with the exception of a recent study by Foo et al. [153]. They noted that rhythmic pulsing compression applied on the torso showed potential to improve focused attention on breathing and adopt a slow breathing rhythm, making it an interesting option for further exploration.

Shape-Changing Interfaces

Shape changing interfaces constitute a novel interaction form as they enable interactive changes of the shape or texture of a material [10]. The increasing maturity of these shape-changing materials and tangible technologies has led to increased attention in the HCI and interaction design field. Recently, we have seen several attempts to clarify what this design space offers when building applications. For instance, Coelho and Zigelbaum [94] try to characterise technological properties of shape-changing materials, while Rasmussen and colleagues [360] identified eight different types of shape changes of relevance to different functional and hedonic design purposes. Others present particular design exemplars, including mobile devices [116, 181, 204], interactive tabletops [152, 436], furniture [187], toys [246], and interactive architecture [335]. A few shape-changing design exemplars have addressed breathing, such as a stuffed animal breathing in synchrony with its user [20], a photo frame reflecting a partner's breathing [249], or morphing physical environments for engaging with one's own breathing [396, 416]. These systems mainly emphasise the visual aspect of shape-changing interaction [249, 320, 396, 416], and only in a few cases are they used to produce tactile feedback [478] or engaging with users' movements [444].

In comparison to the technical development, the aesthetic user experience of interacting with shape-changing materials as well as their affordances have not received as much attention [10, 360]. Rasmussen and colleagues [360] devised two types of expressive parameters to characterise how movements of shape-changing interfaces are perceived by users. These include adjectives like smooth or angry as well as associations, such as a phone expressing sadness through a human-like sobbing pose. Due to their dynamic characteristics, users and designers often use metaphors to describe shape-changing behaviours, associating them with certain personality traits, animals or ascribing them other life-like qualities [258, 361].

Deep Touch Pressure

Deep touch pressure (DTP) is a method used in sensory integration therapy, aimed at treating sensory processing difficulties related to, amongst others, anxiety disorders, in particular anxiety experienced by those on the autism spectrum [186, 219, 254]. The therapy involves using tools such as weighted garments and blankets to provide a comforting pressure sensation. Its calming effect can be attributed to increased activity of the parasympathetic nervous system, which plays a significant role in anxiety management [219]. In therapy practice, DTP has been applied to increase the ability to focus [146], reduce disruptive behaviour [356] and reduce anxiety symptoms [186] in patients with bipolar disorder, developmental disorders and those on the autism spectrum.

In HCI, different types of compression garments have been developed to provide DTP. Vaucelle et al. [452] designed a pressure vest containing pneumatic chambers. A more elaborate project is the Force Jacket [110], an upper body garment that uses pneumatically-actuated airbags to create sensations of directly applied force and high frequency vibrations. Such vests are the most common form of designs for deep touch pressure and make up the majority of commercially available DTP products, such as the Tjacket [288] or the Squease vest [289]; both are inflated using external pumps. Such vests have also been used to simulate hugs in long-distance interactions between parents and children [439].

7.3 Design Process

Our design work started with a general interest in deep touch pressure, but when extrapolating from this concept we came to explore a range of interactions between physical pressure and breathing. Our explorations were done from an embodied, first-person perspective [214], putting the researchers themselves, their movements and subjective experiences at the centre of the design process.

The process was initiated by the author Annkatrin [236] via initial exploration of the breathing sensor, shape-changing actuators and fabrics for creating restriction and shape-change. This initial phase lasted for 1.5 months and allowed for discovering the affordances and experiential qualities of the available technology and materials, as well as experimenting with different shapes and sizes of the inflatable elements. Her first insights from this process informed possible interactions with different actuator sequences, which were further explored in a series of collaborative soma design workshops [211] performed by researchers Annkatrin, Miquel and William (thesis first author). In total, four sessions took place over three weeks, iteratively exploring opportunities for connecting different actuation sequences and breathing techniques in relation to different areas of the body. The soma design workshops were followed by a continued systematic exploration of the deep pressure coupled with specific breathing techniques done by Annkatrin over a period of two months. This led to the construction of a wearable garment which places the shape-changing actuators on the upper and lower back to guide different ways of breathing, as shown in Figure 7.4.

The results discussed in this study are primarily based on the series of soma design workshops performed by the authors of the corresponding publication, Annkatrin, William and Miquel, as well as the further investigation of specific breathing techniques done by Annkatrin afterwards. This was also complimented with additional insights from the design work done by Pavel and Kristina.

Soma Design Sessions

Over the course of four weeks, Annkatrin, William and Miquel performed a series of four collaborative soma design workshops exploring breathing-based interactions with shape-changing pressure feedback. The three authors are actively engaged in the field of embodied interaction with biofeedback systems, carrying modest experience with bodily practices such as yoga and Feldenkrais through regular practice both in and out of the lab. An additional participant, a graduate student from a product design background who is not among the authors of this paper, joined in the third session.

The workshop structure was grounded in soma design theory which places sensory experiences and appreciation at the centre of the design process to incorporate the soma, the integrated whole of body and mind, in a holistic manner and build a subjective understanding of one's somatic experiences [211].

Each of the four sessions lasted about three hours including the setup and incorporated shape-changing actuators in various shapes and sizes, as well as additional fabrics to attach them to different parts of the body and create restriction. The actuators are part of the Soma Bits toolkit [465], a collection of shapes and actuators designed to facilitate soma design workshops, and consist of Thermoplastic Polyurethane (TPU)-coated nylon shapes which can be inflated or deflated at different speeds or stay at a constant level of inflation. Further in the text, we will be using "pillows", "inflatables", "pneumatic pads" interchangeably to describe these shapes. The actuation was controlled wirelessly with an Arduino-based device, capable of inflating and deflating the pneumatic pads at variable pump speed (max 3L/min) within the pressure range of 450 - 1950 hPa, as well as providing real-time pressure sensor readings.

The framework used for sensing and actuation control is illustrated in Figure 7.2. To capture breathing, we used an inductive respiration (respiratory inductance plethysmography, described in Section 5.2) sensor[1] (1) which measures the relative displacement of the chest or stomach, depending on its placement. The sensor data is continuously acquired to compute the subject's breathing rate, which in turn influences the time dynamics of the shape-changing feedback. This data exchange is handled by (4) a Processing server, directing control messages between the browser-based Node-RED GUI (2) and the actuation hardware (5 & 6) via Open Sound Control (OSC). The visual interface allows for the different actuation sequences to be executed with adjustable parameters, while a separate Python script runs in the background for signal processing and feature extraction (3).

Each workshop began with a somatic practice to cultivate a sensitivity towards the bodily sensations, placing the aesthetic experiences in the foreground of the embodied interaction. This was specifically structured as a Feldenkries routine, focused on breathing and micro-movements. Afterwards, the participants took turns in placing the pads on different parts of their bodies to investigate how different placements, actuation sequences

[1] https://biosignalsplux.com/products/sensors/respiration-inductive.html

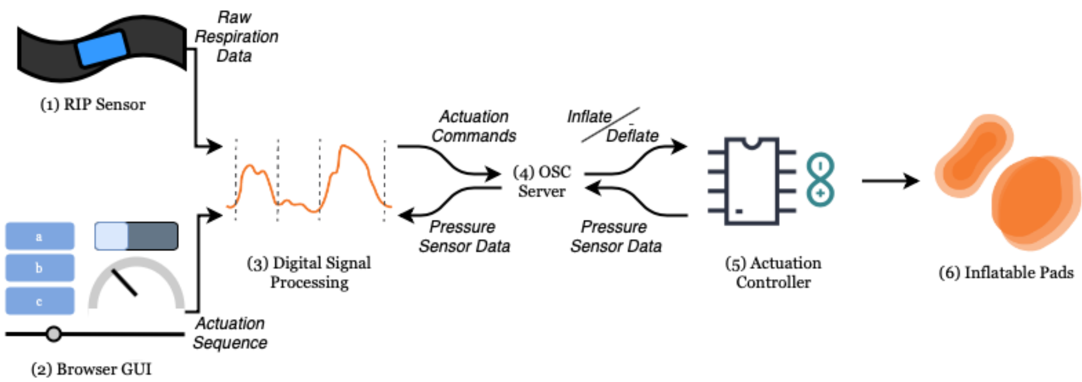

Figure 7.2: Modular framework for sensing and actuation control.

and body positions influence the experience. The explorations followed the soma design method of making strange [282], deconstructing habitual movements to draw attention towards subtle sensations and create a richer understanding of the experience.

In addition to taking notes, pictures and videos during the workshop, the participants used soma body sheets to document and visualise their subjective bodily experiences [280], the drawings were used to aid discussion into the felt bodily sensations that occurred throughout the session. These sheets depict an empty outline of a human body onto which one can draw and write how they are experiencing different parts of their body, as shown in Figure 7.3. These sessions enabled the authors to narrow down the physical schematics that would facilitate meaningful interactions. They included a set of suitable pad shapes/sizes and bodily placements that could be embedded into a wearable interactive system.

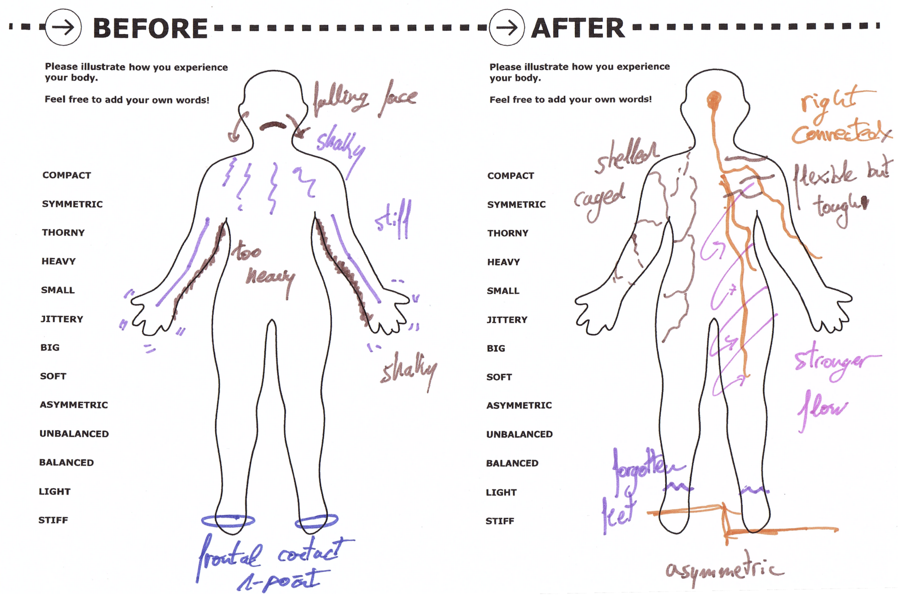

Figure 7.3: Example of a body sheet used to document the somatic experience during the design process.

Figure 7.4: The garment, worn with a breathing sensor and one pad in each inner pocket.

Autobiographical Design: First-Person Engagement with Shape-Changing Materials and Breathing

Based on the insights obtained during the soma design workshops, Annkatrin created a restrictive garment which contains the shape-changing pads, pressing against both the upper and lower back. It was inspired by the design of similar compression garments [154, 452], but not intended to represent a final design outcome nor a prototype for deep touch pressure therapy. Instead, the garment acted as an experiential artifact [433], an intermediate tool in the design process to present new and interesting experiences and discover their affordances through embodied interaction with breathing-based deep pressure.

Figure 7.4 shows the breathing garment being worn. A respiration sensor is strapped around the torso underneath the garment. On the inside, two pockets are attached on the upper and lower back. Each pocket holds one inflatable pillow to apply deep pressure on different areas of the back. When closed, the garment fits tightly and can transfer the deep pressure applied by the pads. The outer material can be closed in the front with a loop-and-hook fastener which allows for a tight fit in the torso area, making the actuation clearly noticeable. The pads can be placed in two pockets on the inside of the garment, one on the lower and one on the upper back. We would like to note that the garment needs to be closed to apply deep pressure and is left open in Figure 7.4 to show the placement of the respiration sensor.

The sessions incorporated different breathing techniques as well as different contexts and positions, including lying on the back, sitting on a chair or doing other tasks such as reading or writing while wearing the garment. These positions and breathing patterns were informed by a two-months systematic exploration of deep pressure guiding different kinds of breath regulation, such as controlling the duration of inhalations and exhalations or alternating between diaphragmatic and thoracic breathing, done by Annkatrin in between the soma design workshops and the construction of the garment.

In total, four different breathing techniques were used:

1. 5.5 pattern: Providing a constant rate of 5.5 inflate-deflate cycles, i.e. breaths, per minute, which has been associated with increased heart rate variability and relaxation [279].
2. Three-part breath pattern: This was inspired by the three-part breathing technique from yoga [402] which combines diaphragmatic and thoracic breathing. One pad is placed on the lower and one on the upper back. The one on the lower back is inflated first followed by the one on the upper back, guiding the user to first fill the stomach with air and then let it expand into the rib cage and chest. Then, the pad on the upper back is deflated again followed by the one on the lower back, guiding the user to release the breath first from the chest and then the stomach. Each inflation and deflation interval has a duration of 2 seconds, with a 1 second pause in between breaths.
3. Standardised feedback based on breathing sensor data with a 2 second pause in between breaths: It mirrors the user's breathing intervals, multiplied by 1.7 to gradually increase the duration of one breath without making the difference between two successive intervals too large.
4. Adaptive feedback with an actuation change triggered by rapid breathing: At baseline, the inflation speed is set to 50% of the maximum, which makes the pads less noticeable. If the calculated inhale or exhale duration is shorter than 2 seconds, the inflation speed is increased to 100% until the breath becomes longer again.

At the beginning of each session, Annkatrin conducted a short body scan to take note of her present bodily sensations and breathing. Then, Annkatrin explored each combination of actuation pattern and position or context for at least 20 minutes before moving on to the next to experience more long-term effects of each condition. A single session was focused on a maximum of two different actuation patterns or two different body positions.

The exploration was documented in the form of an online diary as an intermediate step in the process of articulating the experiences. Initial impressions of the effects of the breathing exercises and the pressure feedback on the breathing and bodily experience as well as notable changes in the inductive respiration sensor data were noted down quickly and informally. As it was often difficult to articulate the primarily bodily explorations while still immersed in the process, it was necessary to take a short break afterwards before reflecting more deeply on the experiences based on the initial notes.

7.4 Experiential Aesthetic Qualities

In the following, we present the four experiential aesthetic qualities that grew out of our design explorations. Such qualities bring out the aesthetic potential of interactions and how they are experienced in use [286], serving as an abstraction tool to articulate the insights which emerged over a series of explorations [425]. These qualities coincide with general aesthetic criteria that has been established in Section 2.6, characterised as spatial or temporal sensations that can be applied universally across all sorts of mediums.

Each quality is introduced with a body of examples that highlight how the quality manifested in different first-person interactions. In reflection of these accounts and the data collected in the design explorations, we then outline the aesthetic potential of shape-changing deep pressure feedback and the overall influence this had on different breathing techniques. We discuss how pressure-based feedback can be used to cultivate breathing awareness, appreciation, controllability and deconstruction. The different experimental configurations allowed us to document a range of experiences relating to our breathing patterns, some yielding a greater awareness by reinforcing our habitual behaviour, and others disrupting the familiar movements.

Placements on the Torso – Symmetric versus Asymmetric

Insights of the importance of symmetrical as well as asymmetrical feedback arose from how the inflatable pads could be moved around to different locations on the torso. This made it possible to put deep pressure on, for example, the back right shoulder at the same time as another inflatable put pressure on the lower left-side of the belly. By symmetrical feedback, we are referring to pressure applied equally on the left and right sides of the torso, i.e. symmetrical on the lateral plane with the same actuation pattern. Asymmetrical feedback refers to one-sided pressure or pressure on both sides of the body, but a) on different body parts or b) with different actuation patterns.

Experiencing symmetric and asymmetric feedback

The team's explorations naturally began with symmetrical placements, leading to a whole range of interesting experiences. For example, when Annkatrin was experimenting with placing the inflatable pillows symmetrically on both shoulders, as shown in Figure 7.5, position (1), she experienced massage-like qualities or *"someone putting a comforting hand on your shoulder"*. When placing the pads near the lower back or waist area when sitting or lying down, the pressure created a sense of support and stability. This was especially pronounced when placing the pads on either side of the lower back in a lying position, forming *"a small indent in the floor to enclose my body, causing a comfortable and safe feeling"*. Annkatrin reported feeling unsteady and in lack of 'support' when the pillows were taken out or deflated, as if she would *"roll to the left or right side at any moment"*. The symmetrical placement of the pads under the body was often helping Annkatrin to *"feel more connected to the floor, more grounded in my body and my environment"*. Generally, interactions with symmetrical placements and patterns invoked calm and relaxed feelings: *"I was left feeling much more in touch with my body, more calm and centred in myself. I felt loose, relaxed and a bit sleepy, similar to how I feel after a yoga practice or a good workout"*.

Inspired by Feldenkrais exercises, Annkatrin, William and Miquel went on to experiment with asymmetrical actuation during the design workshops. Many Feldenkrais lessons aim to deconstruct the habitual coordination of movements. It is done in order to draw attention to their finer details or offer novel ways in which movement can be created, ultimately leading to alternative habitual movement patterns. Based on those Feldenkrais lessons, Annkatrin, William and Miquel tried to re-create a similar feeling of imbalance or deconstruction by placing the pillows on only one side of the body or putting two pillows simultaneously on different body parts. This created two different effects: while applying the actuation to two different body parts made it *"hard for us to decide where to direct our attention which created an ill-fitting, incongruous experience"*, concentrating on only one side of the body *"allowed us to become more aware of how we experienced that specific body part"*.

Later, Annkatrin continued to experiment with asymmetric actuation using two pads with conflicting or complementing rhythmic patterns at the same time. As opposed to random or conflicting feedback, we define *complementing asymmetric feedback* as requiring a regularity of sorts: the actuation intervals of one pad can be a multiple of the second pad, or one pad inflates while the other deflates. A *conflicting pattern*, on the other hand, has incoherent phases, switching from inflation to deflation at different times. These explorations revealed that *"the placement of the pads had to be matched carefully to the actuation"* to avoid interfering with each other or with the user's breathing. In particular, conflicting asymmetric actuation was perceived as distracting and uncomfortable, not leading to any deeper engagements. For example, placing the inflatables on the back of the thighs or using two very distinct actuation sequences *"failed to evoke any strong effect"*. In some cases such placements could even lead to strong negative experiences, preventing learning. Placing the pads asymmetrically close to the neck, as shown in Figure 7.5, position (2), made Annkatrin feel *"like I was not able to breathe properly"*, evoking associations with *"having a snake wrapped around my throat"*. On the other hand, when the position and patterns were complementing – for example, when Annkatrin tried putting two pillows with one inflating twice as fast as the other on the lower back

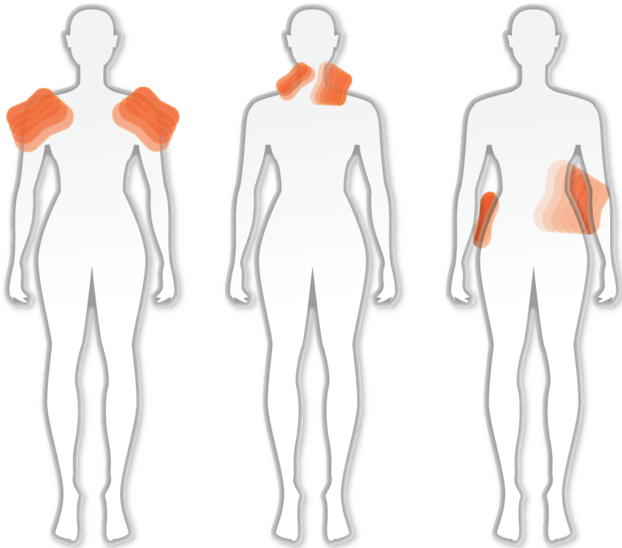

Figure 7.5: Applying symmetric and asymmetric deep pressure to the shoulders (1), neck (2) and lower back (3).

(Figure 7.5, position (3)) – they *"created a very unusual twisting sensation in the torso"*. This in turn lead to insights on how locally applied effects can spread across the entire body, and helped Annkatrin to experience how different parts of the body are connected into a whole.

Reflecting on symmetric and asymmetric feedback

Symmetry is represented in many different forms in the HCI projects focused on breathing. In projects with visual feedback, symmetry has been expressed as: visualization of two living lungs [4]; symmetrical geometrical figures [352, 377] or living virtual structures [339] located in the centre of the screen or virtual environment; or as abstract symmetrical visualizations taking the whole computer screen [321]. In the projects using vibration as output medium, symmetry is found in the relative position of the vibrating artefacts on the body, such as: centre of the belly [70]; centre of the upper chest [163]; or in the blanket that has the same vibro-tactile sensation on both sides of the body [115]. In projects using shape-changing actuation as a medium to display breathing, symmetry is found in: the equable expansion and contraction of a living wall [416]; in dynamic building structures [320, 396], as well as in the whole shape of a particular probe [20, 249]; or sometimes experienced by the whole body symmetrically [431].

Asymmetry as a design quality of breathing feedback has not been explored as much. There have only been a few asymmetrical representations, such as a visualization of tides in the virtual garden [375], and a few examples of providing direct feedback onto only one side of the body, such as the guiding shape-changing pillow under the right palm of the hand in the works by Yu and colleagues [478].

The focus on symmetrical representations in design work may be rooted in the notion that symmetry is commonly associated with perceived beauty and satisfying aesthetic experience [38, 310]. Well-balanced presentations of equal proportions are more compatible with classical mathematical structures, and the link between symmetry and beauty even has explicit associations with our biological presence [80]. However, absolute symmetry is not something we normally experience in the natural world, and leaves insufficient space for unpredictability and thereby discovery [310]. We also note that the idea that symmetry is aesthetically pleasing is more prevalent in western culture [38, 481].

What then is the aesthetic potential of addressing these asymmetries in design? While symmetry and symmetrical feedback is a well-explored and articulated quality and approach, proven to be beneficial for creating feedback that is easy to grasp and follow, asymmetry has not been explored as much. What we found is also how asymmetrical feedback can be quite unpleasant and distracting. But when designed carefully, it can be very informative for the design process – as well as to users aiming to increase their breathing awareness. What is sometimes needed is a journey from asymmetry to putting those asymmetrical experiences back into a symmetric whole, as is often done in Feldenkrais practice [468]. This is achieved by directing attention to just one side of the body, one lung, particular limb or other body part. For example, we might want to address the diagonal connection from the left lung into moving the hip on the right side, and then the connection from right lung to left hip movements, but then we need to put both together in order to explore and feel how all these parts are interconnected. If we leave the user with only one half of this experience, for example the connection from left lung to right hip, they might leave the exercise with a feeling of being lopsided. While we might perceive a human body as symmetrical when we compare our left half to our right half, it is obviously not. All the projects mentioned above in some way or other represent the lungs as a system with the perfect bilateral system. However, in a healthy individual, the left lung is slightly smaller than the right one to make some space for the heart – as the heart is slightly shifted to the left. Our limbs are also asymmetric, often making one side of our body the more dominant one. Some of us are writing with our right hands, some with the left, and even ambidextrous people find it hard to use both hands for every habitual task. Our limbs are not perfectly equal – there is often a limb length discrepancy. We are asymmetrical by nature and through training and everyday habituation, we might become even more asymmetrical in ways that harm us.

Guiding Different Kinds of Breathing

There are many possible breathing patterns promoted by different physical disciplines and body practices. Some are specifically targeted at focusing the mind and increase bodily awareness [72, 257]. To further explore the different muscles and bone structures involved in breathing, we decided to more deliberately impose deep pressure on different locations of the breathing apparatus in a manner that mirrors and encourages these different breathing patterns.

Experiencing breathing in different body parts

Applying deep pressure to different locations on the body not only made it possible to explore symmetric vs asymmetric feedback, but also to feel the breathing in different body parts. The actuation was adapted to the user's breathing by inflating the pillows during inhalation and deflating the pillows during exhalation, including a slight delay as the user's breathing intervals are computed from sensor data. This interaction is from here on referred to as *following* the user's breathing.

The explorations started with taking conscious breaths through the chest while placing the inflatable pillows on and under different body parts which revealed their potential to physically move the body in certain directions. This led to a range of interesting experiences that were not necessarily related to breathing, such as placing them under the feet to cause a movement which Annkatrin related to *"walking on the spot"*.

However, Annkatrin experienced breathing-based actuation mirroring her breathing on the lower body as *"uncomfortable and unnatural since I could not relate those body parts to my breathing"*, which made her feel *"weird, like it's not supposed to be there"*. Instead, the pressure was more readily associated with breathing when it was applied close to the breathing apparatus, i.e. on the torso or upper body. Annkatrin associated forward and upward movements of the torso with an inhalation, *"the pads seemed to push me to inhale"*, while moving backwards and pressing down on the torso were perceived as an exhalation. Placing the pads underneath each armpit *"pushed my arms away from the body"*, creating a feeling of the chest expanding during an inhalation. In this way, the pressure was able to support certain ways of breathing by reinforcing the respective movements. Annkatrin found that when the pads were placed under the lower back, the pressure *"encouraged me to breathe more with my stomach"*, while placing the pads on the upper back *"made me breathe more with my chest"*. Guided by the pressure, Annkatrin was able to learn how to engage different muscles when inhaling and thus practice diaphragmatic or thoracic breathing.

To investigate these different breathing patterns further, Annkatrin, as well as Pavel and Kristina in their explorations, created an actuation pattern based on the three-part breath, a technique from yoga practice which combines diaphragmatic and thoracic breathing in each inhalation and exhalation. Since this exercise requires a certain amount of awareness and control over which muscles are engaged when breathing, Annkatrin had to *"focus a little more to direct my breath from my stomach to my chest and back"*. With one pad placed on the upper and another on the lower back however, she reported being able to follow the guidance of the deep pressure *"without having to think about how I was* *supposed to breathe"*.

Over time, the exercises created a lasting effect which carried over into Annkatrin's everyday life: *"I could feel the muscles in my torso more distinctively when walking around. I was experiencing my breathing more intensely throughout the day, leading me to take deeper breaths than before and use my stomach and chest more deliberately and distinctly while breathing"*. This suggests that by applying deep pressure on certain body parts, the pads may help improve someone's control of their breathing over time, stimulating engagement with certain muscles to assist different ways of breathing with regular practice. While three-part breathing is just one possible option, a plethora of techniques exist, such as letting the rib cage expand towards the arms, chest, back or shoulders when inhaling. Each of these directions engages different muscles around the rib cage, that, when trained, can open up a rich repertory of breathing techniques.

Reflecting on different kinds of breathing

While many different muscles and bone structures are involved in breathing and enable distinct breathing patterns, breathing-based designs have mainly focused on reducing users' breathing rate [354]. Whilst some of these studies account for lung capacity (e.g [4]), attention towards individual breathing muscles is normally ignored, neglecting the opportunity to practice alternative breathing patterns using these muscles.

Only a few breathing-based designs employ different types of breathing, for example encouraging deep diaphragmatic/abdominal breathing to alleviate stress [352] and anxiety conditions [377]. Others measure breathing on different body parts [353], taking into account diaphragm expansion [112] as well as the rising and falling extent of the abdomen [396].

