Contesting control: journeys through surrender, self-awareness and looseness of control in embodied interaction

Benford, S., Ramchurn, R., Marshall, J., Wilson, M.L., Pike, M., Martindale, S., Hazzard, A., Greenhalgh, C., Kallionpää, M., Tennent, P., Walker, B.

University of Nottingham Ningbo China, 199 Taikang East Road, Ningbo, 315100, Zhejiang, China.

First published 2020

University of Nottingham
UK | CHINA | MALAYSIA

Contesting control: journeys through surrender, self-awareness and looseness of control in embodied interaction

Steve Benford [a], Richard Ramchurn [a], Joe Marshall [a], Max L. Wilson [a], Matthew Pike [b], Sarah Martindale [c], Adrian Hazzard [a], Chris Greenhalgh [a], Maria Kallionpää [d], Paul Tennent [a], and Brendan Walker [a]

[a]Mixed Reality Laboratory, School of Computer Science, University of Nottingham, Nottingham, UK; [b]School of Computer Science, University of Nottingham, Ningbo, China; [c]Department of Cultural, Media and Visual Studies, University of Nottingham, Nottingham, UK; [d]Department of Music, Hong King Baptist University, Hong Kong, Hong Kong

KEYWORDS Performance; Multimodal UI; New UI; Brain-Computer Interaction; Human-Robot Interaction; arts and media; HCI design theory; Embodied Interaction; Autonomous Systems
ARTICLE HISTORY Received 28 July 2017; Revised 7 April 2020; Accepted 7 April 2020

1. Introduction

As computer interfaces spread across and even into our bodies, so we find ourselves engaged in ever more deeply connected bodily interactions. From the mouse and keyboard, to wearables and gestural interfaces, to physiological sensors, implants, electrical muscle stimulation, and robotic actuation, there appears to be a movement toward more intimate connections between computers and human bodies. In this paper, we argue that this inevitably leads to situations in which people contest control of both the system and their own bodies and thoughts. Connecting computers to our bodies in more intimate ways – especially ones that involve our autonomic responses, for example, our breathing, heart rate, the functioning of our brains as measured by EEG (electroencephalography) and other internally generated signals – leads us into territory where we are no longer overtly or even consciously in control of the computer, or indeed of ourselves. This situation is further compounded when computers can stimulate as well as sense our internal systems.

We consider the idea of 'contesting control' that we believe is inherent to these kinds of deeply embodied interactions. We present three artistic explorations – a breath controlled bucking bronco, a brain-controlled film, and an interactive musical performance duet with a physically actuated piano – that reveal the opportunities and challenges that are inherent to contesting control during bodily interactions. These examples reveal experiences of control that are ambiguous, challenging and playful, and that demand exploration, interpretation and skill, as control tips back-and-forth between human and machine.

This has led us to formulate a conceptual framework that identifies three dimensions of contesting control: the surrender of control, self-awareness of control, and looseness of control. Together, these define a space of control through which users travel, both within and between experiences. Our dimensions are intended to provide HCI researchers and practitioners with sensitizing concepts to guide both the study and design of embodied interactive experiences.

Our artist-led approach focuses on relatively unusual, some might even say extreme situations, that deliberately foreground the idea of contesting bodily relationships with computers. The sense of contest – of the human losing or struggling to retain control or of the computer seeking to take it – runs as a thread through our three examples. In part, this is because we believe that contest is an important element of play, one that is inherent to games, rides and other forms of culture and entertainment that are enjoyed by many. However, we anticipate that our findings will also be of interest to those who aspire to develop more cooperative relationships between computers and humans, as cooperation inevitably involves a degree of negotiation and on occasion, contest, and conflict. Our final discussion, therefore, widens our argument to consider how our findings speak to two wider themes within contemporary HCI.