Outside of HCI, a handful of studies validate the use of additional sensor placements in order to differentiate between thoracic and abdominal breathing, such as the work by Hamnvik and colleagues on Yolo4Apne [198] which uses two inductive respiration sensors and [131] that uses three resistive stretch sensors across the torso. This approach has shown to be effective in extending measurement potentials, but it does not address alternative representations or interactions to guide users to explore novel breathing patterns.

So far, the interactive systems for breathing guidance do not reflect the immense resources we have for breathing, not only in regards to muscle engagement but also inhalation and exhalation sequences. Instead, breathing is often reduced to a single dimension that only operates from one part of the body, without registering these anatomical intricacies. What then are the technological interventions that may facilitate a richer breathing experience?

Though not extensive, three generic descriptors (clavicular, thoracic, and diaphragmatic) provide a starting point to distinguish types of locational breathing [359]. These also provide the foundation for the three-part breath technique (also known as Dirga

Pranayama), which has been thoroughly studied in traditional yoga practice [402]. It demands specific attention to separate parts of the breathing apparatus, namely the abdomen (lower torso) and thorax (upper torso), and considers how these are used in conjunction to expand breathing capacity through *full* and *complete* breaths, compared to chest-based breathing.

However, there are many other breathing practices, such as those employed by professional singers or dancers, offering hitherto unexplored potential to provide engaging interactions. The way in which we breathe has a direct impact on the body's chemical makeup and behaviour of the autonomic nervous system [380]. Moreover, it is widely recognised that longer breaths incorporating the whole body can lead to improved overall well-being in the long term, particularly in regards to stress regulation [322]. Studies of alternative breathing patterns suggest that by engaging individual muscles and body structures, we can train ourselves to gradually gain greater awareness and control of our holistic body [451].

There exists a multitude of possibilities when it comes to engaging with breathing, and the same goes for halting the breathing. One can pull air into the lungs using the diaphragm or muscles in the neck, let the rib cage expand towards the back or the shoulders, and stop the breathing by pulling down the diaphragm, pushing the stomach out or tensing muscles around the rib cage. Many combinations of these techniques are possible, and can be further combined with other movements such as tensing or relaxing the pelvic floor. All add to the richness of the experience.

Thus, our explorations point towards a potential for interactions which incorporate a richer catalogue of breathing methods, creating the need to measure movements on different parts of the body to differentiate between small muscles involved in breathing. But the breathing rhythm does not consist of one-off breaths; instead, it is a pulsating, vibrant flow that engages a variety of muscles and body structures over time. This raises new questions as to how a system can turn a series of breaths into a malleable and adaptive rhythm, allowing the user to engage with their breathing pattern over an extended period of time.

Synchronous vs Asynchronous Feedback

By *synchronous* feedback we are referring to deep pressure that follows the user's breathing rhythm. *Asynchronous* feedback, on the other hand, provides a rhythm that is slightly or entirely out of phase with users' breathing, at times even pushing back right when the user inhales and expands their stomach or chest and vice-versa.

Experiencing synchronous and asynchronous feedback

At first, the explorations during the design workshops were focused on synchronous feedback, using actuation patterns which imitated the user's own breathing rhythm. These generally felt comfortable and supportive. The deep pressure drew attention to the breathing by making the breathing intervals more tangible and apparent, allowing Annkatrin to *"appreciate my body and its ability to breathe steadily"*. The synchronous feedback also created an interesting interplay when sitting on a chair, since leaning back on the pads made the changes in pressure and thus the chest movements more intense, letting the entire body sway back and forth in the breathing rhythm. As the pads were physically pushing the body forwards to support inhalation, Annkatrin reported feeling like *"they were in charge of my breathing and I could let myself surrender my control over my breathing to them"*, eliciting a sense of intimacy and safety.

Even when the actuation was not based on breathing sensor data but rather on pre-programmed sequences, Annkatrin, William and Miquel tried to match their breathing to the inflation and deflation of the pads. The pressure was not noticeable during the shift from deflation to inflation, which made Miquel feel *"lost till I realised I should have been inhaling already"*, whereas Annkatrin felt *"like I was not supposed or allowed to breathe"* and thus held her breath until the pads began to inflate. Not being able to follow the rhythm set by the pads, which occurred for example when the intervals were very long, evoked feelings of guilt and frustration.

Pavel and Kristina reported on similar experiences of frustration. Kristina in particular found that for certain breathing exercises, she felt pressured to perform and when she could not adhere to the requirement, she felt as if the system was trying to discipline her. For example, she tested "square breathing", a method where you are asked to breathe in while counting to five, hold your breath while counting to five, breathe out while counting to five and then hold your breath again, and then increase the counting, for example, up to 10. The method is quite demanding and it helps train stamina and breathing ability for professional singers. The experience of being 'controlled' by the system became too strong for her when she did square breathing with the system.

Annkatrin, William and Miquel purposefully experimented with asynchronous patterns by using two inflatable pillows with conflicting patterns at the same time, inflating and deflating them in opposite or completely unrelated rhythms. Similarly to asymmetric actuation, these patterns had to be crafted carefully to make sure that actuation sequences which were used simultaneously did not actively work against each other. Otherwise, they were dismissed as *"hindering and annoying"*, such as when one pad was supporting inhalation by inflating while the other was discouraging it by deflating. At times, the asynchronicity also created unpleasant experiences, like feeling *"dizzy or sea-sick"* when using an asynchronous pattern which inflated one pad while deflating the other and vice versa while lying on the back.

Annkatrin noted that when the pads were contradicting each other or the natural flow of breathing, following their guidance felt like working against the body instead of engaging with the body. Switching the two pads during the three-part breath pattern, were guiding Annkatrin to first breathe in with the chest and then with the stomach. *"This way of breathing made me feel like I was not getting enough air, thus appearing forced* *and unnatural"*. Annkatrin also reported finding it difficult and uncomfortable to breathe in an asynchronous rhythm, for example by holding her breath or taking intentionally short breaths. *"Not following the pads seemed wrong since I was not engaging with my body but closing myself off to my body"*.

However, when all aspects complemented each other, the asynchronicity of the feedback was able to provoke interesting and unexpected experiences. The pads were generally seen as a *"small extra pair of lungs"*, connecting inhalation to inflation and exhalation to deflation. To reverse this more familiar way of breathing, Annkatrin tried placing the pads on the stomach. This forced her to breathe in the opposite way, taking the pressure caused by the inflation as a cue to exhale and letting deflation make room for the stomach and chest to expand during inhalation. While such a breathing pattern accommodated the pressure on the stomach in a way that allowed Annkatrin to take deep breaths, it *"required much more concentration because it was different from every other pattern I had tried so far"*. She had to figure out how to adapt to the pressure to be able to accommodate the pads and breathe comfortably, which made the pads seem like they were *"restricting and controlling my breathing"*. Thus, the pressure forced Annkatrin to breathe very deliberately and thoughtfully, *"drawing my attention to the mechanics of breathing and re-evaluating the pads' connection to my breathing"*. When used in this way, the asynchronous actuation was able to deconstruct breathing, creating the challenge to become comfortable with being thrown out of rhythm.

Reflecting on synchronous and asynchronous feedback

Synchrony is a quality that takes different forms in breathing-based design projects. The most straightforward is a direct mapping of a user's breathing pattern to certain feedback from the system. This is mostly done in phase, mapping expansion to inhalation and contraction to exhalation, with the exception of a photo frame that inflates when a remote person exhales and vice versa [249]. The inhalation has been mapped to many different output modalities, including the expansion of a visualised geometrical shape [352, 377, 467] or pair of lungs [4], tides in a virtual environment [375], an increase in light intensity [115, 426], as well as the expansion of a physical artefact [20, 249, 320, 416, 431]. Breathing phases can also be tied to the directions of movement of the protagonist in a video game [421] or of the user in a virtual environment [106, 352, 377].

Synchrony may also involve more elaborate forms of feedback. When the user has fallen out of sync with the system, for example by breathing faster, the system can provide a guiding rhythm in the form of vertically moving on-screen elements [322] or pulsating video and audio signals [174]. In multi-user systems, synchronous breathing of several users can make a sponge grow in a virtual environment [112] or trigger light effects on a garment worn by one of the users [392].

Asynchronous feedback can take form of shaping a soundscape based on different attributes of participants' breathing [453], as well as receiving instructions from a virtual breathing coach to modify the breathing rate without specifically addressing the user's actual breathing cycles ("continue breathing at a slower pace") [404] or showing the current breathing rate as a percentage of the individual resting breathing rate [321]. Asynchrony is also used in various negative feedback loops, in which a fast breathing rate increases the difficulty of a video game [338] or amusement ride [300], or lowers the quality of a song played in the background [200].

However, the majority of breathing-based systems reported in the literature encourages synchronous breathing patterns, aiming for synchronous feedback in harmony with the user's breathing rhythm. This is not surprising, as similar to symmetry, synchrony is an integral construct in technology, finance, molecular biology, physics, music and psychology which indicates coordination patterns among processes as well as precise coincidence of events in time [362]. Rhythm is one of the most important pillars of contemporary music, enabling the singers and musicians to not lose themselves in the music and stay in sync: one may miss a tone, but missing the rhythm can deteriorate the perception of the entire piece [274, 364]. Nevertheless, a well-executed asynchronous element – syncopation, which is a deviation from an expected rhythmical pattern – enriches the piece and may bring listeners enjoyment and a desire to move [414]. Moving away from music, where tones are coherent and concurrently executed, language is also performed in antiphony as individuals take turns in conversations [362]. If we regard breathing as a dialogue between the system and the user, asynchronous forms of feedback can open up a new design space for deeper and more elaborate forms of interaction. Similar to asymmetry, careful and deft application of asynchronous elements in breathing feedback may break the patterns of habitual perception of breathing and make us more self-aware. We recognise that it sometimes takes time and effort to learn a difficult breathing practice, but still, it is important that the user does not lose faith in their ability along the way. There needs to be a path towards overcoming the uncomfortable experiences through practice, step by step learning more and more, but not demanding too much too soon.

Breathing Correspondence: Finding a Balance between Leading and Following

The findings made us think that a really interesting dialogue between the system and the user could be achieved, a dialogue that would rely on both letting users express their breathing, but at the same time being influenced, through feedback, encouragement or even strong pressure. We therefore continued to explore exactly how to find a balance point right between *leading* and *following* breathing patterns by first applying deep pressure – almost to the point of being unpleasant – and then releasing in rhythmic flow. We will refer to this experience as a *breathing correspondence*.

Experiencing different roles in the interaction

The explorations of different actuation patterns revealed how the inflatable pads could take on different roles in the interaction. If the actuation was following a predefined rhythm independent of the breathing sensor data, it was more likely to be perceived as not engaging in dialogue or adapting to the user, but instead leading the interaction and providing breathing instructions. They seemed to be *"guiding or even steering the breath"*, reinforced by the pressure physically pushing the body forward.

When the actuation was based on the breathing sensor data, the pads assumed a more passive role in the interaction by following the user's breathing. In turn, this gave the user a more active role, allowing them to deliberately breathe in a different rhythm in an attempt to control or influence the pads. For example, during the design workshops Annkatrin, William and Miquel experimented with holding their breath and manipulating the length and depth of their inhalations and exhalations. Annkatrin reported having *"the impression that the pads were listening to me which created a sense of intimacy and safety, like the pads were taking care of me"*. Such semi-autonomous interactions created an interesting contrast between breathing "with" the pads when following along to the actuation pattern and breathing "against" the pads when trying to change the pattern. However, it was not always clear whether the pad was adapting to breathing or vice versa, which introduced a sense of ambiguity in the interaction.

This potential for ambiguity motivated further attempts to combine both a leading and a following role in a single actuation pattern by extending the breathing feedback by different factors. We made it possible to influence the actuation by manipulating the breathing while the pressure was at the same time influencing the user to gradually take longer breaths. A dialogue between the system and the user emerged, using the pads as a communication channel: *"As the pads were mirroring my breathing intervals while pushing me to gradually extend my breath, I was trying to match my breathing to the actuation, feeling the changes reflected by the pads"*.

The deep pressure becomes stronger with each interval almost to the point of being unpleasant, pushing Annkatrin to *"take an excessively deep breath completely filling my lungs with air to the point of discomfort"*. Right before the pressure starts to become painful, it is released in a rhythmic flow, prompting the exhalation as a *"sigh of relief"*. As the pressure intensifies and fades away gradually while providing a constant presence, it serves as a constant reminder to attend to the breath. The breathing feedback allowed Annkatrin to *"become more aware of unintentional changes and try to make sense of them. For example, struggling to extend my breathing intervals made me wonder whether I was stressed or worried about something and therefore unable to take deep breaths"*. The pads were perceived as an extension of the physical self rather than an external influence, allowing Annkatrin to *"engage in a dialogue with my body, not just the system itself"*.

However, when this balance between leading and following was disrupted, the pads began to dominate the interaction. After Annkatrin incorporated a threshold which increased the actuation speed and thus the pressure when the breathing intervals fell below two seconds, the experience changed significantly: *"I was constantly aware of the pads and the pressure, trying to identify the current actuation speed and keep my breathing intervals above the threshold"*. Feeling the intervals become longer evoked a sense of accomplishment, while feeling them become shorter caused guilt and frustration which put Annkatrin under stress to extend her breathing. *"It was a relief to take off the garment because I no longer felt pressured to actively control my breathing"*. Such exploration of the tipping point between leading and following can provide insights on how gradual pressure changes help to achieve a harmonic interaction, while strong or sudden changes are perceived like a firm command, taking over the control of the interaction.

Further explorations showed that just sitting with the pressure and breathing in one's own rhythm, neither trying to follow nor influence the actuation, could also create interesting experiences. In such interactions, the pads assumed the role of a companion which provided a *"soothing sense of presence, like there was another person sitting next to me and sharing their breath with me"*. The pressure was not distracting, but rather seemed to complement one's individual breathing rhythm. Annkatrin reported that experiencing the pressure in the background while working led her to *"take deeper breaths subconsciously without making an effort to do so"*.

Kristina reported similar experiences – feeling that she could accept the system more willingly if she just let it act in the background while she was working away on her computer. Whether she was in fact following the feedback from the system or not became unimportant and she could relax into the experience.

Reflecting on establishing a breathing correspondence

According to their role in the interaction, breathing-based designs can be split into two distinct strands: in the Self - System - Self modality [354], the system is following the user's breathing pattern [4, 20, 41, 320, 346, 352, 375, 405, 416, 421], whereas in the System - Self - System modality [354], the user is following the pattern provided by the system [115, 423, 467, 478]. Looking at the prevalence of the two strands among HCI projects, the majority of breathing-based systems belong to the first group, providing a mere representation of the user's breathing pattern of the user and in the process taking the role of a passive follower. Only a few systems take a leading role in the whole dialogue [423, 467, 478] or one of the interaction modalities [70, 339], providing users with a signal to follow. Despite the simplicity of the latter, it has proven to be a powerful interaction modality. Regardless of whether the user follows the interaction precisely or just leaves it as a peripheral stimulus, the interaction can provoke a relaxing and calming sensation when experienced for a prolonged period of time. This is also supported by the studies of Moraveji et al. [321, 322] showing the effectiveness of peripheral respiratory feedback on inducing a slower breathing rate without explicitly promoting focus on breath pacing or distracting users. Some breathing-based systems make the distinction between leading and following more ambiguous by taking users' natural rhythm as a baseline, then feeding it back to them at a slightly slower pace to guide them to gradually extend their breathing [174, 322].

The concept of correspondence proposed by Ingold [224] and further adapted and reworked into *intimate correspondence* by Höök et al. [213] calls for designing an interaction wherein the roles of leader and follower are unclear, the boundaries between user and system become dissolved and they start acting together as 'one'. This creates a more evocative communication to take form implicitly as there is no need to actively reply to the system's query – a correspondence relationship where users' breathing is simultaneously influencing and being influenced by the system.

7.5 Summary

Through a first-person felt engagement over a longer time period, we uncovered several, previously unexplored breathing experiences spurred by different pressure patterns on the torso such as:

1. Imposing symmetrical and asymmetrical pressure as a path to draw attention towards different parts of the breathing apparatus, as well as spurring novel sensations by deconstructing habitual coordination of movements
2. The sequencing of inflation/deflation in accordance with the user's engagement with different muscles when breathing, leading up to more intricate breathing practices
3. Providing synchronous or asynchronous feedback via rhythmic pressure that is in sync, slightly or entirely out of sync with users' breathing rhythm as a step towards deepening aesthetic appreciation and increasing awareness of possible breathing rhythms
4. Exploring the balance point between influencing and simply following the rhythm of the user's breathing – constituting a breathing correspondence experience where it is unclear whether the system or the user is driving the breathing rhythm

We want to emphasise that while our explorations were inspired by deep pressure therapy, the design space we opened also points to other experiences and needs beyond delivering calming and relaxing effects. Deepening users' appreciation of their own breathing can be an aesthetically interesting experience in itself. Breathing provides a rich inner universe where different body parts such as the lungs, rib cage, posture, bone structures and fascia are intricately connected in ways that can be more or less 'known' to us depending on how bodily aware we are. The physiological processes, engaging in habitual as well as non-habitual ways of breathing, can relate to or even spur emotional experiences in the short-term. Apart from the experience in the moment, the lingering effects after a session, feeling like you have had an 'inner' massage, as well as potential long-term lasting transfer effects into everyday life situations are particularly intriguing to explore further.

Apart from breathing guidance, pressure-based feedback may also be used on other parts of the body. By exploring experiences that breach into the domain of discomfort, we can begin to determine an appropriate equilibrium that lies between between gentle/subtle and uncomfortable/unpleasant [32]. We show how discomfort can be imposed by increased intensity of actuation, irregular and asymmetrical positioning of the pads, along with asynchronous inflation patterns that go against users' natural, unreflected breathing. When the interaction is engaging with the non-habitual, the system may elicit conscious physiological reactions, requiring users to be very much present with their breathing. However, if this intensity goes beyond a certain threshold, we lose this relationship and the experience becomes meaningless or even unsafe.

Finally, we would like to point to how our first-person engagement turned out to be highly generative in terms of bringing out many design ideas for shape-changing materials applied on the torso. While more studies are needed to shift our subjective, personal understanding into reliable breathing engagements for larger user groups, our results show that first-person engagements will be one path to designing aesthetically rich, haptic engagements with shape-changing materials. This said, we are fully aware of the potential pitfalls of autobiographical design: the risk of designing only for the few people involved in the design process, ending up with designs that are irrelevant or even harmful to the targeted end-user group, for which we need to call for a larger scale study to overcome. The work we did here must be complemented with further design explorations, specifically aiming at different user groups, involving them in the design process. But as pointed out by Höök and colleagues [214] "*this felt dimension, despite its subjective nature, is what provides rigour and structure to our design research*". That is, the authenticity of the experiences we report on above relies on the long-term, deep, felt engagement of the designers – a rigour of a different ilk.

In summary, taken together, these first-person material explorations engaging with deep pressure feedback using shape-changing actuation managed to open a rich, somaesthetically evocative design space. We uncovered new paths of utilizing pressure-based feedback to cultivate appreciation, awareness, controllability and deconstruction of breathing, ultimately converging to an intimate relationship between system and user – a *breathing correspondence*.

8

Case Study II: Latent Steps

This case study will be given attention over two segments, a technical primer followed by a user study. The first describes the development process and technical composition of a real-time visualisation system, providing details for the generative models used, alongside the interaction process. The next compares this system side-by-side with an alternative approach for visualisation to validate perspectives from the user's standpoint. The preliminary results from the work documented in Sections 8.1 to 8.8, were presented as a conference poster:

William Primet. 2022. Latent Steps: Generative Bodily Animations from a Collection of Human Drawings and Physiological Data Interaction. International Conference on Dance Data, Cognition and Multimodal Communication (DDCMC'19), September 2019. `http://ddcmc19.blackbox.fcsh.unl.pt/programme/`

8.1 Latent Steps in Development: Generative Bodily Animations from a Collection of Human Drawings and Physiological Data Interaction

Latent Steps is an interactive system for dance performance which merges two machine learning models to generate animations using a pre-existing image corpus and physiological data input. The intention is to expose the physical sensations of the user as they revisit a sequence of movements. The image generation model is trained on a collection of 100 bodily map illustrations provided by 10 dancers, who were asked to colour areas of muscular activation and balance during movement. Each drawing correlates to a physical gesture assigned to one of the following semantic descriptors: *Comfortable*, *Difficult*, *Undefinable*, *Aesthetic Form*; and *Open*. When trained, it's possible to generate new animations from two or more drawings by predicting the interpolated frames in latent space.

The input model, responsible for monitoring the user's physical activity feeds two control parameters to the Autoencoder model to complete the interaction loop. When a sequence is re-performed, the system will attempt to recognise what pre-defined gesture is being displayed whilst reporting the relative speed of the movement. The result enables users to determine the style of images being generated whilst influencing the time-dynamics of the animation.

8.2 Background

Soma Design Theory

The study of the soma considers how the body is perceived from one's proprioceptive senses, emphasising importance on the first-person perspective (see Section 2.5). Somatic practices, such as dance movement therapy can improve the participants sense of self, which can link to improvements in one's overall well-being, while granting better resources for non-verbal expression, supporting the use of movements and postures to convey emotion [381]. There are a number of methods available to document the bodily sensations manifested as a result of a somatic activity, including the use of biomedical data [215] as well as visual in the form of bodily map drawings [465]. Several HCI researchers have been exploring the potential of engaging in somatic theories and practices for designing technologies [213]. This turn to the body, or the *soma*, as a holistic approach to movements, body, emotions and feelings, is often referred to as a *somatic turn* in HCI [283]. It is characterised by a shift to methods of thinking through doing and moving, privileging experiential first person methods [214] along with empirical observation and evaluation of users and user experiences. Where somaesthetic theory has been incorporated into design strategies which aim to orchestrate embodied experiences with sociological materials [447], we consider the bodily maps as an aesthetic medium to convey internal sensations. Rather than trying to mapping kinematic data directly to a linguistic model for emotion (see references in Section 3.4), we develop an interactive visualisation framework linked to the user's first-person perception of their actions.

Body Maps as Somatic Representation

Our literature review (Chapter 3, Section 3.5) outlines the relevance of body maps for emotional self-reporting. Comparably, in soma design methods, it is common to document one's individual experience using a body map before and after doing a session of a somatic practice (e.g. Feldenkrais) or a bodily exercise [465]. This process was carried out in our first case study, detailed in Section 7. In such a body map one can draw and annotate the physical sensations they felt in particular areas of the body, reflecting on one's physiology and bodily experience before and after the session. This can enable one to turn inwards and pay attention to bodily sensations often neglected, including for example pain, discomfort or pleasant sensations. Whilst these drawings are used to aid the participants' verbal description, by themselves, they offer an effective method for documenting an experience in a visual way that moves beyond linguistic and verbal descriptions.

For example, using a colourful pen to draw an experience of pain or a pleasant sensation can be more evocative than describing it with words. Additionally, one can compare their documented felt experiences before and after an exercise, and thus possibly become more aware of how the exercise affected their soma. The body map documentations are also used for sharing and discussing individual experiences in a group of researchers and identify experiential qualities that could drive forward the design work in the group [440]. Finally, looking at a body map drawing much later, can remind one of bodily experiences evoked during a particular session of somatic practice done in the past, which could potentially inspire the design of an interactive system that would evoke a similar somatic experience in interaction.

8.3 Motivation

Limitations of Body Maps

Our adoption of body maps builds on our long-term engagement with soma design methods and using body maps extensively in our design processes (as reported in Sections 6 and 7), based on our collaborations with researchers from the KTH Interaction Design group, including those who are teaching soma design [447]. From these experiences, we started identifying a number of limitations of the body maps as a method for facilitating self-reflection and sharing experiences in a group. This work is an attempt to respond to some of the limitations identified, and shows a path towards taking the body maps one step further. Our attempt with the development of the Latent Steps prototype is to suggest a path towards developing tools and mediums that, similar to the body maps, can offer new possibilities for reflecting on one's soma and for documenting such reflections. While, at the same time, keeping the main qualities and properties of the body maps as a useful tool for design processes in HCI, in which somatic practices are core.

The first limitation of the body maps that we identified is that they can only capture an instance, or a static image of a bodily experience. This is due to the existing materiality and actual medium of the maps (a sheet of paper that one can draw on), that enable only a two-dimensional representation of the body. And which also poses constraints when one wants to capture a dynamic experience or sensation felt, such as tension that starts on the neck and moves down along the spine. Moreover, this static representation of the body poses limitations when one wants to represent a movement performed and its impact on the body. Especially since the body is fleshy, alive and active, and the body maps are 2D and static, as mentioned earlier. A third limitation identified has to do with the degree to which they enable and facilitate remembering, or better "re-feeling" a documented experience, when returning to a body maps later in time (e.g. after a few weeks). Through our experience with using the body maps we noted that even though they provide a means of documentation that can be kept, stored, and retrieved later, it is often challenging to remember the exact experience, sensation or impact that an exercise has left on the body.

So we begin questing: How can we expand the possibilities of the existing body maps and create a more “alive” type of body map, in line with the aliveness of our moving and fleshy somas? At the same time we were interested in exploring possibilities of allowing a person to make their own data set of articulated bodily experiences over time, which could probably provide an added value to the existing use of the body maps: To enable reflections on the living and changing body over time, including movements and micro movements performed.

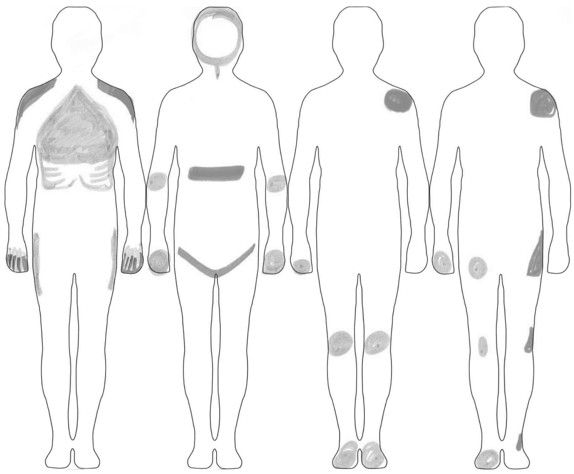

Figure 8.1: Four Examples of Body Sheets used in Latent Steps.

Interactional Approaches to Designing with Bodily Data

In Chapter 3, Section 3.4, we compare a representational approach for emotional modelling, that describes certain aspects of emotions in numerical terms, derived from measurements in the body, with interactional systems, that rather depend on the users engaging with them and interpreting them, and do not attempt to be true and objective. Latent Steps, presented in this section, is more on the interactional side. It creates representations of bodily states and postures but relies on end-user training and configuration of the system and ultimately on end-user personal interpretation. Its aim is not to classify and predict objectively a human posture (we can find in literature many other systems that attempt to predict if the user is sitting or standing or going on a bike based on wearable acceleromters [417]), but rather to provide cues and tips for personal reflection to emerge, interactively with the system.

Interactional Approaches to Machine Learning

The same distinction between representational and interactional can be made for machine learning applications, as it is explained by Gillies [176, 177]. We aim to apply user-centered, interactive machine learning to body maps, which accepts users are the domain experts in their own bodies. They can create a particular language of interaction, adapting a given model, providing training data themselves. In soma design theory, first-person interpretation of bodily data is crucial here. Rather than relying on a population of users and attempting at classifying user data into fixed categories (a representational system), the goal is to design a system that is intended for iterative interactions that end up in the users gaining knowledge about themselves.

Image Generation with Convolutional Autoencoders

Convolutional Autoencoders (CAEs) have been used to reduce the dimensionality of images, such as those in the MNIST dataset [460]. Between the decoder and encoder functions of the trained machine learning model is the bottleneck layer, composed of compressed representations of the input data [482]. In the case that the model has been trained on a corpus of images, we are able to reconstruct the visual data from the compressed vector. From this stage, we are also able to use vector arithmetic to generate new variations of the images that are not contained in the original dataset.

Given that the bottlneck layer requires lower dimentionality data to generate a full scale output, it's more feasible to construct interactive mappings with low dimensional inputs. In our system, we interface physiological sensor data with a Convolutional Autoencoder (CAE) for image generation.

8.4 Data Collection

Visual Data

The image generation model is trained on a collection of 100 bodily map illustrations provided by 10 dancers, who were asked to colour areas of muscular activation and balance during movement. This criteria was inspired by Sylvia Rijmer's *Prime Mover* principles, defined by her as a particular place (locus/loci) in the body from which movement initiates [239, 369]. These original drawings were produced during the first co-design workshop that was documented as Stage 1 in Chapter 6, for which the participants were required to develop and perform a five-part movement sequence and produce corresponding body maps for each. This approach of combining improvisation with different, discrete, sections around a theme is comparable to the procedure followed by McDonald to generate an ML dataset for a dance piece [308]. The workshop involved three activities (the first on day 1, the other two on day 2):

1. The dancers prepared a movement exercise, consisting of five thematic sections, agreed upon collectively between them: *Comfortable*, *Difficult*, *Undefinable*, *Aesthetic Form*; and *Open*. Each dancer then created their own interpretation of the movement exercise, based on improvisation.

2. Each dancer was asked to perform the movement exercise, which was documented. The documentation consisted of video recordings and collection of sensor data of each dancer (explained further in Sections 8.5 and 8.11). The data was labeled according to the dancer and to the section of movement exercise.
3. The dancers drew body maps based on the movement exercise and their somatic impressions of it. We asked performers to create two types of drawings for each section of the choreography: free-form body maps and outline-based body maps, the two types of body maps identified in Section 3.5.

The complete dataset of drawings is provided in the Appendix B, Workshop 1.

For the image generation model described from the the following Section 8.5, we would only train the outline-based body maps, for which the free-form drawings are reserved for an alternative approach, as explained in Section 8.8. To finalise our visual dataset, these drawings are digitised, organised by performer and sequence, then pre-processed before training. The digital images are proceduarally cropped around the body map silhouette, pen strokes are segmented according to colour (blue or red), then to minimise the size of the data, the images are downsampled to 224 x 224 pixels and converted to greyscale format. Although the coloured strokes could depict additional meaning to the body maps, the primary focus was on the locational qualities of sensation, hence opting for monotone representations.

8.5 Technical Composition

System Architecture

The aim of the system is to continuously generate bodily map images that correspond to postural data, which is determined by a set of embodied sensors. The frames are then saved as a means for recording the first-person experience. The frames are then concatenated to produce a video steam that can be used for self-reflection after the activity takes place. The system utilises two machine learning models across two processes. The training process takes data from a corpus of images and sensor values as input for each model respectively. The learnt model enables continuous mappings to be generated based on these inputs. The interaction process relies on the previously trained models and takes IMU data in real-time to generate reconstructed images. Our workflow is illustrated in Figure 8.2. The first model, which is trained in the image corpus is programmed using the TensorFlow library [1] in Python and the second model, responsible for processing sensor data is implemented in an OpenFrameworks[1] application using the RapidLib C++ library[2] for interactive machine learning.

We are placing five BITalino R-IoT devices (introduced Section 4.1) directly onto the body of the user (Figure 8.3), and measuring the relative orientation of the limbs using

[1]openFrameworks: https://openframeworks.cc/.
[2]ofxRapidLib: https://github.com/mzed/ofxRapidLib/

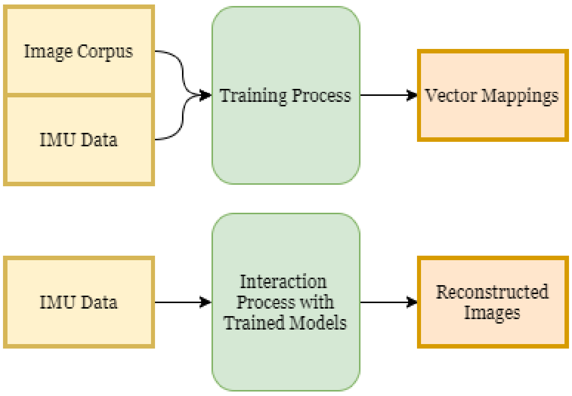

Figure 8.2: System Overview.

the IMU sensor data. We chose to place sensors in the following areas to represent the postural features of the user: upper left and right arm, abdomen, and the up left and right knee. We proposed this solution as a low-dimensional estimator of posture sufficient to differentiate and interpolate between a small set of postures.

Figure 8.3: Sensor device worn on the abdomen and right arm.

Training Process

Using the first model, we train a Convolutional Autoencoder (CAE) to interpret the visual features of the image dataset. The model used in our system encodes each image into 32 float vector representations. These vectors are then used as labels when training the regression model. This second model then takes the static postures recorded with IMU data as an input and produces vector mappings according to the labels (see Figure 8.4). The two models are described in further detail in the respective subsections below.

Convolutional Autoencoder Model

The Convolutional Autoencoder (CAE) is an unsupervised machine learning model, where by the training data is not labelled, independent from any categorical descriptor. The training process initialises with an encoder function that compresses the images into

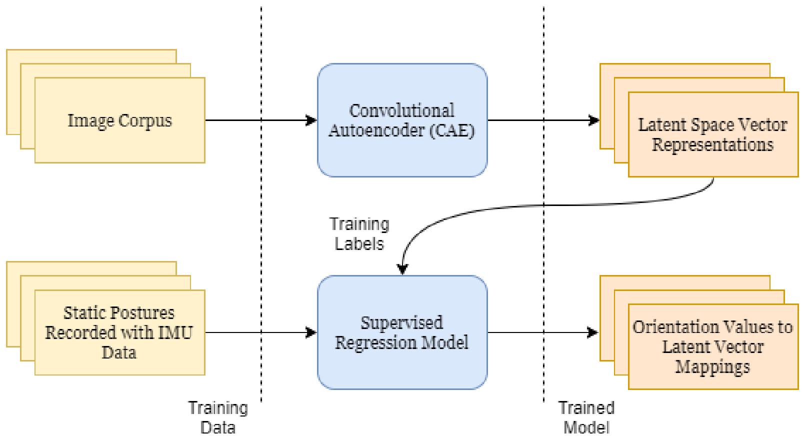

Figure 8.4: Training process for the Regression and Autoencoder model.

vector representations of 32 floats, corresponding to their relative position in the latent dimension. This compressed representation of the image is assigned according to the visual features interpreted by the model, commonly referred to as latent space. As a result, drawings that are more visually related can be described as closer together, where as dissimilar inputs are located further apart in the latent space. We use following formula where i is the complete 256 x 512 pixel representation of a given image with ID of n and v is the latent vector (32 float values) produced by the autoencoder:

$$f : i_n \rightarrow v^n = \{V_0, V_1, ..., V_{32}\}$$

The decoder function takes the latent vector as an input and reconstructs a new image, incorporating visual features from the training dataset. The decoder can produce the close-to-identical image to that of the original dataset, by feeding the same vector calculated by the encoder. In addition to this, we can also generate continuous interpolations between the drawings when applying vector arithmetic, resulting in a new image that the model has not been explicitly trained with.

Supervised Regression Model and Sensor Input

From each IMU, we calculate 4 Quaternion angles to depict the absolute orientation in 3-dimensional space. Our main motivation for using Quaternions is that the output operate on sine and cosine functions, meaning the values do not skip from minimum to maximum (or visa versa) when reaching the angular thresholds of similarly perceived trajectories, making this encoding more suitable when interpolating between gestures by avoiding undesired numerical leaps.

For every generated image that we want to associate with a particular posture, we store the associated latent vector, used as a continuous numerical label when training the model. For each label, we record 5 seconds of the posture being executed, resulting in approximately 50 examples of each pose. In our experiment, each user would train

4 gestures, labelled with a latent vector. When the model is trained, the model will reproduce the latent vector as labelled when a pose is repeated, or if a new posture is provided, the regression function will interpolate between the 4 vectors accordingly to generate a new visual output.

Interaction Process

The interaction loop is completed when we feed the output of the regression model directly to the bottleneck layer of the CAE. Where p is the posture represented by orientational values from the sensors and v is the latent vector representation of a particular image i from the training dataset, we can bridge data from the two models with the following formula:

$$f : p_n \rightarrow v^n \rightarrow i_n$$

Latent Space Conditioning and Navigation

Where the CAE is used to train an unsupervised model that operates on unlabeled data, numerically speaking, there is an arbitrary relationship between the vector representations distributed in the latent space, since the encoding and decoding processes rely on random variables. In recent literature, conditional autoencoders have proven to be a successful method for contextualizing latent dimentions, capable of generating photo-realistic images, allowing for semantic control of the model's output [483].

As a simplified alternative to developing conditional autencoders, we propose a way of intercepting the latent space with the output separate model, trained to interpolate between the known vectors that will reconstruct the original input. Given the intention of "navigating" our latent space, these may be considered to serve as contextual "waypoints", for which we are able to compute meaninful trajectories in a multi-dimensional space. Our latent space navigation framework is illustrated in Section 8.12, Figure 8.9.

8.6 User Feedback & Discussion

For our initial evaluation, we will give attention to the remarks provided as part of the user-centred design workshops that proceeded the case study presented in the following Section 8.8. To maintain a relevant discussion for this segment, we pick out only the specific points directed towards the Latent Steps system.

Embracing Data Collection as Aesthetic Experience

While it was not an intended outcome of the system, the therapeutic quality of the drawing process can surely be acknowledged as complimentary to the holistic user experience. This method of data collection is inherently disruptive, halting the primary activity, and prompting users to pay attention to the internal bodily experiences occurring in that moment. This exercise aligned with some of the core principles of Feldenkrais and even aspects of traditional forms of art therapy. When applying this data into Latent Steps visualisation system, we demonstrate the case for user empowerment through technical transparency, advocating for human-centred workflows. Participants are exposed to the data collection and training processes as they reenact these steps as a prerequisite before they can interact with the predictive visualisation model.

> *But it's also a tool that we somehow coded, like participating in the process of coding, because technology always holds the information of the one who coded it. So it's like biased towards our own body, it's not like something coming from outside, but it's coming from our own somatic awareness. So that's going into ourselves, but also into our own perception.*

> *because the way I understand the system, he took our own notations from Tallin, he combined it with the sensor information and then inside his prototype, if we are repeating movements, it provokes the imagery according to our own notation. So there is this kind of introspective way of notating our own movement, which is provoked by this kind of so-called "objective"measurement.*

Issues of Anthropomorphic Representations and Designing for Pluralism

> *Because I think he used the mapping on the human body, so in this sense I... that's why think it comes from, or it was already like this anthropomorphic thing was very dominant already from the exercise there. And I agree, for me it was a very... the aesthetic of this output and the human form, for me it was very limiting while using it.*

> *And the limitations are indeed in this kind of visualisation of the information in the terms that there are patterns of visualising and immediately when he started with this other (?) that looked too much like a male body, we asked him to delete somehow the male body and then we came up with the aspect of the more abstract figure that you see only the body parts that are shaped, instead of seeing the whole body. And then, I think it was more coming from me, but we all stayed with it, I think it was more appealing in general even. And because the abstraction of it started to open more room for* imagination.

We were made highly aware of the issues that arose from the anthropomorphic model used as a geometric outline, especially as depicted the 3D render (e.g. Figure 8.5), that came across as fundamentally unappealing to the user group. The stock avatar that was used originally embodied highly male-orientated attributes which did not resonate strongly with the user's perception of their own body. This sentiment justifies the inclination for a more abstract figure that were more visually consistent with the original body map data. From this point onward, we opted for projecting 2D figures without a silhouette outline.

Here, it is also interesting to point out that users coming from marginalised groups, commonly feeling less represented by mainstream avatar representations, express their appreciation towards more abstract forms of the body [329]. Correspondingly, “monster” body maps and the flexibility from a normative human figure has shown to offer a dynamic understanding of the body [215]

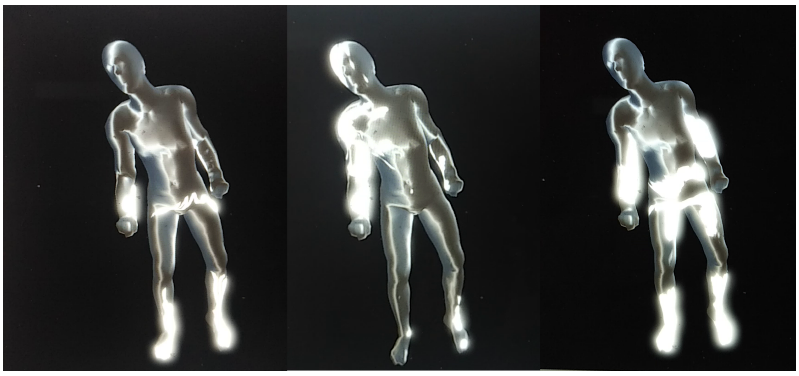

Figure 8.5: Examples of 3D figures with interpolated body map textures.

8.7 Technical Reflections

We have so far provided a technical overview of the Latent Steps system for somatic visualisation, inspired by the outcomes of our initial focus group documented in Chapter 6. Alongside this, we highlight points of user feedback directly related to the system, while the usability of the system is evaluated more thoroughly from Section 8.8 onwards. Here, we construct some technical reflections intended to prepare for applications suitable for new users to take into a live performance context.

Handling Unseen Data

In principle, the complete interactive system should be capable of receiving and processing new visual data on-the-fly and produce suitable interpolations without even needing to re-train the autoencoder model. During the final phase of our multistage research processs described in Section 8.11, the system was adapted to visualise Sylvia Rijmer’s Prime Movers, defined by her as a particular place (locus/loci) in the body from which movement initiates [239]. During an artistic residency, we collected an additional set of hand-drawn illustrations from two external dancers between rehearsal sessions. To test the system, we present the model with this subset of new drawings to complement the choreography, and visualise the Prime Mover shifting around the body as they transition between different performative states.

Separating Layers of Interaction, Representation through Pre-Rendered Material

The alignment of sensory readings to specific bodily areas came with a few issues, as described above. Favouring abstract representations not only for sensation, but for the presentation of the human from, the artists preferred using the sensory input to interact with the sonic layers while visuals would be project separately. This new configuration was used to develop two public presentations (i.e. Stage 4, Secttion 8.12), the first of which which we obtained audience feedback regarding the the audio and visual material. Specifically *"did you find them pleasing, not so pleasing? Did they add for you for that performance?"*

> *For me they really added. I really liked the way how Lis (the performer) was moving, and then it was like even weirder, or the glitch was used really well*

> *I really loved when it was simple, there was just like three copies, and one was bigger and I was thinking like how it's... why I enjoy it, because from the live performer I see the clothes like I see all this information, but this is like pure form and this little bit odd behaviour and it was like really, really nice.*

Working with Other Physiological Signals

The Latent Steps system was intended to function with other input modalities aside from the IMU sensors used in our first model, including more passive modes of interaction. Given that there was substantial training data according to such signals. One participant showed interest in visualising signals from internal biological functions, specifically cardiac rhythm, as this was partially picked up when the EMG sensor strip was placed on the abdomen.

> *And it was even capturing my heartbeat inside, so I think it is, in a way, very sensitive. But then, from the last session here, because of the delay, I think, (...) we didn't see the sensitive parts. But I think there would be interest, there is a potential, because I would be also very interested in this, see more the internal, seeing more the smaller parts*

Potentials for Alternative Machine Learning Architectures

Amongst the exhaustive domain for generative media based Machine Leaning [208], we were not doubted by the potentials benefits of other architectures aside from the Convolutional Autoencoder (CAE) model that was that has been presented in our research. For example, General Adversarial Networks (GANs) have been been praised by contemporary visual practitioners for procedural content generation capable of producing endless streams of realistic and surrealistic images [132, 244]. Additionally, VGG-Networks has been used for Style Transfer, reproducing the stylistic qualities from a range of well-known artworks and projecting these onto other visual compositions, known as style transfer [168]. The main choice of the Autoencoder based architecture in this study was directed at the controllability of the pre-trained latent space from a separate interactive model. An important aspect was also to maintain some level of comprehension from the dancers, and that a more complex architecture may have been harder to grasp. An external reviewer enquired into using a Variational Autoencoder upon examining our representative publication effort [96], framed in the following Section 8.8. The architecture being suggested here would supposedly only require changes in the training process, which the user would not even see, and potentially lead to smoother animations. This would be owed the to the stronger regularisation of the model's latent vectors, achieved by taking statistical variance into consideration.

A more radical alternative would have been to process the visual input not as 2D pixel representations, but instead recording the individual strokes as they are being drawn by the user. This would require a digital apparatus to create the illustration, storing the data as a time series of pixel positions for each map. A sturdy exemplifying the use of stroke features as training data proves an efficient method for modelling with capabilities of reproducing the humanistic quality of pen-to-paper sketches [193].

With all of this considered, there certainly lies a substantial research opportunity to investigate deeper into other architectures and data management techniques. For instance, it's possible that a Variational Autoencoder would adapt better to the inclusion of augmented data, and therefore able to produce different outputs. That said, it's hard to imagine that these outcomes would leave a genuine impact on the experiences of the dancer and audience, but predominantly more interesting to the Machine Learning research community. Such speculation is grounded in the user and audience feedback, given that were no major critiques applicable to the accuracy or smoothness of the Autoencoder function, but more clearly directed to the slow responsiveness of the animation in relation to their input.

8.8 Latent Steps on Stage: Designing Interactive Visuals for Dance from Body Maps: Machine Learning and Composite Animation Approaches

The Latent Steps System described in the previous section is evaluated over a series of workshops and an artistic residency that resulted in a final performance. Participants were invited to experiment with the Latent Steps system, provide their feedback, and develop original works using it´s output. During the same course, we also trailed a non-generative visualisation method that instead calls upon a human animator to produce "*Composite Animations*". This would serve as an experimental benchmark to contrast with the usability and aesthetic affordances of the Latent Steps approach, as deemed by it's users. In this context, the performers and choreographer. Throughout this comparison study, the terminology Machine Learning Interactive Visuals (MLIV) refers to the Latent Steps system while Composite Animation Interactive Visuals (CAIV) represents an alternative non-generative approach.

The following section will report on the outcomes contained in the publication that was delivered during the doctorate programme, including personal contributions as respective co-authors:

N. N. Correia, R. Masu, W. Primett, S. Jürgens, J. Feitsch, and H. Plácido da Silva. "Designing Interactive Visuals for Dance from Body Maps: Machine Learning and Composite Animation Approaches". In: *Designing Interactive Systems Conference*. DIS '22. New York, NY, USA: Association for Computing Machinery, June 2022, pp. 204–216. ISBN: 9781450393584. DOI: 10.1145/3532106.3533467. URL: https://doi.org/10.1145/3532106.3533467 (visited on 06/20/2022)

8.9 Study Motivation

Authors such as Wechsler et al. [463], Obermeier [319] and the OpenEndedGroup [126] have demonstrated the artistic potential of a creative exploration of interactive visuals in contemporary dance performances. Such interactive visuals consist of non-linear imagery, projected on stage, reacting to a specific input(s) in real time (e.g., the movement of dancers or cue-based triggering from an off-stage technician). There has been an increased attention to the role interactive visuals can play in relation to the audience. In a previous study, we identified design strategies for interactive visuals in dance performances aimed towards higher audience engagement [95]. As a way of fostering a deeper connection between the audience and dancers, authors such as Sugawa et al. [429] have recently started to explore the use of biosignal data for interactive visuals. To reinforce this connection between audience and dancers, we follow a co-design process with dancers, to create with them the aesthetics and behaviour of the interactive visuals, to be shown to the audience.

According to our previous findings, in a study involving 10 professional dancers working with technology, a fruitful strategy to use technology in dance performances is to expose non-visible elements in the performance, namely the inner processes of the dancers – such as the thought process of dancers or their bodily data [303]. For example, to convey the thought processes of dancers, technology could assist in revealing "what's happening in the brain before the movement" or "the thinking process of someone doing something incredibly complex". However, there is a lack of research on conveying the inner processes of the dancers during performances, through interactive visuals. In our research, we aim to make non-visible bodily elements apparent to an audience through interactive visuals, relying on the dancers' somatic awareness during their practice.

We draw upon Höök's soma design process complimented with first-person principles granting a singularity bet designer and user [211]. We aim to involve the dancers (the 'end users' of the interactive visuals) in developing interactive visuals for performance that can expose non-visible elements. Dancers can be considered "somaesthetic connaisseurs", following the terminology by Schiphorst [393], which further highlights the importance of leveraging their soma expertise in co-designing the visuals, to achieve our aim of exposing non-visible elements. In Section 3.5, we have referred to the concept of soma trajectories [441], which will be applied here to overcome the static limitations tied with traditional body map representations.

Based on recent research on Machine Learning (ML) and autoencoders for generative visualisation [60, 99], and in the use of ML for embodied interaction design [347], we identify potential in using ML to create interactive visuals for dance performance, from a corpus of body maps. Aly et al.'s research on appropriating biosensors for artistic purposes, identifying that "biosensing decodes inner structures of the performer's body as a control variable" [16], suggest that biosignal sensors can be useful to achieve our aim of revealing inner processes of dancers.

The aim of exposing non-visible elements from the dancers leads to the following research question: *how to design interactive visuals for contemporary dance performance, in a way that reveals the inner processes of the dancers?* Our hypothesis is: *following a soma design process with dancers relying on body maps, combined with interactive technology and machine learning, can make non-visible bodily elements apparent, to be presented as interactive visuals.* To answer our research question, we devised a set of co-design stages involving two workshops with ten dancers each, and an artistic residency with two choreographers.

8.10 Background: Interactive Visuals, Machine Learning, and Dance

Interactive Visuals

In the intersection between dance and HCI, interactive visuals have been the focus of recent research. Hsueh and colleagues investigated creativity in dance [220]. They developed a series of interactive visuals, then invited dance practitioners to use those visuals to generate movement materials. Based on the results of this study, the authors developed a taxonomy composed of three different relationships and two movement responses between dancers and visuals. The classification is composed of six different "interaction patterns" organized in two domains: Relationship to Visuals; and Movement Type. In the Relationship to Visuals domain, there are three levels (Instrument, Partner and Medium). Instrument relates to manipulation of visual properties by the body, helping dancers form a first-person relationship. In Partner, the dancer establishes a dialogue with the visuals, which have an autonomous behavior. Finally, in the Medium level, visuals are used to communicate with other dancer(s), or between choreographer and dancer. We will use this taxonomy to discuss our findings.

We previously conducted an audience study on the experience of live visuals in dance, involving four different dance performances, each exploring a different approach for interaction involving visuals (motion capture, sensors, video camera and minimal interaction) [95]]. This allowed the authors to propose a mapping clarity diagram, as perceived by the audience, and a performance network diagram (with: the different actors; on stage components; and conceptual elements), for dance performances with interactive visuals. Sugawa et al. were able to sense cardiovascular and electrodermal activity from audience members and appropriate this sensor data to influence staging elements, such as visual projections, music, and lighting [429] This allows the on-stage performers to react to the internal states of the audience according to the sensory data. This demonstrates how the visual representations of the body can be used to facilitate å non-verbal exchange between performer and audience. Although this this case, it focuses on the acquiring signals from the audience, whereas in our study, we focus on the dancers.

Based on our literature review on body maps, we identify the use of more *free-form body maps* (such as the ones used in [166]) and *outline-based body maps* (such as the ones used in [465] and [332]). We adopt both types in our study.

Machine Learning

In terms of dance, Silang Maranan et al. developed an ML system that generates real time classifications of movement qualities using Laban Movement Analysis [409]. The system also generates abstract visualisations based on those classifications. Brenton et al. proposed interactive visualisations that react to the free-form movements, allowing to respond to "the idiosyncratic movements of an individual dancer", using ML mapped to visuals [59]. Murray-Browne and Tigas proposed an open-ended mapping process (entitled "latent mapping"), leveraging an ML algorithm trained on a corpus of unlabelled gestural data [326]. Plant et al. proposed a new tool based on interactive ML (*InteractML*) to "make embodied interaction design faster, adaptable and accessible to developers of varying experience and background" [347]. In *InteractML* "the user provides training examples (movement data), classifies these examples and can iteratively edit" those examples [347]. These examples are relevant for us, as we aim to employ real time machine learning for dance.

A particular use case of ML in dance is the creation of an 'artificial dancer', projected on stage. McDonald and collaborators developed Discrete Figures, based on 40 separate motion capture recording sessions [308]. Each session was composed of a dancer improvising in a different style ("robot", "sad", "cute", etc) [308]. This allowed to create a dataset of motion capture data, and from that a virtual "AI dancer", with whom a real dancer establishes a dance dialogue with. Berman and James followed a similar logic, but based on real-time data [36]. They presented a system built for a dance performance, where an autoencoder neural network is trained in real time with motion data captured live on stage. This allows to generate an "artificial performer" projected on a screen and "enabling a mutual exchange of movement ideas" between "artificial" and "human" dancers [36]. The method employed in [308] of different data capture sessions from dancers based on different sessions / themes of dance relates to how we conducted our own data capture, with five discrete sections / themes.

8.11 Methods

In this section, we present an overview of the study design and methods used. In the Design Stages and Evaluation Stages sections, these are further detailed.

Study Design

To answer our research question, we adopted a co-design perspective with dancers. To facilitate the co-design process, we relied on the different layers of appropriation exposed in the design-inuse model by Botero et al. [55]: *reinterpreting* possible uses of an artifact, *adapting* and even *reinventing* the artifacts, when some changes are operated on the artifacts (in collaboration with designers). We distributed the co-design process across four stages over six months (figure 1), in the scope of the Moving Digits project (see Section 1.3): two participatory workshops with dancers; a technological development stage in between the workshops; and a final artistic residency [3]. Throughout the process, we adopted different strategies to engage our participants in the design process.

Our **Stage 1** consisted of a sketching workshop (2 days), where ten dancers (see Participants section below) created movement exercises and then sketched body maps, based on

[3] Documentation for the workshops, residency and performance can be found in the Appendix B

those exercises. In **Stage 2**, our research team developed prototypes to create interactive visuals from the body maps generated, across three months. In **Stage 3** (4 days), the ten dancers tested our systems, and then provided feedback and suggestions, in two final focus group sessions (one per prototype). We used this feedback to iterate the respective designs. In the longer **Stage 4**, the systems were used to create, rehearse and present choreographies by two of the participants in the previous stages, leading to further evaluation (12 days in total, 6 days per participant). Although the design activities took place throughout the four stages, we will refer to Stages 1 and 2 as *design stages*, as the main design features were created then; and Stages 3 and 4 as *evaluation stages*, as we conducted iterative fine-tuning of our previous designs, while focusing on evaluation.