The first, obviously, is embodied interaction, where our paper responds to recent calls for more holistic approaches to designing for mind and body while at the same time foregrounding various tensions that need to be negotiated as part of this. The extent to which we, as humans, can control our own bodies and/or are aware of the extent to which we are doing so, is under constant and often rapid negotiation not least due to the action of our autonomic systems that are tightly coupled to our senses and emotions. This becomes even more fluid as we enter situations in which computers are trying to exert control, and especially when they are tightly coupled to the body, for example, computer-controlled wearables, prosthetics, orthotics, and medical implants as well as vehicles and rides. We shall argue that holistic approaches to embodied interaction need to consider journeys through different states of surrender of control, self-awareness of control and looseness of control rather than assuming that there is one ideal or stable state. This has implications for ongoing discussions about mindless computing, affective computing, and somaesthetic design.

Our second theme is autonomy, which speaks to the burgeoning field of autonomous systems and potentially to artificial intelligence in general. Here we offer two contributions. First, in contrast to much discussion of autonomous systems which, as the name suggests, tends to adopt a 'systems' focus – i.e., considers what it is that makes a system autonomous – we encourage consideration of the human perspective on autonomy – what is it like, as a human, to give up control to or negotiate control with a computer? Second, we consider how interactions that employ physiological sensing and physical actuation may engage a second kind of autonomous system, the human body's own autonomic responses, that now also become part of the mix. Our observations have implications for the design of a wide variety of autonomous systems from human interactions with autonomous robots and vehicles to increasingly everyday interaction modalities involving gaze control, breath control, physiological sensing, and even voice, face, and gesture recognition, all of which may involve involuntary and unaware human actions.

2. Related work

Contesting control speaks to two broad themes within contemporary HCI – embodied interaction and autonomy.

2.1. *Embodied interaction*

Our interest in embodied interaction focuses on the knotty question of mind-body separation. Mind-body dualism has riven philosophy throughout its history, including Aristotle (Hicks, 1907) and Plato (390–347 BC) who argued for the existence of a 'soul' that was separate from the body, and Descarte's (1641) famous argument for separating mind from brain. This mind-body dualism is reflected in much of HCI's thinking about interaction, for example, in the separation of cognitive goals from physical systems, the so-called gulfs of execution and evaluation in Norman's (1986) 'cognitive engineering.' Others have argued against a dualist position, calling for a holistic stance on 'embodied interaction.' Building on the foundations of both tangible and social computing, Dourish (2004) drew on the philosophy of phenomenology to reject dualism and instead argue for an account of interaction in which users create and communicate meaning through their embodied experience of systems in the world. One of Klemmer et al.'s (2006) five themes for designing embodied interaction, 'thinking through doing,' argues that thought (mind) and action (body) are deeply integrated in co-producing learning and reasoning. Höök's (2008) work on affective loops argues for involving both body and mind 'inseparably' in the design of embodied and affective systems. The quest for new relationships between mind and body in interaction design is also reflected in Ju and Leifer's (2008) notion of implicit interactions in which the attention demanded by a system moves between being foreground and background, and Wakkary et al.'s (2016) notion of unconscious interaction that arises from the 'goodness of fit' of designs that are both open-ended and lived-with. Serim and Jacucci (2019) further develop implicit interaction as an analytic concept in an attempt to put it on a firmer footing. They review the various meanings of implicit, including as unintentional, background, unaware, unconscious, and as 'implicatures' (indirect speech acts). This led them to propose an 'intentionality-based' definition of implicit interactions in which the "appropriateness of a system response to the user input (i.e., an effect) does not rely on the user having conducted the input to intentionally achieve it."

However, HCI's growing interest in embodied interaction often misses out on the body itself; what is distinctive and challenging about more deeply connecting our bodies to computers? Notable exceptions include Mueller et al.'s four perspectives on the design of exergames through recognition of the 'responding body,' 'moving body,' 'sensing body', and 'relating body' (Mueller et al., 2011) and Höök et al.'s (2016) observation that "writings about embodied interaction, the actual, corporeal body – our muscles, the way we move, our postures – has been notably absent," which inspired them to turn to Shusterman's (2008) body-conscious philosophy of mindfulness and somaesthetics to inform a holistic and more bodily-centric approach.