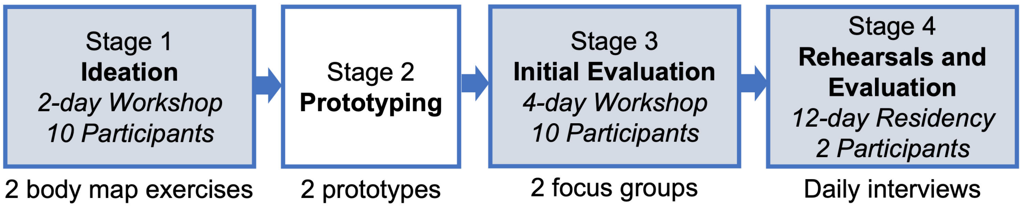

Figure 8.6: Diagram with stages of the research, over a six-month period.

Data Collection and Analysis

Movement exercises conducted in Stage 1 were video recorded and the respective biosignal data was collected (see Stage 1 section). We collected sketches from the dancers related to those exercises, using the two types of body maps identified in the Related Work section: *free-form* and *outline-based*. We asked dancers to annotate the body maps, following the approach by Gastaldo et al. [166]. These materials were scanned for use in the systems to be developed. Each dancer was asked to explain the body maps in their own worlds, to shed more light into the sketches – a body map *testimonio*, using the terminology from [166]. The *testimonios* were also video recorded.

In Stage 3, after the prototype development, we conducted two focus groups for the evaluation of both systems. In Stage 4, we conducted daily interviews with participants (across six days for each participant), for further evaluation and design iteration. These were audio recorded. The systematic data collection in Stage 4 is based on the technomethodology approach proposed by Dourish, involving the analysis of actions "moment-by-moment", promoting a detailed analysis of actual practice [124] – adequate for the setting of choreography rehearsals. Therefore, we combined a shorter data collection and evaluation with more dancers (Stage 3), with a more extended and continuous evaluation, with fewer dancers (Stage 4).

The audio recordings of the two studies, in Stages 3 and 4 (focus groups and daily interviews, respectively), were transcribed and subjected to thematic analysis [58], independently. For each of the two thematic analyses, we coded the data using an inductive approach, and the codes were then organized into themes. We followed an inductive 'bottom up' approach to identify patterns within the data: "a process of coding the data without trying to fit it into a preexisting coding frame, or the researcher's analytic preconceptions". Therefore, in this process we were not driven by theory or the questions we asked. The analyses were conducted by the first author and cross-checked by the second.

Study Participants

The two workshops involved a total of 12 international professional dancers in the field of contemporary dance, between 27 and 49 years old (11 female, 1 male), selected from an open call distributed to contemporary dance mailing lists (resulting in 92 applicants, 73 female, 19 male).

Ten participants took part in the workshops on Stages 1 and 3. Two of the participants from Stage 1 could not attend the Stage 3 workshop due to scheduling issues, and were replaced by two other applicants from the initial open call. The two participants in Stage 4 (both female, 32 and 45 years old) were selected from the previous group of participants. The selection was based on a call for proposals, between Stages 3 and 4, targeting previous participants, to develop choreographies using the prototypes.

One reviewer of the corresponding publication critizised the gender imablance of the user group in respect to generizability. We may direct this to a higher number of female dance artists in the field of contemporary dance, and that the CVs of the male applicants were considered less fitted to the project than of the female applicants. It could even be commented that this effort actually poses to counter a historical overshadowing of non-male perspectives in Science and Technology Studies (STS) [215, 458].

8.12 Design Stages

Stage 1 - Sketching Workshop

The first stage consisted of a two-day sketching workshop, which took place at STL, a dance center in Tallinn, Estonia. The objective of this stage was to gather visual ideas and data about the dancers' inner bodily processes during movement, to assist in the design and development of the interactive visuals systems for performance. Following approaches from our literature review (Section 3.5), we used the two types of body maps identified (free-form and outline-based) as the main tool to collect visual ideas, and we used biosignal sensors to gather bodily data. This was intented to cover the different approaches identified in literature, and experiment with diverse designs for interactive visuals. Participants were given paper, colored felt pens and also clipboards for their drawings, so that they could move freely in the studio, and reenact the movements at will for accurate representation, while having the drawing materials at hand.

We decided to use biosignal sensors as one of the strategies toward our aim of revealing internal information from the dancer's body. We used the BITalino R-IoT to acquire muscle activity, acceleration, and orientation data. The use of these sensing modalities is informed by the corresponding literature review, particularly in regards to stability and usablity during intense phyisical activity [16].

The free-form body maps (figure 8.7) resulted in very diverse and individual approaches. Each dancer produced five free-form body maps – one per section. Following the approach by Gastaldo et al. [166], we asked participants to annotate these body maps. In our case, the annotations were done in an overlay sheet, which was stapled to the main page for the drawing. That way, the drawings could be scanned independently of the annotations, in the future (e.g., for animation purposes). We also recorded video *testimonios* of dancers explaining their body maps.

Figure 8.7: Free-form body maps. Left: dancer executing a movement section. Right: free-form body map drawn by the same dancer corresponding to that movement section

The outline-based body maps (figure 8.8) were more constrained, and involved coloring the main body areas involved in that movement, as perceived by the participant (ten drawings per dancer – two per section of the choreography). The silhouette adopted was based on one of the outline-based body maps identified, used by [332]. Each drawing was labeled according to the specific section of the choreography that it corresponds to. A total of 150 body maps were produced (50 free-form and 100 outline-based body maps).

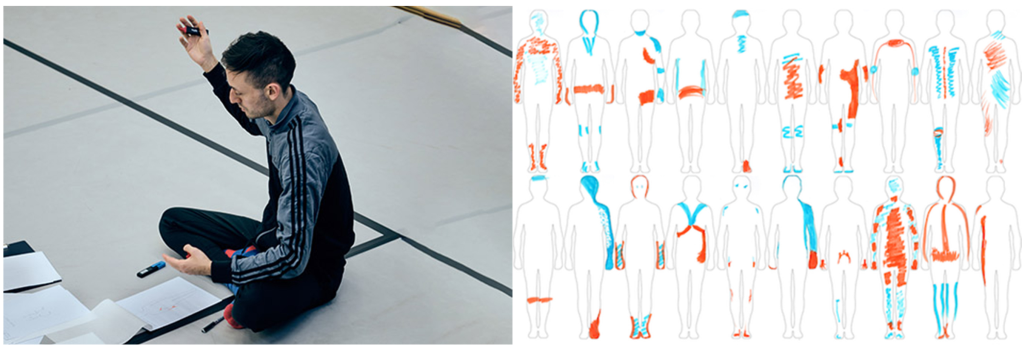

Figure 8.8: Outline-based body maps. Left: dancer partly reenacting a movement section while drawing an outline-based body map of that movement. Right: 20 of the total 100 outline-based body maps.

Stage 2 - Prototype development

After the initial workshop, our research team set out to conceive approaches for interaction design and visualisation, which would leverage the visual material created by dancers in Stage 1, informed by related literature. We aimed to generate motion graphics from drawings created by the performers. To fulfill that, we followed two different approaches, each considered more suited to outline-based or to free-form body maps, resulting in two prototypes.

Machine Learning Interactive Visuals Approach

For the outline based body maps, we employed an approach we entitled Machine Learning Interactive Visuals (MLIV). Each body map was labeled according to a specific section of the choreography and then matched with the sensor data recorded, while the movement was being performed. We developed a MLIV system based on Latent Steps (detailed in Section 8.1), capable of morphing between the performer's body map drawings by predicting the interpolated frames, according to biosignal sensor data. The workflow is illustrated in figure 8.9. This is done through a Convolutional Autoencoder (CAE), an unsupervised model consisting of an encoder and decoder function. We adopted an autoencoder approach informed by Berman and James [36], who found that it was suited for live applications in dance. The encoder computes compressed representations of the images, assigned according to the visual features interpreted by the model, referred to as the latent vectors. To allow navigation between these vectors, the decoder is capable of generating continuous interpolations between the drawings, resulting in a series of new, reconstructed, images.

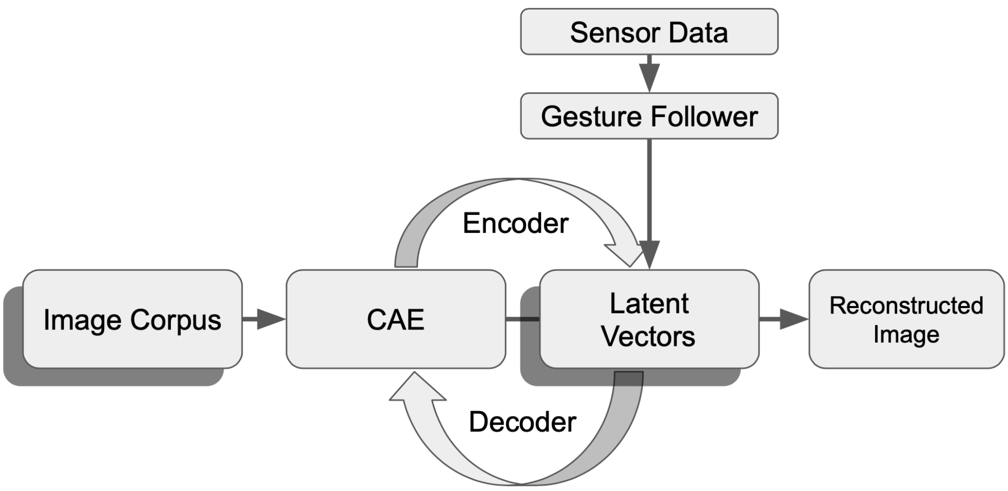

Figure 8.9: MLIV design framework diagram, as followed in the respective prototype.

To enable user interaction, we adopted a regression-based model, trained on a set of postural gestures from the performer, producing a continuous output while gestures are repeated and performed. We coupled the regression model with the incoming acceleration and electromyography sensor data captured from BITalino R-IoT. This orchestration allows the performers to manipulate the style and time-dynamics of the animation through movement (navigating around the latent vector space through movement).

This work led to the MLIV prototype. The system analyzes in real time the incoming sensor data from the dancer's movement (Figure 8.10, first row). When fed into the gesture recognition layer, it tries to match the incoming sensor data with a segment form the pre-trained data corpus. It identifies the closest data segment match from the corpus, retrieves and adapts the body map corresponding to that movement segment (figure 5, second row). Following that, the process is repeated. When the next body map match is found, the system generates interpolated frames between the two matches (current and previous match), creating an animation (Figure 8.10, third row). The process then repeats again. This way, the system can generate in real time a vast number of possible animations based on the movement being executed, which would be unfeasible to generate manually.

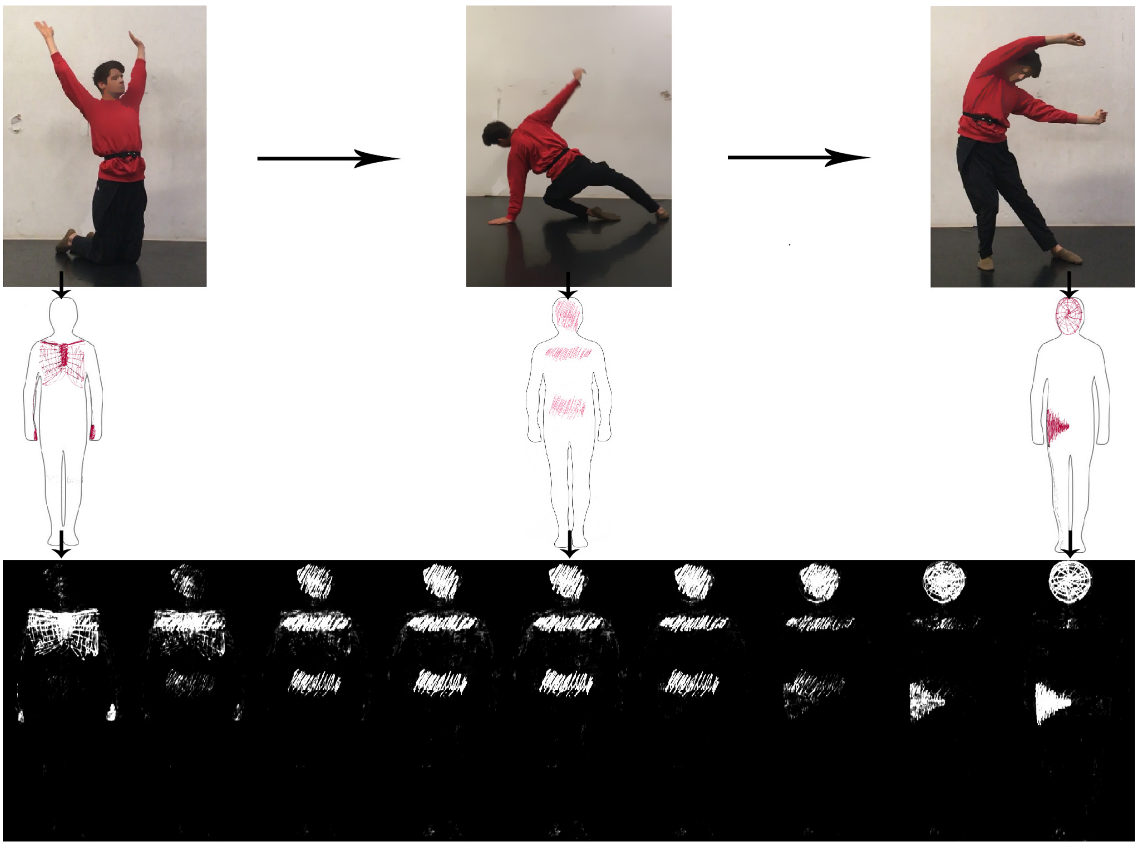

Figure 8.10: Sequence of real time visualisation frames from the MLIV prototype, based on movement and matching body maps.

Composite Animation Interactive Visuals Approach

We were aware that there would be difficulties using MLIV with the free-form body maps. Due to the relatively small number of drawings (50) and the diversity of visual features, there was a strong likelihood of overfitting – thus presuming our computational model (presented above) would not recognize meaningful patterns in the dataset. This was apparent during the initial prototyping phase, when feeding new inputs. We observed the inferred outputs would either resemble near replicas of the original data, or noisy representations, so incohernet, they held almost no association with any of the dancers' visual intentions (i.e. the original sketch).

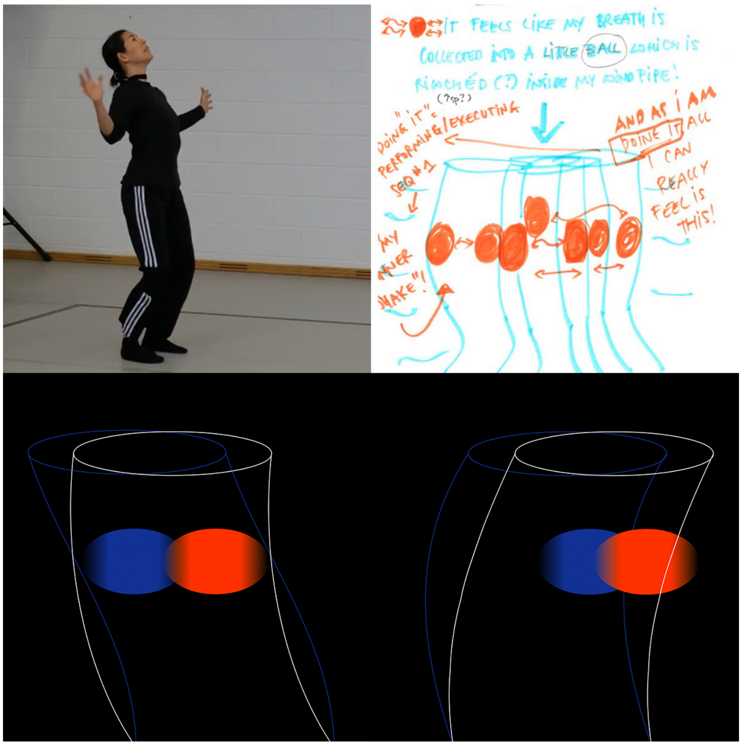

Figure 8.11: CAIV approach. Top left: dancer executing a movement section. Top right: the free-form body map drawn by the same dancer corresponding to that movement section, with annotations. Bottom: two frames of the motion graphics created by the animator, based on the documentation of the movement section, represented on top of the image.

Instead of MLIV, we adopted a 'human learning' approach we entitled Composite Animation Interactive Visuals (CAIV), to create interactive visuals from the free-form body maps. We use the term 'composite animation' to adapt the concept of composite drawings to animation. Composite drawings are used in forensic art and can be defined as freehand drawings, created by a forensic artist, combining various sources into a single graphic image [427]. These sources can be, for example, witness descriptions and CCTV footage related to a crime. To pursue this concept, we hired a professional illustrator and animator, André Carrilho, to transform the free-form body maps into motion graphics, also informed by the annotations on the body maps and the matching video sequence. With these elements, he created the different animations, in a way that respected the original body maps, while slightly simplifying and harmonizing the different animations (Figure 8.11). These slight simplifications and harmonizations aimed to allow for a better 'mixing and matching' of the animations during a performance. In this stage, the animator created ten motion graphics sequences, one per dancer (with the possibility to add more in the future) – chosen based on the potential of the respective body map for animation, while covering all five section themes. Our research team reviewed the animations as part of a 'quality assurance' process, to check if they conveyed the dancer's materials well. In some cases, the animator fine-tuned the animations according to our suggestions.

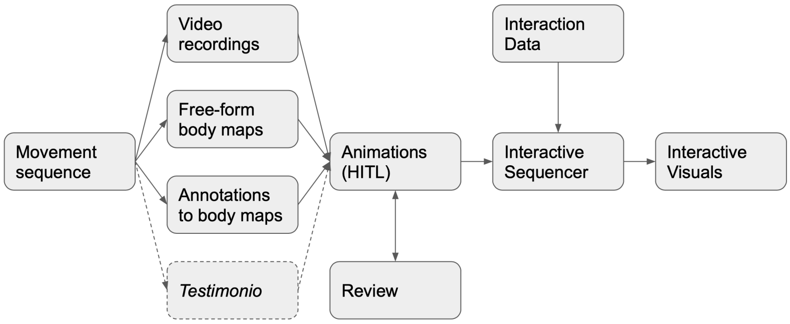

Figure 8.12: CAIV approach diagram, as followed in the respective prototype.

For the interaction design in our CAIV approach, we did not use ML or biosignal sensors, and focused on the non-linear sequencing of animations, in a way that would support flexible choreographic decisions. We created a visual sequencer for the animations using *Isadora* [4], an *"easy to use but also sophisticated software for both workshops as well as performance"* [109]. We designed a customizable Graphical User Interface (GUI) for the sequencer, to structure and trigger the animations non-linearly, on-the-fly. Figure 8.12 shows the GUI coexistinging with video thumbnails, video preview and the data flow, allowing for spontaneous reconfiguration, while maintaining ease of use for the operator (e.g., the choreographer, the dancer or a technician).

The animations could be used, for example, as an onstage virtual 'partner' for the dancers (using Hsueh et al's terminology [220]) or as a 'director' (that could represent the choreographer, or another role). During the performance, it allows to display not just a single animation, but also multiple ones, as a 'menu' of options for the next animation (for example, visualising the options for the next movement of a virtual entity, or the next instruction for the dancer to follow). As placeholders for animations, videos, images or text can be used. Our CAIV approach is modeled in figure 8.13.

8.13 Evaluation Stages

Stage 3 - Initial Evaluation Workshop and Results

Stage 3 consisted of a four-day workshop, which took place at the Interactive Technologies Institute, Madeira, Portugal. The main objectives of this second workshop were to

[4] https://troikatronix.com

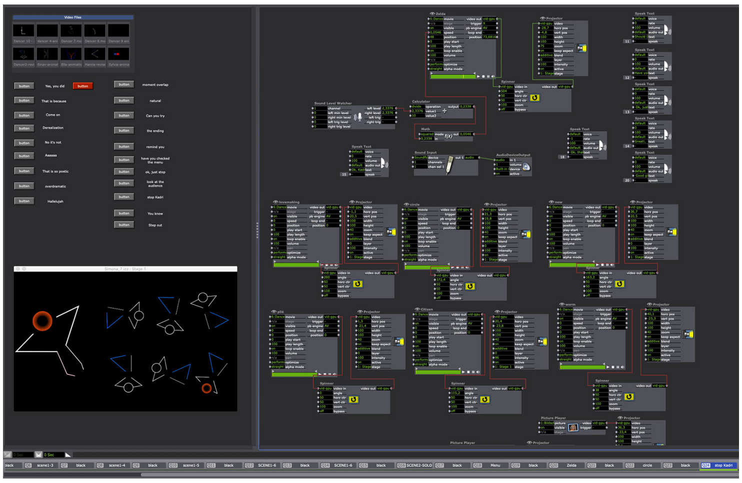

Figure 8.13: CAIV prototype screenshot, as seen by the operator. Top left: animation thumbnails and GUI to trigger animations. Bottom left: preview of the visuals to be projected on stage (in this case, a image of the 'menu' of possible next animations in the sequence). Right: *Isadora* data flow.

evaluate the prototypes and collect feedback, leading to their improvement. Ten performers attended the workshop – eight from the first event (two of the original participants could not attend), and two new performers (D5 and D10), recruited from applicants to the original call. During the four days, the dancers freely tried out the prototypes, and gave us informal feedback, which we used to iterate on those prototypes on-the-fly. On the first day, after a general introduction to the prototypes, each participant was asked to choose one of the two prototypes, for more in-depth testing during the rest of the workshop. From then on, the dancers were organised into two groups of five participants: MLIV group, composed of D1-D5; and CAIV group, composed of D6-D10; focusing on the respective prototypes (Figure 8.14). On the last day, we organised two focus groups (one with each group of participants), aiming to give feedback to the respective prototype. In the focus group sessions, participants were asked to convey their impressions of the prototypes, and were prompted to mention positive and negative aspects. The two sessions had a duration of approximately one hour each. The transcriptions of the two focus groups were subjected to thematic analysis (as presented in the Methods section), resulting in four common themes: introspective visualisation; affordances as inspiration and instructor; communication with audience; and openness and modularity.

Introspective Visualisation.

MLIV group: All participants mentioned they appreciated the capability of the MLIV prototype to visualise the subjective and introspective aspects of the body, as exemplified in the following statements:

Figure 8.14: Initial prototype evaluation. Top: MLIV group. Bottom: CAIV group.

> *It takes your internal experience, this subjectively live body experience and puts it outside. (D1) [The researchers] included our initial perspectives in order to develop this prototype, not just the movement, not just the shapes of movement, but also the introspective aspect of how you feel concerning movement. (D2)*

Although some participants enjoyed that the MLIV prototype took their sketches as a starting point: "It provokes the imagery according to our own notation" (D2), others considered the visuals monotonous (D3, D5).

> *it was already like this anthropomorphic thing was very dominant already from the exercise there. And I agree, for me it was a very... the aesthetic of this output and the human form, for me it was very limiting while using it*

CAIV group: D9 enjoyed the capability to visualise the dancer's decision process in the CAIV prototype: "We are revealing things that happened in the dancer's head while we are dancing (...) to reveal this process that we are doing, actually most of the time unconsciously. Deciding. What is next? ”

Affordances as Inspiration and Instructor.

MLIV group: Participants enjoyed the bodily data affordances of the MLIV prototype (D1, D3, D4), which changed their behavior: “It puts me in a state of not doing form, because it’s not a camera, but it puts me in a state of exploring, like, weird internal stuff that I don’t usually do” (D3). All participants considered using sensors to be inspiring for movement. As D2 stated: “It opens a lot my imagination of how to interact with a system, and what the system reads in me, and what it incorporates in my somehow subjective feelings toward my own movements”. Participants mostly disliked the slow reactivity of the MLIV prototype (D2, D5), although this was considered adequate by D1: “it takes a bit of time to see, which is how I deal with my dance practice”.

CAIV group: The dancers valued the non-linear flow of the CAIV prototype. A possible scenario that was identified is the system providing instructions to the dancer: “I think of a live situation where the dancer is kind of a slave of this big king of dance who’s sending me here and there. And I think it could be interesting because the performance would be different every time” (D10). Two dancers (D6 and D10) suggest using randomness to select the next steps in the sequence, instead of an interactive selection. 5.1.3 Communication with Audience.

MLIV group: Participants recognized potential for communication between dancer and audience in the MLIV prototype: “I can make it clear enough the relationship between my movement and what the audience sees” (D2).

CAIV group: D7 identified potential in the CAIV prototype to make the audience move, using the system to output instructions for that movement. Related to this logic, D6 identifies pedagogical potential in the prototype, as a teaching and learning dance tool, suggesting adapting it to an interactive installation.

Openness and Modularity.

MLIV group: D2 felt involved in the co-design process of creating the MLIV prototype: “It’s also a tool that we somehow coded, like participating in the process of coding”. Dancers wished to combine the prototype with motion capture (D2) and other types of sensors (D1). The wish for modularity was summarized by D4: “I am also more interested in trying out different possibilities, what are the possibilities where I can take the input from, which are the possibilities for the output” (an opinion echoed by D3).

CAIV group: The CAIV prototype showed potential as a tool to build choreography (D6, D7, D9), characterized as: “An open structure, which can be put down and rebuilt in a different way” (D9). However, it can be laborious, due to the need to prepare visual materials (D7, D10). Participants wished for a modular structure for it, combining features and functionalities taken from the MLIV prototype, such as: to add sensors (D7, D9) or ML (D7, D10)

Stage 4 - Rehearsals of Choreographies and Evaluation Results

After the Stage 3 workshop, participants could submit proposals for choreographies to be developed in the scope of Moving Digits. Eight participants in the previous workshops submitted proposals, and four were chosen by the research team, based on the quality of the artistic concept, innovative approach and feasibility. Two of the selected proposals included the use of the MLIV and CAIV prototypes. For the scope of this paper, we focus on the work developing the two respective choreographies. The two participants (authors of the proposals) will now be referred to as 'choreographers', to reflect their change of role. The choreographer using MLIV will be referred to as C1, and the one using CAIV will be referred to as C2.

C1's proposal text was aligned with our aim of exposing non-visible elements:

> *In augmenting the interior realities through explorations of imaginary, sensations, creative fantasy, and the inner body-textures of the dancers relative to the exterior world (spectator), I seek to demonstrate unusual characteristics of dancing by creating a (visual) menu consisting of unusual perspectives of a dancing Body*

C2's proposal was equally in line with our aim, focusing on the thinking and choice processes of the dance artist. It stated:

> *I want to give the audience an insight on dance making, by showing the invisible process behind the choices one makes when creating a piece. (...) The audience will perceive 2 types of presentations: a human one and a virtual one. (. . .) Its proposals [of the virtual entity] would materialize in Animated Drawing, that envision its own movements, accompanied by related poetical explanations.*

Meanwhile, we made improvements to the prototypes, to address limitations identified in Stage 3. In the MLIV prototype, we introduced the wearable form-factor for the *BITalino R-IoT*, with the sensory components embedded into a wearable enclosure; this reduced the noise in the signal during rapid movements, while allowing for faster setup times. In the CAIV prototype, we added new GUI elements in *Isadora* for ease of operation, this fine-tuning of the GUI continued also during the residency according to the needs of C2. The animator was commissioned to develop ten more composite animations, defined with C2.

In Stage 4, we organised a 12-day artistic residency with the selected participants. The residency took place in the Sõltumatu Tantsu Lava (STL) performance space. The objective was to develop each choreography and rehearse it, while continuously evaluating and fine-tuning the respective prototypes. It was intended to be more in-depth than previous workshops: it had fewer participants, and a longer duration, suitable for the rehearsal of a short choreography, building upon previous work. Choreographers were given the chance to work with local dancers (C1 chose two dancers, and C2 picked one).

We arranged six separate six-hour studio sessions with each choreographer, across the 12 days, in alternating days (Figure 8.15). At the end of each session, we conducted short semi-structured interviews (six in total for each choreographer). We asked questions related to the use of interactive and visualisation technology and the development of the respective project. The transcriptions of the interviews were subjected to thematic analysis (as presented in the Methods section), resulting in three common themes (body visualisation aesthetics; feedback loops and connections; workflow and workarounds).

Figure 8.15: Images from the residency rehearsals. Left: MLIV approach. Right: CAIV approach.

Body visualisation Aesthetics

C1 enjoyed how the MLIV prototype facilitated visualising biosignal data: *"It's nice to be able to see how biological information through the human body can affect or create [visual] effects"* (day 1). In particular, she felt that its pulsating aesthetics highlighted the physiological side of the dancer: *"It gives the breathing element. It shows the humans a little bit more delicate. It simulates organs, the idea of breath"* (day 3).

C2 used the animations in the CAIV prototype to simulate an artificial entity: *"This visual means the body of another entity in a way"* (day 4). She enjoyed the minimal animations, representing the body of this entity: *"I like André's drawing very much, I think we will get to a very beautiful action, a minimal kind of body"* (day 6).

Feedback Loops and Connections

C1 used the MLIV prototype to create a feedback loop between dancer and visuals, where the dancer influenced the visuals through the sensors, and the projected visuals in turn influenced the dancer: *"a looping system, biological, digital, back to biology"* (day 1). To find that feedback loop, she explored different movements and system settings, *"Trying to find the right kind of feedback that can trigger a movement or generate movement that's still justifiable in contemporary dance"* (day 1). By day 4, she felt *"It did generate new movement, at least new possibilities for movement"*.

C2 wished to have a *"dialogue"* with the dancer, by interacting herself with the visuals, through the CAIV prototype (day 1). With this system, she felt that she is connecting visuals and dancer: *"I'm creating connections between image and body"* (day 4). By the end of the residency (day 6), she felt that the operator role is very efficient: *"I liked that I could interact with [the dancer] in real time"*.

Workflow and Workarounds

C1 recorded and edited a large number of visuals generated during rehearsals, which she used to create a balance with interactive moments that she could not control, due to slow responsiveness of the MLIV prototype: "The film was something I could control, which was a nice balance with everything i could not control. Which was the live situation" (day 6).

C2 considered that the CAIV prototype was a quick tool in setting up the animations and visuals in the software, despite the laborious aspect of the prototype identified in Stage 3: *"I think it's very good to work like this, really have a software that helps you create this structure, because it's about scoring and structuring in real time, and being able to make modifications in real time"* (day 3). On the final day (day 6) of the residency, in reference to our system, C2 stated *"I have discovered this very efficient tool of structuring material very very fast"*. This allowed C2 to overcome the short time for developing the choreography: "Five days is not a good time for research. Meaning we need more time" (day 6, last day, in reference to the five previous days).

8.14 Discussion

We developed two design approaches to create interactive visuals for dance, based on machine learning and composite animations (MLIV and CAIV). Both rely on body maps drawn by dancers, based on their somaesthetic impressions. We first discuss aspects related to each of our two approaches, and then more generic aspects.

Organic and Introspective Interactive Visuals, Machine Learning Approach

The MLIV prototype was considered successful as a tool for revealing internal bodily processes, by the five dancers that evaluated it in Stage 3. Dancers appreciated that visuals took their own “notation” (D2) from their body maps as a starting point. C1 used the system for a longer time in Stage 4, and described the aesthetics of the system in more detail, showing a deeper understanding of its design, namely its organic and breathing-like visual affordances. On the interaction side, dancers in Stage 3 highlighted the impact that the system had in their own movement and even in their imagination (D2). In Stage 4, C1 explored this to create a feedback “looping system” between the biological, the digital, and back to the biological. She felt she achieved “new possibilities for movement”. We believe our MLIV approach complements related ML and movement approaches, such as [326, 409]. These focus on other aspects of the movement data (flexible mapping and data classification), while our system focuses on visualisation of inner aspects of the body.

Accounting for Slow Responsiveness in Latent Steps

The MLIV prototype had limitations in terms of responsiveness, which can be attributed to a small corpus of body maps (only 100) and limited sensor data collected. We applied a low-pass filter to the frame interpolation layer to compensate for identified abrupt jitters. However, this resulted in slower reactivity, both in terms of latency and slowness of the visualisation, relatively to the corresponding movements. This slow reactivity was considered by some dancers to be problematic in account of their first impression taken during Stage 3. To mitigate the risks of a slow responsiveness of the system in a performance, C1 combined real time visuals from the MLIV prototype with pre-recorded videos of visuals from rehearsals. We hypothesise that adding more drawings to the corpus, and collecting more matching data from the moment (potentially, with added sensors) could improve this responsiveness.

Connecting Idiosyncratic Visuals with Movement, Composite Animation Approach

Due to the more idiosyncratic nature of the free-form body maps, a different approach based on composite animations was pursued. To add interactivity to the resulting animations, we developed a dedicated system with Isadora, the CAIV prototype. The resulting animations were considered aesthetically successful by C2, and she enjoyed their minimalism. She used the animations to represent the body of an artificial entity that would enter a dialogue with the dancer. C2 controlled this artificial entity herself, by operating the CAIV prototype. This way, she could interact with the dancer in real time, which she enjoyed. The animations, grounded on dancers’ movement and related somaesthetic impressions, together with the sequencing system, allowed her “creating connections between image and body" (C2). The sequencing system for the animations was also considered successful in terms of visualising inner processes. This relates to the proposal of revealing a movement decision process realized in our preliminary focus group [303]. In the initial evaluation, D9 stated that the CAIV prototype had the potential for "revealing things that happened in the dancer's head while we are dancing", the decision process of what movement to execute next. This logic was implemented by C2 in Stage 4 by showing a 'menu' of animations that could come next, and then triggering one of them.

Comparing visualisation Approaches

We now compare the two adopted approaches for revealing the inner processes of the dancers. We argue that an MLIV approach can be beneficial with more constrained body maps – such as the outline-based ones, with specific rules for drawing, as we have used. In our case, coloring specific areas of the body according to specific criteria – parts of the body involved in a movement. These constraints are beneficial for training an ML system, especially when having access only to a relatively small corpus of drawings.

A CAIV approach can be preferable when the body maps are more freeform, where the visual qualities are harder to represent with a computational model. This CAIV method is clearly more laborious, as there is a need for manually generating animations. It also requires a system for adding interactivity to trigger the individual animations (such as our CAIV prototype), rather than a continuous morphing of the visuals, in the way that MLIV allows.

We are aware that forcing a choice upon participants between constrained and free-form body maps creates a "conceptual dichotomy" that should be avoided in soma design, as stated by Höök et al. [215]. Our participants were dancers, hence "somatic connaisseurs" [393] and fluent in expressing their impressions in both types of body maps. But other participants may not be as comfortable expressing their somatic experiences with both. Therefore, it is useful to have the option to use either MLIV or CAIV, or both, depending on the preference of dance artists. Eventually, a future hybrid solution could also be developed, combining both approaches.

Recent literature in embodied interaction has focused on the importance of accounting for "non-normative bodies" [424]. We believe that our MLIV approach has a potential for this, due to its flexibility of mappings – it is not a 'one size fits all' solution and can be adapted to a wide range of bodies. However, it relies on constrained, outline-based, body maps. These may suggest a 'body norm', which is undesirable. The free-form body maps are more inclusive in terms of body representation, as they allow for an entirely individual approach. This points once again for the potential of a hybrid solution, merging the flexible mappings of MLIV and the idiosyncratic representation of free-form body maps.

Non-human Engagement in Hybrid Virtual Environments

Using a multistage co-design process facilitated that the systems developed for interactive visuals respected the vision by the participants, from the early sketches until the final rehearsals. Throughout our study, other perspectives have emerged. Our participants identified other actors and use cases that could benefit from our visualisation approaches. In particular, this emerged in Stages 3 and 4, when our participants could use and explore the artifacts created. In **Stage 3**, the focus was mainly on testing, and therefore on the use. Different possible uses and contexts of use were suggested by participants based on their reinterpretation of the artifacts. In line with our design aim, dancers identified potential for enhancing the communication between the dancer and the audience, in both prototypes (D2, D7). However, three further possible uses for the CAIV prototype were also identified: as an audience interaction tool (D7); as a dance pedagogy tool (D6); and as a choreography creation tool (D6, D7, D9). This positions the artifacts beyond the originally intended category of augmented performance and into the categories of *education* and *choreographic tools*, according to the taxonomy in [357].

Stage 4, the last stage of our study, stands out as a longer phase that combined evaluation and design fine-tuning, toward the creation and rehearsal of a choreography. In this longer phase, we aimed to facilitate multiple perspectives and forms of appropriation [118]. During this artistic residency, indeed, C2 highlighted the potential of the CAIV prototype to be both a virtual 'partner' for the dancer [220] and a mediator between choreographer and dancer. This situates the system (as used by C2) in the category of agent collaboration, in the taxonomy by Zhou et al. [484]. This observation was not only a *reinterpretation* of the system, but actually lead to the fine-tuning of the design, *adapting* the GUI, to facilitate the role of C2 as an operator in dialogue with the dancer. C1 also appropriated the artifact to create a feedback loop between the visuals and the dancer, introducing further adaptations, as different movements were tested in combination with adjusted system settings. In this case, the visuals became 'self-reflective' [220]. The findings from Stage 4, with its changes in actors (dancers become choreographers) and the rich connections between visuals, dancers and choreographers that emerged, confirms the findings of Felice, Alaoui, and Mackay: "Designing grounded CSTs [Creativity Support Tools] for choreography, thus, requires us to study how dance artists collaborate, paying attention to the perspectives and expectations of each" [145].

8.15 Summary

We conducted a participatory study with 12 dancers across four stages, developing two systems with a soma design perspective, aiming to achieve a visualisation of unseen aspects of the body, for interactive visuals in dance performances. This resulted in two different approaches, based on leveraging machine learning (MLIV approach) and composite animations (CAIV approach) to convert two types of body maps into interactive visuals. Our study confirms our hypothesis: both our approaches can successfully transform static body maps into interactive visuals, which reveal unseen aspects of the body. These approaches allow for novel pathways to create idiosyncratic and introspective visuals for dance, grounded in the somatic experience of dancers, and how they convey it visually through body maps.

We believe that our MLIV and CAIV approaches can be a relevant addition to the field of creativity support systems for dance performance. With our approaches, we draw upon the field of soma design, to facilitate imagining through the senses and movement, taking into account the participants' somas. In particular, our work is informed by recent research on body maps, and provides new pathways for creating interactive visuals for dance performance from body maps. We believe that our approaches can complement the concept of soma trajectories, by providing approaches to overcome the temporal limitations of body maps, while preserving their visual richness.

Our main contributions with this research are the two approaches toward visualising inner aspects of dancers' bodies: MLIV and CAIV. In practice, this led to two software systems (available as open-source), with design framework descriptions, for creating interactive visuals from, respectively, outline-based and free-form body maps. We identified strengths and weaknesses of each system. We hope these contributions can be useful to designers in the field of dance and technology, of soma design, and more broadly in the field of embodied interaction. By analysing the approaches followed in our study, we also provide a critical reflection on their deployment, including a comparison. Finally, we discuss different uses and actors in different stages, tensions between research and dance creation, and potential applications. The main limitations of our study were a small corpus of body maps and an identified insufficient timeframe to adequately develop artistic ideas with the technology. The study is a first step toward interactive visualisations for dance based on body maps for dance performance, and further research is needed.

Designers can replicate our MLIV and CAIV approaches to interactive visuals from body maps by: 1) adopting a similar procedure to the one described in section Stage 1 Sketching Workshop, for collecting body maps; 2) following the system descriptions in section *Stage 2* Prototype development, modeled in figures 8.9) and 8.12, for creating animations and interactive visuals from those body maps; and 3) using our MLIV and CAIV software prototypes, released as open-source, or similar technical solutions.

9

Case Study III: Sound Feedback for Social Distance

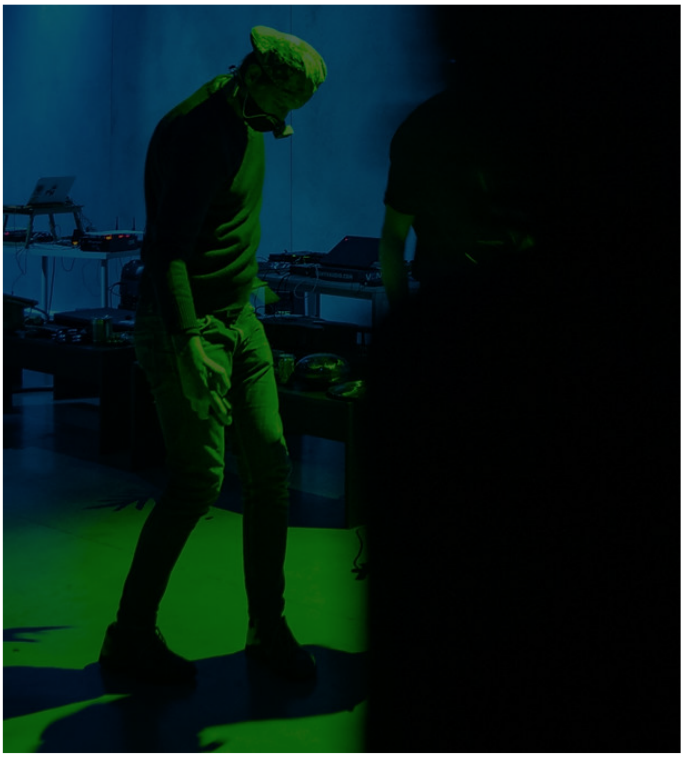

Figure 9.1: Performer with mask wearable sensor.

The following section will report on the journal article that was delivered at the concluding stages of doctorate programme, co-authored by the thesis supervisors:

W. Primett, H. P. Da Silva, and H. Gamboa. "Sound Feedback for Social Distance: The Case for Public Interventions during a Pandemic". en. In: *Electronics* 11.14 (July 2022), p. 2151. ISSN: 2079-9292. DOI: 10.3390/electronics11142151. URL: https://www.mdpi.com/2079-9292/11/14/2151 (visited on 07/14/2022)

The major research actions for this study were carried out over two separate investigation periods during the COVID-19 pandemic. The first being instigated in October

2019, hosted by Carpintarias de São Lázaro as part of the Residência Músicos De Rua (Music Buskers' Residency) programme [1]. The latter took place during November 2021 set in a public square, Largo da Achada in Mouraria, Lisbon where the interactive system was made freely accessible to passing members of the public. The public instalment was supported by the Câmara Municipal de Lisboa though the Eufonia Festival network for participatory sound art. We note that the latter installation, detailed in Section 9.5 was publicly disseminated as the *Anti-social Distancing Ensemble*, with additional information provided in the Appendix C.

9.1 Sound Feedback for Social Distance

The Coronavirus Disease 2019 (COVID-19) was affirmed as a pandemic by the World Health Organization (WHO) on 11 March 2020 [101] presenting numerous unforeseen novelties given that symptoms would range from severe to unrecognisable over an indeterminate timeline [466]. As the effects of the pandemic intensified on a global scale, central governments enforced new regulations that compromise public space interactions against the preceding normality. While the specific constraints varied between countries and eased accordingly over time, a key component throughout was to prohibit physical contact almost entirely where viable and to avoid close proximity with others [445, 449]. Simultaneously, the sudden ubiquity of protective face coverings has introduced a plethora of unanticipated complications regarding verbal and non-verbal expressions that are habitually relied upon to interpret emotional states [79, 188, 301].

In accordance with these measures, a vast majority of public events were jeopardised, particularly in the case of live performances and artistic installations. As pandemic regulations were gradually alleviated, however, public activities were re-authorised on the grounds that all participants complied with mask-wearing and distancing orders [386]. We foresaw a need to address the tensions surrounding safe social conduct as well as the risks of viral transmission newly associated with on-body sensor technologies [231, 403]. The physical space observed between bodies can be linked to various social cues during an interaction [255, 432, 455]. However, these inferences can deviate massively between individuals and therefore it is unintuitive to commit to a one-size-fits-all model that is wholly representative of all sorts of social contexts and cultural environments [422, 479].

We propose an intervention to challenge the conventional dualisms between physical distancing and social connectedness, based on sound and movement. This begins by reconstructing our approach to both sensor-based monitoring and the delivery of live performance, looking beyond the introspective experience, and considering affective processes that occur externally from the body. We then present a wearable system for sound–movement interaction centralised around interpersonal distance and collective movement. Following a series of ideation sessions, over a two-week period, the system

[1] https://www.carpintariasdesaolazaro.pt/residência-musicos-de-rua

was situated in a live performance setting from which we evaluate the performer's quality of movement in relation to the sound feedback. We describe some of the system's key influences contextualised in the socio-emotional domain, inducing entrainment, spontaneity and awareness. We formulate the following research questions: **RQ1** How can sound feedback improve collective awareness and sensibility to interpersonal distance? **RQ2** What movement patterns are influenced by external mediation materials? and **RQ3** What technological interventions are appropriate for proxemic interaction in public space?

Our work continues to extend the rich design space for collective sound environments with movement sensing. We outline our perspectives on mediating social interactions with regard to the proposed coupling of distance sensing with sound actuation. Following this, we acknowledge the vital limitations of our initial framework and put forward research opportunities that may arise from extended exploration. Namely, the incentive of transitioning into open public environments where participation can occur pervasively. Additionally, we document the necessary measures taken with respect to the restrictions put into force by the COVID-19 pandemic, the impact of which remains prevalent up until the time of writing. Howbeit, our findings should be interpreted as universally relevant toward orchestrating spatially aware interventions even in non-pandemic circumstances.

9.2 Background

Social Distancing and Public Presence

It is evident that regular social engagement plays an important role in community wellbeing. Not only bonding with our close companions in organised situations, but inclusive of unanticipated interactions that emerge in public [18, 413, 430]. Progressive urban space planners have taken this into account, and been considerate of the spatial arrangements that help to encourage spontaneous encounters [268, 314, 334]. The first wave of the COVID-19 pandemic elevated some attention to this. The course of existing outside of our own home meant weighing out the chances of a life-threatening infection against the consequences of avoiding social connection, endangering one's health in other ways [62, 137, 372, 487], that is, to even fathom an intuitive protocol under such agonising circumstances.

As emergency COVID-19 measures were becoming standardised globally, epidemiologists from the WHO firmly recommended a linguistic shift from *social* to *physical* distancing on the basis that modern technology is capable of keeping us connected in spite of the new regulations [374]. Given that the anticipation of the first wave would in essence reject in-person contact in the way it was known; this narrative was therefore appointed to the normalisation of fully remote communication. However, as society would phase in and out of non-confinement periods, conventional face-to-face interaction could take place again, persisting with the caution of physical distance, embracing *Social Proximity* as a safe practice for social wellbeing [285]. Irrespective of this major adaptation to safer re-socialisation, we argue that the development of in-person interventions has not matured to the same extent as remote interaction technologies and that there still lies a vast design space yet to be fulfilled.

Proxemic Behaviour and Re-socialisation

The attention toward interpersonal distance coincides with the study of proxemics, examining the function of physical space during face-to-face interactions [190, 196]. Proxemic theory has been given a lot of attention in a wide range of behavioural studies [307] and thus spurs incentives from several ubiquitous computing projects [298, 342]. A majority of these accept the proxemic zones set out by Hall [196], by which interpersonal distances are generally categorised into the following boundaries: *Intimate*, up to 1.5 feet (0.45 m); *Personal*, 1.5 to 4 feet (1.2 m); *Social*, 4 to 12 feet (3.6 m); and *Public*, more than 12 feet (7.6 m). We believe, however, that the rich contextual nature of interpersonal movement behaviour poses a challenge for conventional computational modelling, calling for expertise to break down and articulate expressive features of human motion and sensation [142, 393]. With regard to proxemics, we cannot solely depend upon the measure of distances and angles to define the affective characteristics that occur during any given exchange.

Coping with the current risks of infection in everyday social contact, the *new sociable space* implies a new urban etiquette that expands upon the standardised dimensions proposed by Hall's proxemic theory, preserving conversational affordances at double the distance [315]. In a general sense, spontaneous, informal encounters are recognised as an essential part of growing one's social circle, fostering a sense of belongingness within the community [475]. However, the circumstances in which these are likely to occur are vulnerable to the spatial dynamics and physical distance between bodies [35, 140]. These types of relationships fit into the social formation of indirect contact, which can take place seamlessly by way of intergroup behaviour, alleviating the pressures of face-to-face enactment [464] that are increasingly present in the midst of pandemic concerns [128]. While, of course, many will long to reconnect with their peers during moments of close physical bonding, these new sociable spaces provide an enlightening deconstruction of proxemic acceptability where strangers and non-strangers are both welcomed into everyday social encounters. The linguistic connotation of 'distancing' assumes active separation from others, while its function should instead be geared towards social affirmation, organised in a safe manner. We propose an interactional view on social distancing that is unconditional to definitive measurements, advancing upon the outlooks contained in the following study [23] that insists on expanding Hall's discrete interpretation of proxemic zones when applied to continuous mappings of movement.

The orchestration presented in this case chapter is set out to capture the affective outcomes when proxemic behaviours are exaggerated during social exchange, where sensory intervention goes beyond being an assessment tool, but a modality for non-verbal expression.

Sensor Technology and The Right to the City

When considering proxemic behaviours in public, urban pedestrian areas have long exemplified the effectiveness of street-installed technology to manage the mobility of crowds; however, the vital function is vulnerable to being overthrown in the case of high-intensity overcrowding [173, 293], which has been associated with feelings of anxiety, frustration and claustrophobia [248]. Certain demographics are more sensitive, while others are far less cautious of invading the personal space of others [340, 365]. With respect to interpersonal distance, initiatives in response to pandemic conditions rely upon a level of altruistic responsibility, by which the public are inclined to follow a protective etiquette [209]. When taking a look at the technologies that have become ubiquitous in response to the pandemic: Contact Tracing Applications, Skin Temperature Scanners, and contactless patient monitoring, for example [313, 438], we note that the user is constrained to one interpretation of the data made available to them. When contrasted with alternative interventions that explore emotional bonding in urban environments, e.g., [5, 167], we begin to question the limitations of the prior, and subsequently, practices that exist at the intersection of social affirmation and long-lasting public health. Building upon the insights presented by Howell [217], calling for a progressive turn in public space sensing technologies [217], we insist that the data-driven motives pushed onto current smart city development schemes are non-compliant with these sorts of shared emotional experiences [30, 68, 267].

The long-standing notion known as “the right to the city” has been embraced by Interaction Design researchers, commentating on the industrialised approach that we are seeing with sensor technology that is being increasingly embedded into urban spaces, shifting the perspective from data-driven smart cities to “social” or “playful cities” [85, 217]. Such case studies express a necessity for inclusive participation to establish grounds for progressive social integration, framed as the collective right to be in control of the surroundings through co-creation. Acting upon the current situation, we enquire into a sensory intervention that aids awareness of one’s physical presence and self-affirmed boundaries, without the need to declare any action as right or wrong.

Appropriation of Social Distance and Interpersonal Touch

The urgent nature of the pandemic demanded disruption to common interactional norms, namely the concern of keeping distance and avoiding touch [245, 285]. However, despite a reactionary appeal for spatially-aware behaviours, this call for action has been relevant for a while now. There exist several rationals for designing systems that are considerate of one’s personal space, which in our view, have been neglected by relevant research areas.

For many, the apprehension of close contact in urban space serves as an evaluation criterion for everyday safety [139, 340]. A preference for greater interpersonal distances is also evident for those suffering from anxiety disorders, commonly assumed to an avoidance of social interactions entirely [180]. Intersecting this view with the subjective quality of skin-to-skin contact, praised by a substantial volume of research for inciting profound therapeutic sensations [100], presented as an appealing method to relieve anxiety, strengthen social bonds, and even elicit physical health benefits [122, 149, 344]. However, this is not always the case if we take into account, for instance, those who experience hypersensitivity (or lack of) to introspective stimuli [44, 415]. Furthermore, the perceived benefits associated with affective touch are largely subject to the qualities of the pre-existing relationship of the dyad [191].

Drawing parallels between inclusive proxemic interventions and safe re-socialisation [285], we want to understand the liberties that can emerge from contact-less mediation while protecting the right to physical presence. Therefore, it is important to depart from the assumption that everybody is entirely comfortable with close contact, and understand that the degree of comfort largely depends upon who is approaching them and in what context [261, 434]. In Section 9.5, we discuss the importance of flexible boundaries when designing for interpersonal distance, conditional to the social context at hand and the proxemic sensitives of the individual.

Non-verbal Contingencies and Face Coverings

Proxemic interactions, given the alliance with mutual gaze, would assume the inclusion of facial expressions, where conventionally, more salient emotional attributes are depicted between the nose and the chin [46, 151]. The visibility of facial expressions and clarity of speech is both highly relied upon in everyday communication, but the regulated use of the face mask disregards this modality almost entirely [79]. This becomes even more crucial in the context of physical distancing regimes [75], where proxemic studies report a habitual reduction of eye contact when spaced more than twelve feet (3.6 m) apart, i.e., public distance [22]. Additionally, studies related to pandemic behaviour have demonstrated how face masks influence interpersonal distances [82]. Our facial muscles can expose a great deal of how we are feeling [355, 443], sometimes completely unknowingly to the extent that one may exert themselves into forcibly concealing these expressions while under pressure [40]. In comparison, how we move in space is normally a consequence of deliberate coordination during an interaction [233, 349]. Hadley and Ward [194] point close attention to the physical gestures used as a substitute for verbal exchange where background noises impair vocal comprehension [194]. The normalisation of face masks worn during conversation has been shown to degrade the acoustic quality of the voice as a result of suppressing higher frequency ranges, commonly depended upon to recognise articulations of consonant sounds [331, 358, 388]. This poses a further disadvantage to those hard of hearing [309] as well as non-native speakers, often more dependent on reading the face [223, 226].

In Section 9.3, we outline our fabrication methods, taking the newly ubiquitous face mask, commonly condemned as a social hindrance and reshaping this as sensory material for non-verbal exchange, isolating communication channels aside from the face.

Measuring Interpersonal Movement

Aside from interpersonal distance, we are also interested in movement qualities that can characterise aspects of a social situation. Such qualities are recognised by Rudolf Laban's Movement Analysis (LMA), a well-established notation framework used to depict expressive features of human movement, originating from the perspective of dance and physical therapy [260], and since adapted to all kinds of contexts (e.g., routines of factory workers) [107]. With ongoing advancements toward body-centred applications, Laban's theory on movement has firmly settled itself into Human–Computer Interaction research [485].

It is apparent here that the intersections of HCI and Laban Movement principles tend to focus on individual accounts. Pluralist qualities, on the other hand, comprised of two or more persons moving together, are observed as the *Relationship* category. The following article from Roudposhti et al. affirms a scarcity of literature in this domain [379], expressing the unexplored potential for social interactive systems. The authors propose a global feature space that combines Pentland's analysis model of social signals [341] with LMA qualities, taking upon the following descriptors: *Indicator*, *Empathy*, *Interest* and *Emphasis*. In Section 9.5, we borrow two of these qualities in our evaluation, *Indicator* to describe the exchange between influent and influenced members, presumed by the difference in energy between them, and *Interest* representing one's engagement to the situation or outside context, gauged by energetic movements. Similarly to Laban's Movement Analysis, each quality operates on a continuous scale between two polarities.

Sound Interaction as Social Mediation

Throughout the extensive literature surrounding proxemic interfaces, we came across a surprising lack of studies related to sound, given this is already an established modality for movement interaction with ties to affective representation [265], supported by a base understanding that physical action and sound perception are mutually responsive [256]. As a tentative presumption, we can point to the inherent limitations of distance detection with typical camera-based tracking technologies [470] as well as the obtrusiveness of on-body sensor devices [205]. An affirming study that fits into this criteria installs a proxemic augmentation into a gallery space [363], supporting the role of proxemic audio interactions in a *"post-screen world"* [66]. Our preliminary survey of sensor actuation couplings (see Section 5) demonstrates the usefulness of audio-based biofeedback as a way to foster physiological synchronisation and somatic awareness, noting that the human hearing system is highly sensitive and that sound is a convenient medium to share amongst many users. Further, recent literature suggests that synchronous motor activity can be indicative of prosocial affiliation [194], particularly when contextualised with sound, be it disruptive or complimentary [419].

Within the context of music performance, the concept of a collaborative system is not a novel phenomenon, far from it in fact. Reports date back as far as 1978 [43] with progressions to real-time remote interaction [26], later supporting the establishment and maturity of interactive music systems (IMSs), e.g., [160, 234]. A recent review from Aly et al. discusses the pervasive nature of sound interactions in the context of biosignal-driven IMSs when capturing data from many users simultaneously [16]. Giving attention to collective movement, Hege presents an artefact by which the members of the Princeton Laptop Orchestra showcase democratic expertise through intentional yet delicate control of the sound output [203]. IRCAM researchers advocate for a human-centred framework for gestural sound control in a group scenario [397], not only for performance but also justified in clinical use-cases [39].

Moving away from the audience–performer dynamic, related case studies demonstrate how social encounters can be mediated through embodied sensor data [19, 217, 376]. We would like to further investigate this approach to engage multiple users simultaneously, in this instance, representing an assembly of interpersonal distances through sound.

9.3 Materials and Method

Composition of a Wearable Sensing Medium

We decided to design a wearable sensing medium centred around the face mask. These were a mandatory possession for local citizens that had already become a cultural norm for one's public appearance [86]. Our pursuit towards an on-body device was supported by Montanari et al.'s investigation into a novel proxemic sensor, welcoming a sacrifice in the high-level attributes that come with camera-based tracking in preference of environmental flexibility, quoting the affordance *"to collect data even in areas that cannot be instrumented, like public spaces or during large events"* [318]. We consider the worthwhile benefits of a wearable solution that is more versatile in non-laboratory situations [195, 197, 419]. In essence, this bypasses the challenges articulated by Jürgens et al. directed towards using an unobtrusive markerless motion capture technology in an on-stage environment for contemporary dance performance [239]. The authors highlight digital errors inflicted by particular lighting conditions, clothing contrast, as well as scenarios where performers were in close proximity to each other. For our study, we were incentivised to capture the point of view of the user, aligning the sensing trajectory with the user's gaze during an interaction, as detailed in the following sections.

Overview of Components

We have interfaced low-cost HC-SR04 ultrasonic distance sensors with the BITalino R-IoT microcontroller using a modified firmware (included in the Appendix A); this allows the acquisition of proxemic data from multiple participants at 10 samples per second. When initiated, each module streams data wirelessly over a designated local Wi-Fi network to a host computer, which is then responsible for signal processing and sonification. With this sampling rate, the maximum response time is accepted as 100 milliseconds (ms) plus any wireless latency, averaging at 10–11 ms in such conditions (benchmarks are reported in Section 4.2). This sensing technology is highly prevalent in robotics and IoT educational fields, typically used as part of introductory curricula [165, 206] while sustaining relevance in the state of the art (e.g., [130, 472]). Fundamentally, the sensor measures the distance from the first physical interference at a given direction by transmitting and receiving ultrasonic frequencies outside of the human hearing range [337]. The range and accuracy benchmarks for the ultrasonic sensors are partially dependent on environmental variables such as ambient temperature and humidity. When working in typical indoor conditions, the ultrasonic sensors are expected to ensure a stable accuracy of up to 13 feet (4 m), within a 15 degree angle [3].

With respect to providing a wearable form factor, and minimising the size and weight of the components, we implemented a discrete voltage divider onto the sensor's Ground and Echo pins to comply with the power specifications commonly found in smaller microcontrollers, usually rated at 3.3 Volt. With this configuration, there was a minor but notable drop in accuracy compared to our tests using 5-Volt compatible microcontrollers. However, this was mostly resolved with signal processing to the extent that the effects would not hinder the overall sound-based mediation experience. Following technical directions from Kielas-Jensen [295], we were able to incorporate data from the R-IoTs embedded temperature sensor into the distance acquisition function, this improved the reliability and consistency of the readings when transitioning between distinct environmental conditions. For example, a computer lab, open exhibition space, performance theatre holding maximum occupancy, or even installed in an open outdoor area.

Material Design and Fabrication

In order to publicly distribute the sensory masks in a safe manner, respecting the government guidelines, we assigned the following design principles: (1) The sensory components are modular and detachable, allowing for sanitation while the mask fabric is being replaced; (2) These components must remain at a fixed position and be robust in situations of rapid movement; and (3) The mask should feel sufficiently comfortable for users to wear for prolonged periods of time. Additionally, for the system to accommodate mass participation, we favoured a scalable solution that was low-cost and easily reproducible (4). For each wearable, we modelled two separate housing elements for the respective components, i.e., the microcontroller and the proximity sensor. The 3D models are included in Appendix A)

For the sensing mechanism, the ultrasonic sensor casing was merged with an arched nose clip and secured onto the mask fabric. The microcontroller and battery were encased

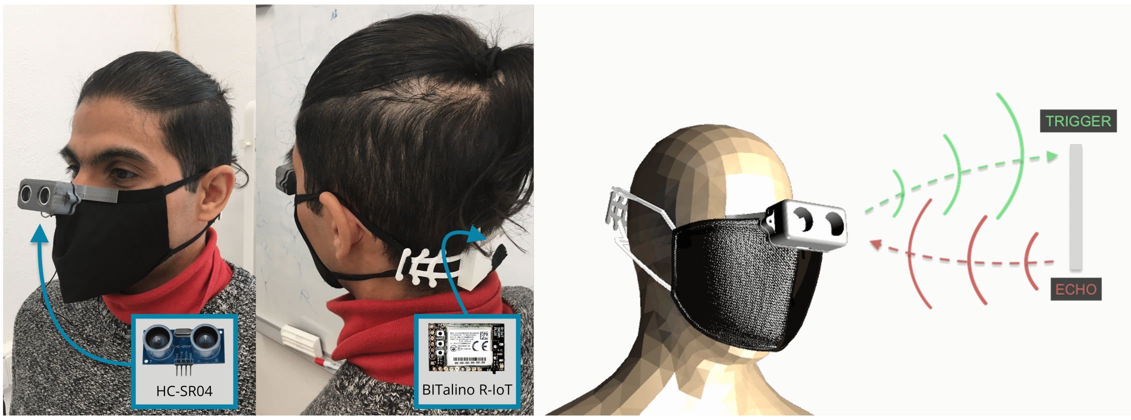

Figure 9.2: Proximity sensor enclosure fitted onto the face mask with trigger (output) and echo (receiver) signals.

in a custom mask strap that would be tied around the back of the head. The components are connected via a flexible cable, splitting into four wires each connecting to the corresponding inputs of the sensor and microcontroller, transmitting analogue signals back-and-forth to retrieve proximity data, represented as trigger and echo in Figure 9.2. These are assembled by positioning the sensor component above the nasal dorsal, resting front-most of the face, in line with the gaze with minimal obstruction. To overcome the precariousness of the sensors dropping down from the nose during movement, we increased the tension of the elastic ear straps and fastened a flexible rod between the mask fabric and sensor attachment. While this modification improved the structural reliability, our capacity to freely substitute sensory modules, along with spontaneous user alterations was limited as a consequence.

Data Processing and Sound Mapping Strategies

The orchestration does not require participants to conform to a fixed minimum distance. We lend our trust to the users to coordinate themselves in a safe manner without explicit orders, as it is expected in their daily life. Prompted by our first research question, **RQ1**, the sound interaction is purposed to strengthen one's awareness of the other's presence, unbounded from discrete categorisation, engaging one's auditory senses while verbal modalities are restricted. In addition to this, the experience should not call for virtuosity or a specialist training process. The system assumes engagement from the moment the user is being sensed and become progressively accustomed to the sound–movement affordances. This aligns with the presumption that the participants are expected to work together to develop their understanding of the system and stay vigilant to each other's actions.

During these first trials, we used granular synthesis [2] to interpolate between 4 field

[2] Grain Scanner by Amazing Noises: https://www.ableton.com/en/packs/grreciprocateain-scanner-amazing-noises/

recordings as base sound textures. Inspired by Laban's qualities of space and relationship, we proposed a transition between "open" to "closed" sound textures, continuously modulated in real-time as the average distance reaches the minimum sensing boundaries of 4 feet (1.2 m), before succeeding social distance. This process starts with a lot of fluctuations in timbre and then closes in on a limited range of frequencies that form into a staccato rhythmic feel. A one minute sound sample is visualised in Figure 9.3.

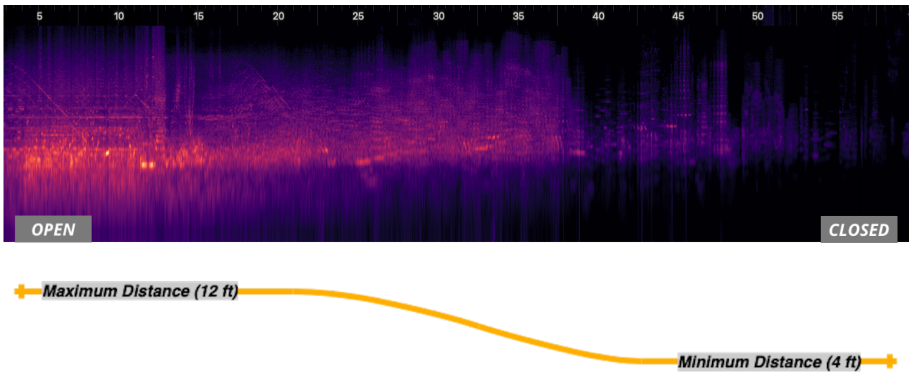

Figure 9.3: Spectrogram sample of interactive soundscape showing "open" to "closed" transition.

Combining Sensor Data from Multiple Users

The essence of proxemics implies the use of multimodal information. Our system does not take an explicit measure of orientation, however, we can combine the relative proxemic data from all the sensors in order to distinguish when two or more users are facing towards one another, and register this as periods of mutual gaze. This pluralist gesture reveals a lot about the situation. Generally, we may discern moments of intentional exchange and affirmation, whether that in a comforting or confrontational manner. Of course, this data does not reveal the entire social context by any means, but in contrast to one user staring at the back of the back of another, given the same radial distance, implies a totally different dynamic. In our system, the sonic representations are designed to emphasise periods of interpersonal gaze. This is detected when the pulse signal from two or more sensors start interfering with one another.

Performance Structure

The system's initial deployment exposed a significant level of confusion from new users when given the chance to freely experiment with the device. Aside from the technical ideation, we speculated upon ways of stimulating movement whilst sustaining an appropriate degree of improvisational freedom. This reiterates that we were not interested in forcing a strict sequence of movement, but rather providing geometrically informed cues set out to prompt dyadic gestures. We devised three scenes that each focus on distinct

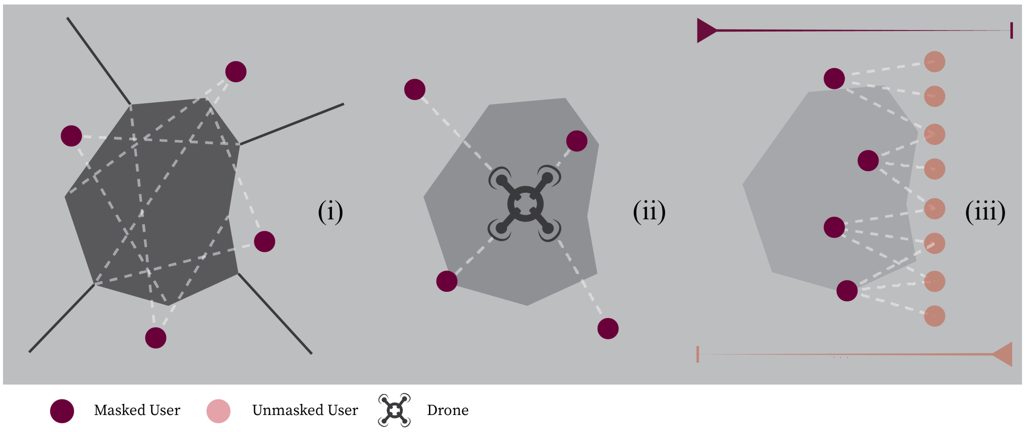

Figure 9.4: Visual representations for each scene. From left to right: (i) Geometric boundaries and interceptions, (ii) Interacting with the non-human, (iii) Participation from external users.

affordances of proxemic mediation, as illustrated in Figure 9.4 and presented in the following order:

The group was made aware of the performance structure and interactive elements described in Section 9.3, while granted the freedom to explore the space and move intuitively to the sound feedback, whilst maintaining a minimum interpersonal distance of 5 feet (1.5 m). For these actions, a 225 m^2 performance area was used accompanied by two concert-grade loudspeakers.

Performers and Objects

These geometric arrangements are predominantly inspired by William Forsythe's architectural approach to choreographic environments [155], a radical staple in contemporary dance culture, bridging deeply into other artistic mediums [92].

Giving attention to our second research question, **RQ2**, the following passage redirects the proxemic attention from the neighbouring bodies, onto the surroundings (Figure 9.4(ii)), supported by Kinns's recommendations for mutual engagement with shared representations [67]. In the extended proxemic criteria presented by [23], the relationship to other objects, both digital and non-digital, is embraced. Adopting theories of gaze-based interaction into the format of proxemic awareness, authors claim to enrich the user's attention to the space by attending to implicit responses from the user's surroundings.

Autonomous flying drones have been incorporated into a stage performance [136] and movement-centred practices [259] proceeding efforts to enhance kinesthetic awareness through intercorporeal engagement [442]. During Scene ii, the drone represents more generally an unpredictable external influence, comparable to the external nuances that occur in public space environments.

In relation to this, Ballendat's evaluation of screen-based proxemic interactions considers the attention directed to other people, allowing for conventional social exchange to coexist alongside the technological artefact itself, accepting natural influences that would arise in coherence with an everyday social situation [23].

Scene i) Geometric Boundaries and Interceptions To begin, the performers position themselves around the boundaries of the performance area, facing the centre (Figure 9.4(i)), standing 18 feet (5 m) apart. The first sounds are activated as users cross to the opposite side, alternating back and forth until coinciding with the linear path of one another, after which an anticipated diversion is required. One participant offers the following interpretation: *"The soundscape intensifies as the collective tightens in space. Before collision, we have to figure out our next steps, to dodge, retrace or simply pause for a moment"*. Our improvisational framework here is designed to inspire proxemic exchange, while the primary responsibility of avoiding near-contact is handed over to the performers.

Scene ii) Interacting with the Non-Human A technician is assigned the role of navigating the stage with a flying drone, weaving between the masked performers. When advancing towards the bodies on stage, specifically targeting the sensory components, the drone serves as an external trigger as it reaches close enough to the face. As a result, this synthetic artefact would provoke instantaneous reflex responses from the performers that consequentially would instigate dynamic changes in the soundscape.

Scene iii) Participation from External Users Finally, we invite external users that are not individually equipped with any wearable sensors but are authorised to manipulate the behaviour of the mask-wearing user group. Nine additional participants were instructed to approach the mask-wearing group, directing them to move back until reaching the end of the stage. The two collectives both march between the right and left extremities of the stage, constantly maintaining a mutual gaze and a forward distance of approximately 6 to 10 feet (1.8 to 3.0 m) from the closest person opposite (Figure 9.4(iii)).

Study Outline

Our study derives from the experimental framework of Performance-Led Research in the Wild [33]. This compromise relieves some of the social confines imposed in a lab setting while bypassing the highly unpredictable nature that comes with arbitrary participation [207]. In this current research action, we set up an open call, as a result of which 12 local artists were chosen to take part in a 2-week residency that would conclude with a public performance. This was structured to build upon compositional practices that were stimulated by a series of performance and improvisation workshops that took place 3 weeks prior. From the residency group, 4 participants were selected to use the wearable during the final performance, presenting the three scenes described above, which lasted just over 8 minutes in total. We recorded video and sensor data throughout each scene in order to evaluate the qualities of interaction. From this sub-group, 3 identified as male and 1 female with ages between 24 and 51 years old. All 4 held long-term experience as highly-skilled musicians, performing internationally and retaining regular musical practice. An additional 4 participants, 50:50 split male and female, trialled primitive iterations of the system during the prior rehearsal stages, from which we produced field notes and recorded user feedback. Aside from a handful of local encounters, the user group was considered strangers amongst one another, not closely bonded and only acquainted during the preparation stages.

The first study took place in Lisbon, Portugal between October and December 2020, before the national vaccination rollouts were initiated. Cultural activities, such as live performances, were permitted in accordance with the measures set out by local authorities [386]. In the scope of COVID-19 distancing measures, the user groups were respected as a support bubble throughout the research period, assuring that in-person interaction was permitted under the same conditions as those they share a home [446]. With that said, at no point would the sessions explicitly require a disruption to the standardised safety regimes, particularly those concerning close contact and sanitation of shared materials to minimise viral transmission.

9.4 Preliminary Results

Here, we summarise the perspectives of the individual participants and indicate moments where the first-person accounts are complemented by the acceleration data. We apply statistical analysis to the collective sensor pool to discern group-level features, later used to substantiate relevant design guidelines for proxemic intervention strategies. We acknowledge the analytic restraints when subjected to a single recording from an individual user group that by no means should be taken as a comprehensive survey of the proxemic orchestration. This provisional study is purposed to demonstrate novel adaptations for proxemic interaction and prescribe design insights for future work.

Data Collection

Throughout a 2-week prototyping period, we recorded participant observations and first-person experiences, based upon the user-centred design actions proposed by Bernardo et al. [37]. This was comprised of eight day-long rehearsal sessions that each allowed one hour focused on exploring the wearable followed by a brief interview with participants, asking about any limitations that were discovered and features of the interaction that influenced their behaviour. These sessions took place alongside a course of improvisation exercises fitted towards musical performance. After the study, we extract comments from a series of recordings and field notes. Participants were made aware that they were taking part in a study set out to evaluate the general usability of the wearable device and sound feedback mapping.

We recorded video and audio of the final performance and rehearsals using a single-point microphone and camera. The video clips were colour graded to obtain a clearer view, especially when there was a lack of ambient light being projected onto the stage. When probing deeper into a handful of significant events depicted by our written assessment, we extract still frames from the recordings and overlay these with graphical annotations to comment on the positional qualities present. Audio was processed through Sonic Visualiser[3] for feature extraction. The sensory masks were embedded with an accelerometer sensing component located at the back of the head, recording three axes of directional acceleration from each user. The triaxial sensor data are unified by computing the Signal Vector Magnitude (SVM), representative of the combined acceleration coordinates x, y and z, as validated by Ward et al.'s proposed method for monitoring synchronous motor behaviour within a group of live performers [461]. Each accelerometer was recorded at 10 samples per second (s), with the data being synchronised and smoothed in post-processing.

When probing deeper into a handful of significant events depicted by our written assessment, we extract still frames from the recordings and overlay these with graphical annotations used to commentate on the positional qualities present. In Figure 9.5, we present the median average magnitude acceleration measured from the four users to represent the collective movement, indicated by a series of peaks throughout the three scenes. The median acceleration timeline (top) serves as a guide to navigate the general progression of movement qualities presented throughout the performance, while separating the data stream for each individual user (middle), and assessing the alignment of the peaks, provides a numerical evaluation of interpersonal responsiveness or absence of. Finally, the peak acceleration points are partitioned according to a series of successive bursts over time (bottom), detected using a k-means clustering algorithm. The clusters help us to convey the collective movement dynamics and relationship qualities that are observed throughout each scene, partly revealed in the average duration and amplitude of the clusters.

We formulate the following clustering features: Peak Density, the total number of peaks detected relative to the duration of the cluster, and User Effort Dissimilarity, based on an equal alteration of active users.

$$\text{Let } C(x) = \sum_{i=1}^{n} [s_i = x]$$

$$\begin{array}{c}\text{User Effort}\\ \text{Dissimilarity}\end{array} = \sum_{i=1}^{n} \left(\frac{s_i}{C(x)} - \frac{1}{n}\right) \cdot 100. \tag{9.1}$$

The User Effort Dissimilarity is calculated according to the proportion of peaks exerted by each individual user, where *C(x)* represents the total number of acceleration peaks, s_i being those exerted by each individual user.

[3]Sonic Visualiser: https://www.sonicvisualiser.org/doc/reference/4.4/en/

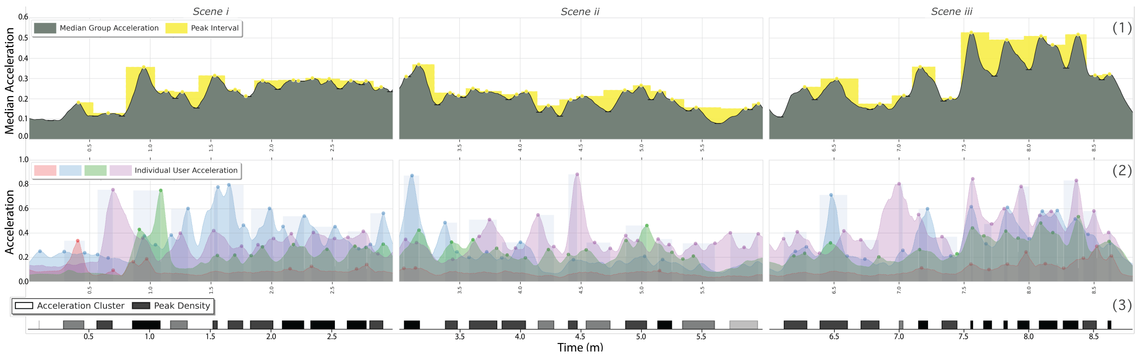

Figure 9.5: Acceleration data recorded from scenes i–iii: the top row displays group median averages (1), with individual user data shown below (2). The final row aligns the peak cluster periods detected along the x-axis (3). A high-resolution version of the image is available in Appendix A.

Interpersonal Synchrony

During Scene iii, we observed participants engaging more confidently before and after the sound mapping is disrupted by the unmasked participants. In these moments, the mask-wearing group march in parallel alignment, maintaining a consistent pace with each other. Additionally, we note the persistent use of eye contact towards the unmasked group, voiding obstruction until reaching the end of the stage. As the procedural soundscape is overridden by the choral chants voiced by the unmasked performers, we see the groups disperse in the opposite direction, subverting the momentum and common alignment. This interplay repeats itself 4 times, where the two sub-groups voluntarily hand over the leading role of the march, alternating every 6–10 s. In Figure 9.6, four masked performers walk towards and away from a group of those without wearable sensors whilst maintaining a forward distance. For these frames, the annotator was tasked to visually mark the alignment and walking direction of the mask-wearing group.

Figure 9.6: Annotations from Scene *iii* rehearsal video. Four masked performers walk towards and away from a group of those without wearable sensors whilst maintaining a forward distance. The arrows show the walking direction with a dashed line to trace the dispersion of mask wearing group. A video recording is included in Appendix A

We compare the synchronous activity of each scene based on the separation of the clustered peaks. From this measure, we determine that the most consistent levels of synchronous movement take place during Scene iii, with far fewer occurrences during Scene ii. Both scenes have a similar number of peaks per cluster (Table 9.1), with a greater density of peaks in Scene iii; this is shown by the constrained duration of the clusters formulated in more consistent intervals. This perception is reassured by the increased amplitude of acceleration values throughout, perceived as an intentional syncopation of movements that are highly responsive to one another, and agreeable to the feedback given by one of the users.

> *"we had only a short moment to be respond, similar to a call-and-response situation you sometimes see in concerts. The motivation was no longer about controlling the timbre (of the sound), but just to assert dramatic impulses before the others take the lead."*

Scene	Mean Peak Interval (s)	SD Peak Interval (s)	Median Peak Amplitude (g)
i	**183.7**	**149.9**	0.31
ii	182.1	141.4	0.29
iii	155.8	138.2	**0.36**

	User Effort Dissimilarity (%)	Alternating User Peaks (%)	Mean Cluster Concentration (Peaks/Cluster)	Mean Cluster Duration (s)
i	25.5	90.2	**4.5**	8.9
ii	**44.7**	78.7	3.8	**10.0**
iii	17.2	**96.6**	4.1	5.6

Table 9.1: Peak and cluster statistics from each scene, calculated from the individual user acceleration data that correspond to rows (2) and (3) in Figure 9.5.

Our observations and data taken from this final arrangement indicate vastly different group behaviours from before. We would suggest that the major influence lies behind the "call-and-response"routines as the opposing bodies assert themselves into the space, inducing a series of structured interruptions that we probe deeper into in the Discussion, Section 9.5. We will not neglect here that these behaviours were inherently dramatised under theatrical persuasion, but, nonetheless, insist that the core reactions are authentic to the invasive confrontation as the opposing bodies assert themselves into the space.

Spontaneous and Sustained Engagement

Given the premise that regular social engagement is an effective precursor to community wellbeing, generating and sustaining interactions are both considered to play a key role in urban design practices [268, 314, 334]. We question how sensor-based mediation can be used to not only provoke, but actually extend the longevity and quality of a new encounter, described as, *"what makes the experience comfortable, interesting, and meaningful"* [314]. In this case study, we gauge spontaneous engagement from the rotation of users asserting themselves as a leading influence (i.e. a new person exerting an acceleration peak), and how peaks are partitioned between individual users. Sustained interactions are more nuanced, recognised as lingering behaviours that take place amidst the succession of new movements, for which we draw upon the user's control over the sound output.

Responding to our research question **RQ2**, we enquire into the user's relationship with the external mediation materials, and the way these momentarily interfere with the continuity of the sound output in scenes ii and iii, separating these external influences by their level of predictability. In Figure 9.7, we recognise a major disparity in the arrangement of the non-structured interruptions incited by the flying drone compared to those anticipated by the unmasked group (i.e. structured interruptions). The unpredictable manoeuvres imposed by the flying drone disrupt the course of sustained dyadic gestures, from which we dissect the rapid, unplanned interchange of users controlling the sound output. Referring back to Figure 9.5, this parallels with sporadic changes in peak intervals, with individual exertions coming at arbitrary intervals. Scene iii, on the other hand, the course of sonic deviations better emphasises a uniform sequence of interruptions. This repeatable turn in controllability infers an attentive reciprocation with the other users, showing an advancement from sporadic reflex actions to meaningful group gestures, also granted by steadier peak intervals and the overall progression of synchronous movement that's detailed in the subsection above. One participant describes an impulsive reaction while being approached by the flying drone, suggesting its non-human form carries a provocation for spontaneous engagement:

> *"the drone would keep coming closer, like I was being chosen out of the crowd, so I would start following. I was comfortable with running towards the wall or even a flying object, but into somebody else, it's not the same. Even if we do not get so close, I feel like I am threatening someone or just being a nuisance."*

This correspondence is not so apparent in the acceleration data, where we actually notice a drop in energy regarding the lower mean cluster density and substantial user effort dissimilarity, supposing an imbalance of individuals dominating the space. Though, we may testify that the shared positional influence of the drone on stage engaged all users in the shared space, even when at a standstill.

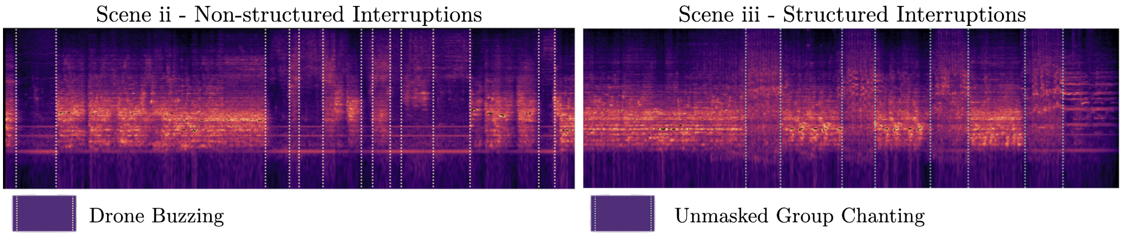

Figure 9.7: Spectrogram recording from two scenes, *ii* and *iii*, marked with interruptions of the granular soundscape.

Technical Venerability against Proxemic Awareness

In hindsight, the placement of the sensors of the face, constantly shifting their projected angles meant that misreadings were highly probable. When tested in lab conditions, these proximity sensors are expected to perform reliably at differing trajectories [3], but when we inspect the sound recording and video footage, we observed many cases of unexpected readings during the performances in contrast to the testing phase. Participants would move closer together with no perceivable feedback. Moreover, the detectability of the ultrasonic reflections was highly dependent on the material of the occlusion. Figure 9.2 provides a set of sample signals recorded when approaching the sensor using three different surfaces. These were recorded separately in controlled conditions. The ceramic tile provided the greatest detection range, while the clothing material resulted in more noise and vulnerability to drop-outs. Though our signal filtering methods helped remove extreme anomalies, there would still be a great deal of inaccurate measurements being fed into the system. For these reasons and more, this particular sensor technology has been discouraged for measuring interpersonal distance in a review of wearable devices for proxemic interaction, which exposes multiple scenarios by which ultrasonic sensing was proven to be partly inadequate [318].

Fdili Alaou writes about the perceived messiness that inevitably comes with adopting personal tracking devices into performance-based practice (noise, sensor placement, classification failure) [141]. However, instead of seeing these as issues that need to be resolved, actually encourages artists to embrace the technical nuances, turning technology resistance into creative material. It is important to appreciate that, in non-lab conditions, imperfections will constantly prevail and, therefore, we should welcome and validate the experiences that come with each iteration. In spite of such cases where the sound–movement relationship was not sensible to the performer or even the audience, as revealed repeatedly during the user studies, we contend that there remained a genuine influence from the physical artefact alone. Throughout the study, users demonstrated a strong awareness of their surroundings to control the sounds, recognise technical faults and overcome them through persistent trial and error.

Material	Minimum Detection Range	Maximum Detection Range	Dropout Rate
Ceramic Tile	5.1cm	288.7 cm	0.0%
Skin	10.2cm	246.4cm	3.85%
Clothing Fabric	25.4cm	201.8cm	4.55%

Table 9.2: Comparison of reflected materials from benchmark test recordings. From left to right: ceramic tile, skin from the hand, torso covered by clothing

9.5 Preparing for Public Space

New Sociable Space

Modern communication technology has been shown to facilitate rich social engagements in a remote setting, by which some degree of face-to-face affairs continue to be viewed redundant, even after confinement measures have subsided [97]. We, therefore, propose that solutions should also exist to support meaningful discourse from an extendable distance that is suitable for the social environment and individuals involved. Taking sound feedback as the core of proxemic mediation, we adopt Mehta's *new sociable space* concept into our design considerations, this being the capability to capture and hold one's attention from a comfortable distance, encouraging spontaneous encounters with non-acquaintances before confrontation into personal space [315]. Inviting flexibility to traditional proxemic theory, we can call upon Roudposhti's behavioural model that was introduced in Section 9.2, demonstrating mannerisms of Indicator and Interest. While this desirable social dynamic is provisional to a wide spread of design implications, we put forth the benefit of authorising drop-in and drop-out participation, whereby the formation of a group can be altered at any point to openly accommodate new users. Additionally, this functionality insists upon an agreed focal point of interest that establishes a proxemic cornerstone regardless of the group's composition, continually subject to change. We find this inclusive control structure to be very much customary in the context of interactive installations, such that the initiation of the sound feedback invites new unsuspecting members to engage before even being aware of the artefact's existence [184, 378]. In our performance-led study, we were enlightened through the inclusion of foreign mediation artefacts, acting as a vital component for exposing new dynamics of the sound, shown less prominently when the mask-wearing group were isolated from the external surroundings in Scene i. This draws upon the gestural limitations while adhering to a minimum interpersonal distance of 4 feet (1.2 m), absent from any positional cues to prompt collective engagement.

Proxemic Sensibility & Sensitivity

Section 9.2 of this chapter is comprised of studies that support the vital function that routine social interactions have on public spaces and the proceeding benefits that come with this. We also bear in mind the negative view that undesired social isolation can be detrimental to one's mental condition [137, 325, 487]. The pandemic forced prolonged periods of isolation that would ultimately cause a rise in self-reported loneliness [156], reported to be particularly harmful for those who already experienced anxiety prior to the pandemic period [62, 277]. Such conditions have been shown to suppress one's tolerance for engagement within intimate proxemic boundaries [270]. We can also include recent findings related to isolation and cognitive function, locating harmful effects on the brain region associated with spatial orientation, learning and memory [371, 372], which presumably foreshadows a long-term disassociation with in-person social situations. A critical motivation behind our work is to examine what interventions open up a safe intermediate to re-socialisation for individuals who do not yet feel comfortable exposing themselves in public [290], understanding that each person will hold their own preference for personal space.

Moving away from a standardised proxemic model, we form an empathetic view around personal space, appreciative of boundaries that are unfixed and individualistic in light of one's past experiences and various other factors that are undisclosed between strangers. Reinforcing Pentland's descriptors assigned previously, this derives from the sentiments that embody Empathy and Interest. Addressing **RQ1**, we articulate the call for proactive awareness as part of the following design considerations with regard to sensory intervention, *Proxemic Sensibility* and *Sensitivity*. Sensibility is the altruistic responsibility that ensures safe coordination of bodies, mindful of the surroundings and presence of any individual, paired with Sensitivity, for those to stay receptive to the actions projected by others, with the willingness to alter their paths accordingly. We still cannot be certain of the system's influence without any sound feedback since the study does not include a specific control condition for this. However, given the mixed experiences that arose in the presence of external interactive artefacts on stage, these being the flying drone and the unmasked participant group, we speculate on the suitable conditions for effective social signalling through the participatory engagement with sound. Rather than trying to incorporate all of the users simultaneously, we suggest that individualistic control mechanisms can help to elevate one's agency to the surroundings, while the anticipation of regular interchange is necessary to preserve attention. Consequenty, we favour the use of structured interruptions by way of turn-taking procedures, whereupon users are compelled to listen to one another, then allocated a sufficient time window in order to react accordingly.

Constrained Complexity

This work fits into the domain of proxemic interaction strategies, asserting novelty in the non-categorisation of physical distances. The early phases of experimentation lead us to try complex, nonlinear sound-distance mapping strategies without the anticipation of hindered usability. However, we were enlightened early into prototyping that such sophisticated mapping strategies are only intuitive on the presumption that users are sufficiently acquainted with the apparatus and expected results, reiterating discussions around the virtuosity of musical instruments within the NIME research community [471]. We first insisted on more abstract mappings, layering sound elements each influenced by multiple users simultaneously; this approach was designed to provoke collective actions and, consequentially, for the group to act upon the movement patterns that made the most sense to them. From this composite sound feedback strategy, however, a great deal of confusion emerged from new users, leaving them with a feeling of disempowerment. We found this ambitious setup expected far too much knowledge from new users, made clear during testing, where participants would express their frustrations with the system's behaviour while not understanding how their individual actions influence what they were hearing. At a minimum, they would want to walk closer or farther from someone and hear an instantaneous reaction. We were able to recover the user's association to the sound feedback when resorting to a linear distance to amplitude mapping according to the smallest distance detected, allocating control to only one individual at a time in favour of being perceived as more receptive. Though, in many cases, the irregular substitutions would cause excessive shifts in volume, disrupting the continuity of the controlling gesture. In particular, when incorporating external objects and additional users onto the stage, we find more instances of abrupt sound bursts, depicted by the intermittent gaps in the audio recording, as shown in Figure 9.7.

While working in this semi-controlled setting, we benefited from the user's past experiences using digital musical instruments. However, when gearing toward a public space intervention, the importance of bridging with broader audiences would become most salient, to engage those unfamiliar with the system and each other, as described in Section 9.6. Such a pursuit calls for an accessible means of individual control that also encourages collaboration amongst strangers. Here, we advocate for a turn-taking framework that operates on a fixed time interval. This conveniently aligns with the step sequencer metaphor proposed in Bengler and Bryan-Kinns's work with non-musicians, studying how a constrained control paradigm can improve engagement with the general public [34]. To build upon these considerations, we prescribe the function of sequencing for distributed control and attention in group interaction, maintaining the usability of single-user mappings whilst emphasising the quality of observing the other.

Precautions for Public Inclusion

The change in pandemic circumstances that happened during the research timeline meant that only a maximum of four participants were authorised to use the wearable at any one time, dismissing any substitution of users between daily intervals. This compromised the conditions for open public inclusion while the measures gradually became stricter, bringing serious doubts in justifying any sort of artistic action that persisted in congregating different social bubbles. In these circumstances, we were confronted with the fragility of the sensory components embedded onto the mask. More often than not, assistance was required from the workshop coordinator to secure the wearable around the user's head; this would unfavourably call for physical contact near the mouth, posing an additional risk of viral transmission. That considered, a misfortune such as this would have been far more problematic if widespread into public hands.

The deferred extremity of the situation was only realised around one month later, as these measures would come forth as a final phase of provisionary measures before the nation was required to fall under a compulsory confinement period (i.e., lockdown). On these terms, the study was committed to a public space intervention with elevated awareness of safety and robustness, particularly in regard to the exchange of wearable components between alternating user groups.

At the time of reorganising the study, this absence of open public participation was deemed somewhat a pitiful solution, albeit one that avoids abandoning the in-person field study indefinitely. Though, in hindsight, we realise these intermediate steps were absolutely necessary before the system could be made freely accessible to the public, ensuring usability and safety to a minimum standard. This mentality of turning restrictions into opportunities for precaution is highly acclaimed in the discussions drawn out from Howell et al. [217]. This work rationalises the function of private space experimentation which would merit design guidelines for public interventions, detailing concerns around safety that would omit the likelihood of welcoming fruitful interactions between strangers. Nonetheless, due to a lack of public exposure, the opportunity arises to grasp deeper insights from the user group. We factor this progression into our design considerations, insisting that new systems intended for public use should first be evaluated in a low-risk environment for a substantial period of time, taking opportunities to carry out data collection and open-ended experimentation. The controllable nature of the performance-led study allowed us to gain insights from a consenting user group, willing to follow instructions, undergo trial & error testing, and contribute to data collection. As a result, we were able to construct benchmarks for usability, later informing design adaptations for pubic inclusion.

9.6 The Case for Public Interventions During a Pandemic

Taking what was learned during the first phase of experimentation and preliminary results, we introduce an adaptation for a proxemic-based sound intervention designed for open urban spaces, which materialised some months later. The installation was publicly active during October 2021; at this point, the fully vaccinated population was reported at 80% [370], and the majority of cultural actives could presume, as the most prominent pandemic regulations were already lifted [387]. This demonstration was set out to provoke collaborative engagement through sound, similar to what was observed during the closed user study, but in contrast, situated in the public space format. The system was installed for three full days in a touristic square close to the city centre, completely open to any passing members of the general public. Participants were expected to make use of the system independently, and offered only a set of essential instructions that were made accessible online through a mobile web application. Enlightened by our design considerations, we detail an alternative method for distance-to-sound interaction and assess to what extent, this intervention was capable of preserving the qualities of interaction that were preconceived in the discussion. Here, we evaluate the following strategies: drop-in and out participation, structured interruptions, and sequencing.

Instrumentation and Physical Arrangement

The public sensing environment brought many challenges to the system's physical orchestration. The major conditions here may be subject to the installation sustaining itself outdoors, and the considerations in order for it to operate independently without facilitators. We were also intrigued to experiment more deeply into proxemic affordances shaped by the surrounding environment and non-human objects. First off, we reconsidered the mask-worn device to grant user independence, improve safety against viral transmission and refrain from dealing with inaccuracies. As an alternative, four proximity sensors were secured around the lower branches of a tree, pointing slightly downward to establish a path from the tree's crown to a seating area set up 16 feet (4.8 m) away from the base of the tree.

Along with each sensor hangs a brightly coloured ribbon from the branch, representing the origin of the individual paths, indicating the course for users to walk under, as annotated in Figure 9.8. The extent of the projected sensing area was bounded by the maximum sensing distance, capped at 12 feet (3.6 m) to maintain reliability. Granted that the sensor's performance is dependable on the ambient temperature and humidity, we noticed the detectable range varied more throughout the day than when we were working indoors. The air temperatures would fluctuate from 9–20 °C daily, with generally worsening detection rates during the night.

Figure 9.8: Public installation using four proximity sensors placed inside foliage with hanging ribbon. Sensors are physically separated by sensing trajectories, identified by colour.

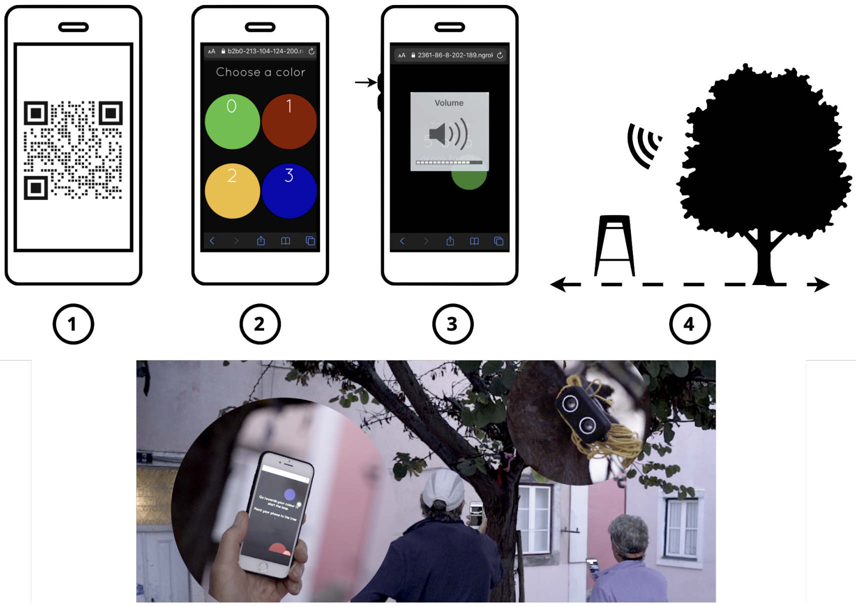

Figure 9.9: $1 instructions for installation: (1) Access QR code; (2) Load the app and select a colour; (3) Increase the device volume, and (4) Walk towards the chosen colour to initiate sound

Spatially Distributed Sound Output

It was in our prime interest that the intervention would preserve the inherent tranquillity of the pedestrian area. To avoid any unnecessary disruption, we insisted that the installation would not exert any sound until participants were willing to engage with the system. We speculated upon a feasible solution by which the public could initiate the sensing mechanism and listen to the installation from their mobile phone. A web app was developed using the Soundworks web framework by Matuszewski et al. [304]. Upon loading the app, participants are prompted to select one of four colours each allocated to one of the sensor placements, determinant of a walking path (Figure 9.9). The individual sensor measurements are broadcast to each of the mobile phones connected to the current session, activating new notes when someone is detected in the space and continues to do so while the participant moves within the measurable path.

The occlusion distance from each sensor was recorded in consecutive order, cycling through the complete batch every quarter of a second. The distances are converted into MIDI notes on a single octave chromatic scale, allowing 12 possibilities spread out between 30 cm intervals, rising in pitch as the distance measured from the sensor increases. When a user is detected, the app arpeggiates through the incoming notes every cycle. As one note is released, a new note is triggered from the neighbouring user according to their detected distance. Each note is emitted from the mobile device that is assigned to the coloured sensing path, accumulating into short loops that are continuously recorded and echoed in ongoing circulation. A video extract is provided in the Appendix C

From Lab to City, Transferable Experiential Qualities

Over the course of the installation period, we made notes of third-person observational accounts, similar to the rehearsal sessions and performance described prior to this. In particular, we give close attention to moments of group engagement that resonated with the spatial qualities examined previously, thus disclosing the experiences that were transferable from the wearable device to the public space adaptation. This numerical evaluation here does not intend to go as in-depth as the initial study, instead, this closing segment can be considered as a technical primer to fortify our design considerations for future research set in public space environments.

Advancing upon *proxemic sensibility* and turn-taking qualities, we found the mobile distributed sequencer fostered a certain degree of mutual agency, in that participants would invite their peers to join them and instinctively feel inclined to listen to one another. While exploring different spatial configurations, users would continuously experience new melodic loops with each note coming from separate directions according to the user's position. The separation of the mobile speakers in itself provided an additional modality to the acoustic quality of the soundscape, formed by the relationship between perceived intensity and distance. For the most part, however, users were staring directly at their mobile phones during the interaction process, with their bodies constantly turned towards the sensing apparatus standing parallel to each other, majorly discouraging prospects for mutual acknowledgement through eye contact.

From an observational standpoint, it was not possible to discern synchronous movement patterns inspired by the installation, or any definitive collective movement traits for that matter. Compared to the first case study, resourced with a large stage, the spatial exploration was far more limited here, restricted only to a linear sensing area, revolving around one focal point. Users would insist on staying idle, waiting for the sound to loop for a while, perhaps experimenting with walking forwards or backwards a few steps to trigger new notes. This coincides with the outcomes that presented themselves in Scene ii (Section 9.3) in the way that, when the directional influence of the sensors is displaced from the body and onto the surroundings, users show more infatuation with their own movements over anyone else's. With the ambition to cater for a *new sociable space*, the non-wearable arrangement combined with the drop-in and out functionality of the app was assumed to incentivise a flexible interchange of users, inclined to welcome those non-acquainted into the space. That said, we did not observe any instances of strangers simultaneously engaging at the same time, only those already affiliated, supposedly conditioned to the tensions when asserting oneself into a predetermined social clique.

In this instance, we wish to examine how well the intervention harmonises with the everyday operation of the space, blending with naturally occurring social exchanges, and staying respectful to those not actively participating. We found from a sample of 10 individuals and groups passing by during a weekday afternoon, that 7 of 10 would continue walking, 3 would feel captivated to read the information board with 1 going as far as entering themselves into the application, and starting to engage with the sound feedback. During the weekend period, the installation would be stationed along the route of a few public walking tours, serving as an amusing artefact to intrigued bystanders, without pulling enough attention for anyone to abandon their personal schedule. In the evening, we observed a spontaneous social gathering take place in the square comprised of 15 or more people mingling beside the installation area. Small groups would approach the installation and briefly engage in a new session, triggering just a few notes before returning back to rejoin the social event. Accepting the severe limitations in retaining interest from new users, these impulsive engagements showcase a strong starting point for public inclusion, by which the artefact successfully captures the attention of broader audiences enough for voluntary initiation. This can partly be owed to our preparation stages, pleading for *constrained complexity* to minimise the learning curve.

Limitations of Public Space Adaptations

In this supplementary case study, we were granted the opportunity to confront the challenges of proxemic sensing in public space; this exposed a number of external factors that were less problematic in semi-controlled conditions. To confront our final research question **RQ3**, we discuss design decisions that were influenced by environmental changes, technical durability and usability, contributing to pervasiveness and inclusion. The non-wearable solution was less susceptible to errors, but at the expense of a confined sensing area. The linear note-based interaction combined with the fixed placement of the sensor improved the system's usability when it was made openly accessible to a public audience. With that said, we believe this approach minimised the user's resilience to unexpected outcomes, and made apparent the moment that sound would stop playing, user's would immediately lose interest and move on to proceed with the rest of their day. In lack of a firm recommendation here, these outcomes continue to linger onto the feasibility of engaging unskilled users with novel interactive music systems [311], only to be exaggerated in a pervasive setting where prolonged participation is nonobligatory. In its wearable form, the original orchestration was purposed specifically to capture group dynamics by way of geometric and temporal relationships. However, here, we discern that the users were not highly aware of the movements happening around them. This persuasion may be accredited to the animations that are triggered concurrently within the application window, for which the extra stimulation has an overriding effect on mutual engagement, as is inferred by Bryan-Kinns's study [67]. Coinciding with the issues we faced when introducing additional visual elements, the authors ultimately caution against an excessive exposure to non-essential information in order to maintain attention in a collaborative interaction setting.

9.7 Summary

This chapter reflects upon the common attitudes associated with interpersonal distancing and social connection during the most critical moments of pandemia. We speculate upon a spatially-informed intervention to be deployed as part of a performance; this incentivised the design of a sensory face mask, coupled with a system for sound interaction. This wearable orchestration was trailed over a series of workshop sessions, inviting participatory feedback used to refine the physical design and mapping strategies in anticipation to be presented in a live performance setting. Reflecting upon observational notes and data analysis, we construct design considerations that respond to the pivotal challenges surrounding safe, inclusive re-socialisation in public and in theory, what spatially sensitive systems can offer to overcome such issues. This ultimately calls for an individualistic understanding of proxemic boundaries, giving agency to neighbouring bodies through sequential control, adaptable participation and constrained complexity strategies. We frame our findings in a broader perspective on sensory interventions that are not solely relevant to pandemic measures, generating critical reflections that later inform future developments as we appropriate the system towards urban sensing environments, proving transferable qualities amidst persisting limitations when subjected to the general public.

10

Closing Remarks

In this final chapter, we summarise the outcomes in response to the major research goals described in Chapter 1 in addition to their corresponding publications serving as documentation these works, reviewed externally. We put fourth reflective insights gathered from three major case studies, framed into a cohesive narrative to be extended into future research efforts. Finally, we discuss some of the social implications to be accounted for when applying these theoretical frameworks to a new generation of communication technologies.

10.1 Non-verbal Communication with Physiological Sensors

In response to our major research questions that follow our initial motivation statement in Section 1.2, we declare the following outcomes of our research as a whole. Expanding upon previous works in this domain, we focus on the prospect of retrieving data of the subject's personal experience as part of the interaction itself that would in theory, allow interactive systems to be adaptable to its individuals and specific context of use, and to do so continuously to remain emotionally relevant.

Why should embodied sensor technologies be used to mediate speechless dialogue? Starting from the theoretical and technical concepts introduced in Section 2, we explain the importance of non-verbal behaviours during an interpersonal exchange, even when being acted and perceived unconsciously, these reveal various emotional cues that are not evident from speech alone. From here, we are interested in how our physiological activity, the internal changes that occur within the body could be appropriated as a tool for expressive mediation. Acknowledging the possibility to capture such information using embodied sensors, we look towards the interactive potentials of abstracting and transforming this data upon its raw numerical form. Finally, we make a resemblance with Somaesthetic theory to depict felt physical sensations according to one's personal experiences, further supported by a comprehensive literature review in Section 3, taking inspiration from previous studies from which we justify aesthetic function as a capable means for physiological representation.

What mediums are capable of producing emotionally meaningful representations of physiological signals, suitable for social intervention? A survey of relevant sensing and actuation technologies are presented as part of the preliminary research actions in Section 5, followed by three use cases in Chapters 7, 8, and 9, each showcasing novel orchestrations used to assess visual, sound and haptic feedback mechanisms for real-time sensorial engagement.

We first uncover how shape-changing materials can be physically provocative when imposing unconventional movements onto the subject's limbs and organs, specifically when targeting the extremities engaged in the interaction at regulated intervals, forming a correspondence with the somatic nervous system. However, these systems revealed major drawbacks regarding portability between different spaces and users. Screen-based mediation opened up the possibilities of producing highly granular unique representations, leveraging proprioceptive sensibility and spatial aesthetics qualities described in Section 2.6. Finally, working sound interaction arises a genuine viability to share feedback amongst multiple participants, capable of sustaining interpersonal dialogue and collective gesture, without disrupting one's other somatic resources, such as sight or touch. Additionally, mobile actuators along with rhythmic distribution strategies can maintain cultivate awareness to one's environment and surrounding behaviours.

In terms of sensing, we have documented our experiences with the following modalities: inertial motion (acceleration and orientation), proximity, respiration, and electromyography. Additionally, optical motion capture was incorporated in our second case study (Section 8.8), accepting however, that this does not fit into the criteria of a wearable sensor per se. Other physiological signals of interest such as electrocardiography and electrodermal activity have merely been discussed in relation to previous works, for which we propose our findings can be transferable to using such inputs for an interactive system.

How can aesthetics be incorporated into visuals, sound and haptic mechanisms to articulate and express emotional content? And how do we encourage user empowerment and penalisation for effective intervention? The process of representation in non-verbal interaction has been routinely evaluated throughout the thesis, proposed as a way of conveying emotionally meaningful content by presenting identifiable traits from one's bodily activity to another person. We first describe representation in a theoretical manner, by which we perceiver and interpret new information based off of past experiences, then applying this to the design of novel mapping strategies. We offer three strategies for applying user-specified information from the user to context-aware emotional modelling.

The first case study points focuses on the physical sensations aroused from haptic actuation materials according to user-controlled parameter adjustments, continuously responding to the conscious experiences of the individual at that given time. Following this, Latent Steps considers novel representations of physiological sensor sensor data, navigating non-linear patterns within several introspective interpretations as illustrated by the user during a self-reflective session for data collection; this was made possible with neural network modelling and conditioning of the latent space. Our final case study, focused on interpersonal communication, considers the social aspects of an encounter that are influenced by the way subjects coordinate themselves within a given space according to a distributed interaction architecture, and how one may feel about approaching such interactive environments, even without explicit invitation to do so.

Regarding empowerment, we recognise that flexible mapping strategies grants the user the final responsibility to determine what the system is inferring about their emotional experiences, as it has been expressed in the writings of Ståhl, Löwgren, and Höök [425], and related works. Advancing from current human-centred modelling practices praising a heightened degree of user empowerment as a result of personalised mappings (e.g. [81]), we embrace contributions from the user in order to curate unique training data resources. In addition, we propose that open inclusion and voluntary participation are crucial components when curating a valid sense of authorisation.

10.2 Contributions

List of publications

Journal Papers

Sound Feedback for Social Distance: The Case for Public Interventions during a Pandemic **W. Primett**, H. Plácido da Silva, and H. Gamboa en. In: Electronics 11.14 July 2022, p. 2151. doi: 10.3390/electronics11142151

Biosensing and Actuation—Platforms Coupling Body Input-Output Modalities for Affective Technologies M. Alfaras, **W. Primett**, M. Umair, C. Windlin, P. Karpashevich, N. Chalabianloo, D. Bowie, C. Sas, P. Sanches, K. Höök, C. Ersoy, and H. Gamboa en. In: *Sensors* 20.21 (Jan. 2020), p. 5968. doi: https://doi.org/10.3390/s20215968

Conference Proceedings

Designing Interactive Visuals for Dance from Body Maps: Machine Learning and Composite Animation Approaches N. N. Correia, R. Masu, **W. Primet**t, S. Jürgens, J. Feitsch, and H. Plácido da Silva. In: *Designing Interactive Systems Conference.* DIS '22. New York, NY, USA, June 2022, pp. 204–216. doi: 10.1145/3532106.3533467

Exploring Awareness of Breathing through Deep Touch Pressure A. Jung, M. Alfaras, P. Karpashevich, **W. Primett**, and K. Höök. en. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems.* Yokohama Japan, May 2021, pp. 1–15. doi: 10.1145/3411764.3445533

How do Dancers Want to Use Interactive Technology?: Appropriation and Layers of Meaning Beyond Traditional Movement Mapping R. Masu, N. N. Correia, S. Jurgens, I. Druzetic, and **W. Primett** en. In: *Proceedings of the 9th International Conference on Digital and Interactive Arts*. Braga Portugal, October 2019, pp. 1–9. doi: 10.1145/3359852.3359869

Secondments

KTH (Stockholm, Sweden), Supervised by Professor Kristina Höök for project *SomaSensing: First-person approach to design toolkits that raise emotional self-awareness*, January 4 to Febuary 4, 2019. Followed by workshop:

https://www.affectech.org/2019/02/6th-affectech-training-in-milan-italy-emotion-regulation-and-virtual-reality-based-biofeedback/

M-ITI (Madeira, Portugal), Supervised by Professor Nuno Correia for project *Moving Digits: Augmented Dance for Engaged Audience*, May 2 to June 18, 2019. Followed by workshop:

https://movingdigits.eu/2019/05/moving-digits-tech-week-report/

Dissemination Activities and Collaborations

An Alternative Protocol for Ubiquitous Sensing and mHealth Applications, The Case for Sensory Audio and Mobile Web Frameworks. Seminar Doctoral Program, FCT-UNL, Caparica, Portugal, 2022.

Anti-Social Distancing Ensemble. Interactive Sound Installation, Sound Circuits Festival, November 2021.
Appendix C

Latent Steps: Generative Bodily Animations from a Collection of Human Drawings and Physiological Data Interaction Poster and Demo Session **W. Primett** International Conference on Dance Data, Cognition and Multimodal Communication. DDCMC'19, September 2019. http://ddcmc19.blackbox.fcsh.unl.pt/programme/

"A Beautiful Glitch" S. Rijmer, H. ', L. Vares, S. Jürgens, R. Masu and J. Feitsch, **W. Primett** Performance, Talk and Video Presentation, Moving Digits Artistic Residency, Sõltumatu Tantsu Lava, Tallinn, August 2019. https://movingdigits.eu/artistic-residency/

10.3 Reflections

To complete our research outputs, we present a number of perspectives given the speculation and assumption that this is already a matured research space. Some of which are already put forward in the previous sections, but described more in-depth and unconfined from the current research outcomes of the thesis, which for now can be considered elementary.

The Case for Integrating Technology with Established Movement Practices

Contemporary Interaction Design (IxD) research groups have incorporated Contact Improvisation routines into their work, enlightening new perceptions of mobility through a collaborative practice that involves the transfer of body weight between partners [28, 50]. Where the principal activity presumes that intimate space is to be co-occupied and that touch is freely permitted, in some cases using intense pressure, such practices emphasise the importance of consent and appropriating of physical contact, though several practitioners have come forward to challenge this idealism [31, 435].

Managing Experienced Practice with Pervasiveness

In our initial pursuit towards integrating established somatic practices to the domain of sensory technologies, a two month research residency commenced with KTH, Royal Institute of Technology. The proposed outcome for this collaboration was ultimately to develop an Interactive Machine learning framework that models specific physiological characteristics informed by Contact Improvisation (CI) and Feldenkrais. To initiate our design process, a small series of workshop sessions, guided by an expert practitioner, serving as a somatic connoisseur. Between each activity, participants would highlight some of the aesthetic sensations that occurred, and try to develop sensor-actuation couplings that would mirror the inter-user movement qualities.

On a personal account, the intermediate CI workshops did not enlighten the prolific research opportunities that were naively anticipated up until the research residency. First off, we were not so clear as to the major role of technological intervention. For example, to guide movement patterns in substitute of a facilitator, or exaggerate tactile sensation that occur. In terms of inclusion, the experiential gap between the facilitator and the researchers felt disruptive to personal exploration. Even given a successful digitisation with embodied sensors, how would this experience be distributed outside of the lab, or even a studio? Moreover, prospects for guiding non-verbal communication only become more distant. Without dwelling much further, this segment concludes with the a call to new research directions that realised throughout our research outputs. Ultimately, we are interested in systems capable to instigate interaction without the necessity of explicit instructions. To essentially allow participant to experience the interactive artefact through experimentation, preferably shared with others.

Tensions Between Research and Artistic Creation

One of the problems identified in the second case study (Sections 8.8) was the lack of time to adequately develop artistic ideas with the technology.This reflects a tension between the time and budget available for academic research (in this case, involving professional artists, recruited through an open call, being rewarded for their participation in the project), and the time and budget needed to develop a performance in the intersection of contemporary dance and interactive technology. Although some positive aspects came out of this tension, such as finding functionalities in our systems that would speed up the workflow (Section 8.13), or strategies to counterbalance the slow responsiveness of a prototype (Section 8.14), efforts should be made to attenuate time tensions when involving artists. A possible solution could be to consult with dance artists already when preparing the research plan and budget, to obtain advice regarding the adequacy of the time planned for artistic development, and what trade-offs to apply if needed.

In this particular study, there is also a risk of bias due to the fact that the study participants were professional dancers, and rewarded as such by our research project in terms of an artist fee. The fact that our research team worked closely with the group of participants for a long time, leading to familiarity and sympathy, may also have induced bias. As researchers, we were leading the organisation of the project, its activities and aims. Therefore, we might have introduced additional bias, as there might have been a perception of a power shift toward our research team. These elements could potentially inhibit some harsher criticism. However, we believe we mitigated that risk by stating repeatedly at each stage that all feedback, positive or negative, was important to improve the research being conducted.

Validity in Self Studies and Non-lab Environments

The deliverables of the thesis carry upon theoretical underpinnings grounded in complex movement and bodily practices, namely Yoga and contemporary dance performance. It should be noted that the self-studies carried out during the prototyping in the evaluation stages lack the expert opinions of movement specialists, which would require inclusion professional practitioners. While study subjects were able to admit to holding some valuable experience, at least in complimentary practices, we openly the acknowledge having a limited understanding of the rich intricacies that lie in such specialist areas.

In the case of the research actions that called upon specialist users (e.g Preliminary Actions II, Chapter 6), our results can be praised for interdisciplinary inclusion, for which we benefited from gaining alternative perspectives of the given technologies. That said, this approach without a doubt compromises on longitudinal prospects, imposed by time and budget contingencies. In our case, we found that it was more difficult to obtain highly structured data from these user studies, as we embraced more an exploration process of the experiential affordances, proceeding to outcomes in the form of interviews and focus groups. We found many difficulties to come against the scientific rigour seen in clinical trials, and the possibility to validate numerical findings. In reflection of the thesis outcomes, we construct a multi-stage research methodology that first embraces the incorporation of specialist users during an intensive preparation period, supporting longer-term studies that can be safely situated “in-the-wild” when ready. In public space, the participants are not burdened by being critically observed, their behaviour, even if not aligned with the study protocol, is authentic. They are responsible for using a system according to their personal intuition, not necessarily what the designer intended. Unlike lab trials, public space experimentation lends itself to unforeseeable events. Every encounter is unique in a way that cannot be perfectly repeated.

10.4 Future Work

Extending Individual Works

Our Case Study I, Chapter 7 takes a look at shape changing materials for respiratory feedback, taking an introspective account of aesthetic sensation. While the results are not directed toward social communication, we know that learning to control our own breathing apparatus may also lead to better control over what we communicate to others. For example, consciously breathing in rhythm with someone else can lead to better communication and empathy [247]. Given that this investigation was incentivised by the experiments described in Section 5.4, uncovering motivations for sound-based actuation and physiological synchrony, we foresee potentials for shared tactile engagment also.

Our Case Study II, Chapter 8.8 compares two strategies for generating somatic representations, one procedural (MLIV) and the other produced manually (CAIV). We hypothesise that both approaches can be complementary, and combining both could lead to a ‘third way’. This ‘third way’ could also be adequate for free-form visualisation: where the human interpretation simplifies and harmonises the raw visual data, resulting in animation frames that are then used to train a generative machine learning model. This would combine the humanised and procedural qualities identified in these two adopted approaches. On the technical side, our Section 8.7 proposes benefits for a further investigation into alternative machine learning architectures and data collection strategies. Though acknowledging that such technical efforts should be adequately balanced with steps for improving the user’s comprehension of the process.

In our Case Study III, Chapter 9, we outline the standout progressions between the two sensing mechanisms, one situated directly onto the body, the other installed into the surroundings, proving transferable qualities amidst persisting limitations when subjected to the general public. For future work, we foresee the benefit of incorporating a hybrid system comprised of wearable and environmental sensors, suitable for large open spaces in the confidence of robust operation. From here, we also look towards long-term studies with diverse user groups, crucial in forming generalisable conclusions of social behaviour with interpersonal feedback strategies.

Designing for Emotional Availability

To construct speculations for future works, we would like to reflect on the importance of spontaneity, comfort and familiarity as part of the (non-verbal) communication process. Familiarity has been long-established to play a pinnacle role in general applications of interaction design [119], accepted as a method of empowering users to routinely execute functions without deliberate thought processing. In everyday life, the non-sensory clothing and accessories that one wears cultivates an aesthetic engagement with the surroundings, not necessarily in a solitary state, but while being perceived as part of someone's overall appearance, and contextualised within a social scenario. In this manner, perhaps it's desirable to shift our perspective away from wearable technology to the normalisation of expressive materials that also happen to be embedded with sensors and actuators, as it is becoming the case with other constituents of modern urban environments, encompassing new aesthetic characteristics in our everyday life. For example, in architecture [14], mobility [327], and fashion [73, 350]. Where there exists a mutual entanglement bet wen technology and physical space, Kitchin and Dodge explain how it's possible to reduce the presence of computation to the extent of conceiving augmented environments, where by our experience of the world is conditioned by digital articulations [250].

The emergence of 'invisible' technologies showcase a viable alternative for traditional wearable sensors, enabling users to bypass the voluntary procedures of contacting electrodes with their skin in a specific manner [385]. Another highly promising research path for ubiquitous sensing technologies can be seen in smart garments and e-textiles [227]. One example in particular, recently exposed to academic literature is the development of transducer-embedded fabrics, achieving pervasive physiological monitoring when fitted into sensory garment [473]. Given that such innovations are able to be *"woven into everyday life"* [420], we insist that future works should prioritise the use of non-invasive sensing technologies to facilitate natural interaction in new environments, to preserve the ubiquitous nature of street-embedded technology without compromising the physiological fidelity that comes personal embodied technologies, and to coexists with familiarised spaces and practices. In this circumstance, the garment that one wears unconditionally truly serves as a social mediator, without being expected to instigate or characterise the interaction from the beginning.

10.5 Designing Technologies for Expressive, Speechless Dialogue

Over 7 chapters, we document a thorough enquiry into potential communication strategies with wearable sensors. The process of which took place from July 2018 to August 2022 , thus compiling just over 4 years of investigation. This emerges from a relevant understanding of aesthetic experience as emotional engagement, impartial to linguistic descriptors in a way that can be interpreted from third-persons. This develops into a generalisable criteria that appeals to two fundamental parameters, rhythm and space, applied to the practice representing the physical sensations derived from embodied sensor data, orchestrating various digital mediums and modalities. These concepts are realised into a series of orchestrations, taking upon the following scenarios, starting from self-experimentation, then into live performance, involving specialist users and audience perspectives, and eventually public spaces, commentating on the role of ubiquitous sensing technologies to facilitate spontaneous communication between participants non-acquainted with one another. This offers an alternative perspective on affective technologies, with the interest of developing one's sense of belongingness alongside their community, and sustaining long-term wellbeing. To conclude, we defend our initial research proposal, for which non-verbal communication can be considered an expressive resource that inspires novel social situations to arise as part of one's daily routine, and therefore asserting aesthetic consideration at the forefront of technologies for expressive, speechless dialogue.

> *"More than mathematical mathematical machines, computers are linguistic machines that happen to be particularly effective at manipulating numbers. At the same time, they treat language, as they treat numbers, login, and pretty much everything else, 'with an odd combination of practicality and philosophical abstraction' that inevitably shapes our own human language. For humans and computers, language operates in the liminal space between reality, its description, and its construction. human consciousness runs on information and develops a simulacrum, a virtual reality that allows us to negotiate with the external reality, to monitor our bodies, predict our behaviours and those of others. For this we use representational systems and signifies as standings for other things, working in their absence, allowing memory and imagination to call to mind things that are either not present or do not exist at all."* Carvalhais [84]

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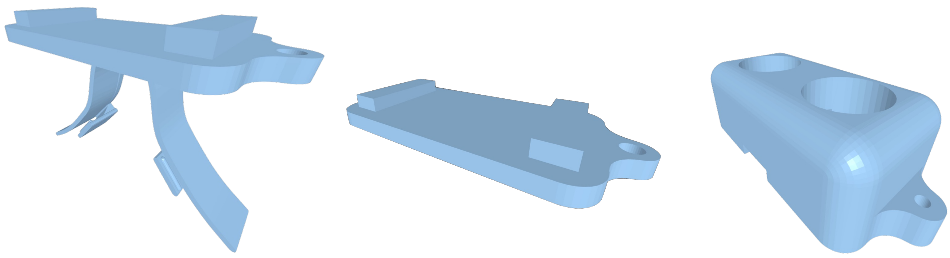
A

Case Study III: Supplementary Material

The following supporting information relevant for Case Study III (Chapter 9) can be accessed via the MDPI website for the published article. The files are organized as follows: Figure 5: Acceleration Data Graph; Video S1: Video Extract; Video S2: Performance Video Extract; Video S3: Sound Installation Video.

Supplementary Materials:

https://www.mdpi.com/article/10.3390/electronics11142151/s1
(accessed on 25 June 2022)



Adjustable mask strap and microcontroller enclosure, Sensor housing and nasal attachment (front and back panel). Printable STL files are available as part of the Supplementary Materials above.

Adapted firmware and circuitry schematic:

https://gitlab.com/wprimett/bitalino-riot-hc-sr04/-/tree/master;
(accessed on 25 June 2022)

B

Moving Digits Workshop Details

Several research actions documented in the thesis were observed in collaboration with the Creative Europe project, Moving Digits. In the descriptions listed below, our participation is referred by the representative partner, PLUX.

Workshop 1

Video and Details:

https://movingdigits.eu/workshop1/ *(accessed on 28 August 2022)*

Sketch Dataset:

https://drive.google.com/open?id=192MmXdPs5Z78hMnzBtS65AfVxStFZRCS
(accessed on 28 August 2022)
(10 PDFs, 5 sketches each, 2.1 MB .zip)

Workshop 2

Video and Details:

https://movingdigits.eu/workshop2/
(accessed on 28 August 2022)

Artistic Residency and Performance

Video and Details:

https://movingdigits.eu/artistic-residency/
(accessed on 28 August 2022)

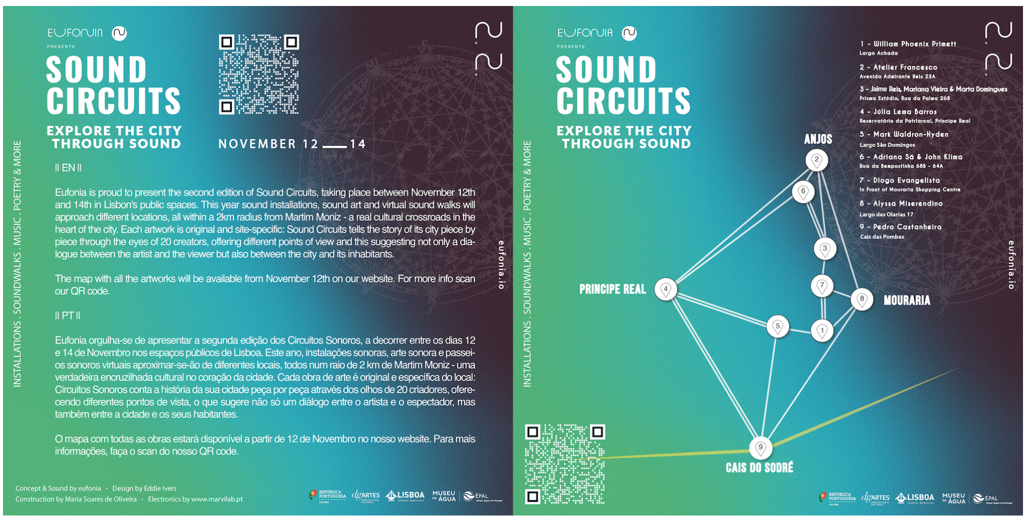
C

Anti-social Distancing Ensemble

Public Event Information

The public installation described in Case Study III (Chapter 8.8) was showcased as part of the 2021 edition of Sound Circuits, curated alongside a series of sound art interventions situated in a selection of public spaces around the centre Lisbon, Portugal.

> *"Eufonia is proud to present the second edition of Sound Circuits, taking place between November 12th and 14th in Lisbon's public spaces. This year sound installations, sound art and virtual sound walks will approach different locations, all within a 2km radius from Martim Moniz - a real cultural crossroads in the heart of the city. Each artwork is original and site-specific: Sound Circuits tells the story of its city piece by piece through the eyes of 20 creators, offering different points of view and this suggesting not only a dialogue between the artist and the viewer but also between the city and its inhabitants. The map with all the artworks will be available from November 12th on our website. For more info scan our QR code."*



https://eufonia.io/sound-circuits-2021 *(accessed on 25 June 2022)*

Installation Details

The following information was published online prior to the Sound Circuits event:

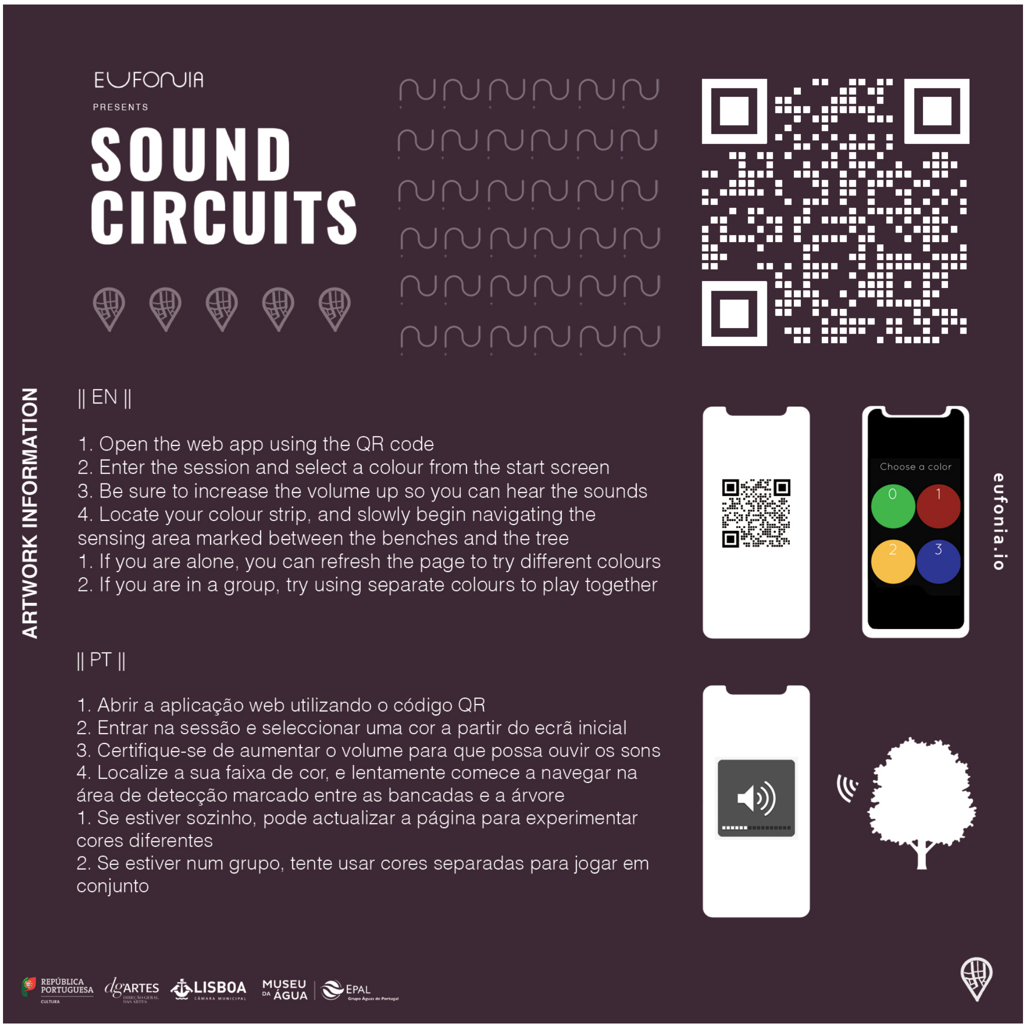
> *The Antisocial Distancing Ensemble aims to address the current attitudes towards the COVID-19 pandemic and positional sensibility with the other. The intervention is designed to challenge the conventional dualisms between physical distancing and social connectedness, mediating collective interaction with sonic biofeedback. As an iteration of our previous work designed for contemporary dance performance environments, our objective is to consider interpersonal relationships in a public setting, non-contingent to occupying one's personal space.*

`https://eufonia.io/william-phoenix-primett` *(accessed on 25 June 2022)*

Participant Instructions

The following information was printed as a poster and situated in the interactive space to guide new participants into the space.

1. Open the web app using the QR code
2. Enter the session and select a colour from the start screen
3. Be sure to increase the volume up so you can hear the sounds
4. Locate your colour strip, and slowly begin navigating the sensing area marked between the benches and the tree
    a) Solo: you can refresh the page to try different colours
    b) Group: try using separate colours to play together



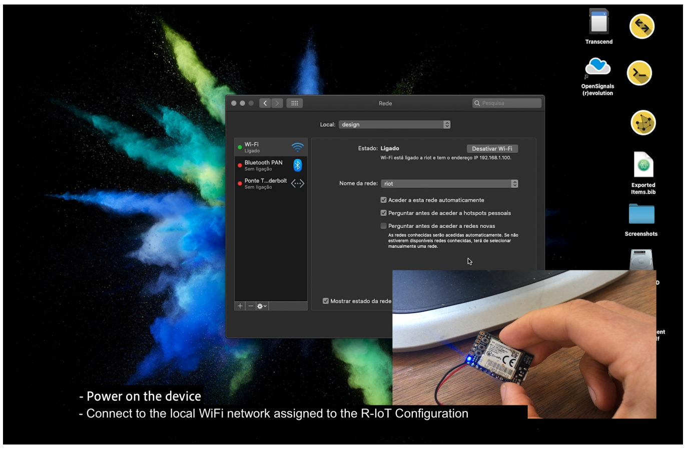
Sound Installation Video

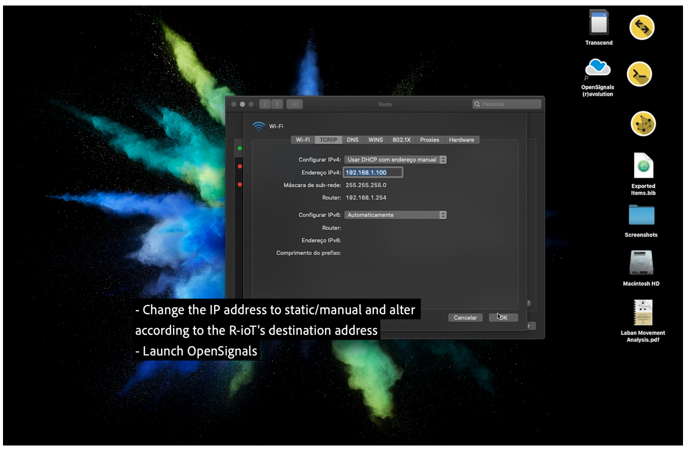
Video documentation for the public installation is available from the article publication website, provided in Appendix A.

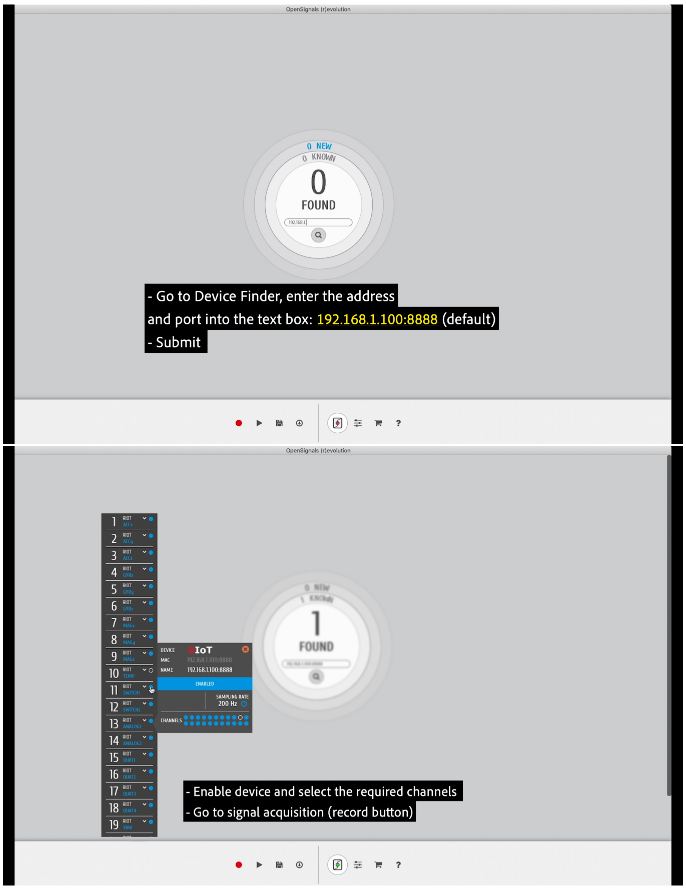
I

Annex 1 Configuring R-IoT

The screenshots below overview the configuration steps required to stream data between the R-IoT device and host computer over a local WiFi network. As part of our technical preparations described in Section 4.3, we developed a middleware program to simplify this process. These are specifically directed to the OpenSignals software package, though the general procedure may applied to other applications also.







1. Power on the device. Connect to the local WiFi network assigned to the R-IoT Configuration

2. Change the IP address to static/manual and alter according to the R-IoT's destination address. Launch OpenSignals

3. Go to Device Finder, enter the address and port into the text box: 192.168.1.100:8888 (default). Submit

4. Enable device and select the required channels. Go to signal acquisition (record button)