A second relevant notion of dualism is to be found in dual-process theories from psychology that divide the mental processes that govern human behavior into two categories of thinking known as the 'automatic mind' (more formally called System 1) and the 'reflective mind' (System 2) (Gawronski & Creighton, 2013). System 1 thinking has been characterized as being fast, parallel and automatic, requiring little or no effort, whereas System 2 has been described as effortful, slow, serial, and working in a controlled fashion. A planned decision is typically considered as System 2 thinking whereas an immediate reaction such as "disgust" corresponds to System 1. However, the two systems interact with each other, with System 1 suggesting feelings, impressions, and intuitions to System 2 that may be directly adopted with little modification (Kahneman, 2011). A widely studied technique for driving System 1 thinking is to deliver subliminal stimuli which fall below the level of conscious awareness (Dehaene et al., 2006). This dualism has been adopted by psychologists and behavioral economists who are exploring the challenges and possibilities for behavior change, and who have shown that subtle changes in behaviors can occur without the human being aware of them, leading to distinctions between mindful and mindless thinking (Langer, 2000). These theories have been taken up by HCI researchers who have incorporated them into the theoretical underpinning of persuasive computing (Pinder et al., 2018) and taken them as inspiration for the approach of 'mindless computing' in which persuasive technologies subtly influence behaviors without conscious awareness, for example, through plates whose lighting changes the color of food or gently pitch shifting people's voices when they speak (Adams et al., 2015).

Our paper also addresses holistic approaches to embodied interaction and especially the challenge of mind-body separation. We present three interactions that are in turn, very body-oriented (riding a breath controlled bucking bronco), more overtly mind-focused (a brain-controlled film), and one that sits between the two (the interactive piano performance). By contrasting these, we draw attention to the tension and fluidity between mind and body in designing deeply embodied interactions.

2.2. *Autonomy*

Autonomy is a widely discussed concept in multiple fields of computing including robotics, autonomous vehicles, automated building management systems, and software agents to name just a few. Unsurprisingly, there are different perspectives on the term. Parasuraman et al. (2000) define the 'level of automation' of autonomous systems on a 10-point scale, ranging from low autonomy in which the human takes all of the decisions, to high autonomy in which the system ignores the human and decides everything, with variations between including: the computer suggesting possibilities, executing actions with human permission, or executing them, and only informing the human if asked. Goodrich and

Schultz (2008) identify additional factors in autonomy such as neglect tolerance, meaning how long the system can be left alone to fend for itself. Bradshaw et al. (2004) define autonomy using the dimensions of 'descriptive' (actions a system is capable of undertaking) and 'prescriptive' (actions it should be allowed to perform). Considering human-robot interactions, Bartneck and Forlizzi (2004) define social robots as being autonomous or semi-autonomous robots that interact and communicate with humans by following expected behavioral norms and classify them according to form, modality, social norms, autonomy, and interactivity. Abstracting from such facets, Bradshaw et al. (2011) discuss three styles of human-system interaction: co-allocation, cooperation, and collaboration, and note the importance of inter-predictability and common ground. Turning to software agents, Beavers and Hexmoor (2004) consider how agents can reason about their own autonomy as a social process, classifying them according to the two dimensions of 'individual capacities' and 'individual rigidity.' Considering the design of ubiquitous systems, Ju and Leifer's (2008) notion of implicit interactions (introduced above) considers the extent to which the autonomous system takes the initiative, ranging from being proactive to reactive, comparing this to the extent to which the system demands human attention, ranging from background to foreground. The four quadrants defined by these dimensions span ambient agents (proactive, background), increasing levels of abstraction and automation (reactive, background), the system giving alerts and directions (proactive, foreground), through to direct manipulation interfaces (reactive, foreground).

A key concept to emerge from research into autonomous systems is that of mixed-initiative interactions. According to Allen et al. (1999), this is "a flexible interaction strategy, where each agent can contribute to the task what it does best" in which often "agents' roles are not determined in advance, but opportunistically negotiated between them as the problem is being solved." Horvitz (1999) articulated principles for the elegant coupling of automated services with direct manipulation to create mixed-initiative user interfaces, including ensuring that automation adds genuine value, considering uncertainty and attention, supporting dialogue, and continuing to learn by observing. Research in autonomous vehicles has introduced the H-metaphor that likens the idea of negotiating tightness and looseness between human and system to using reins to control a horse (Goodrich et al., 2006). The H-metaphor subsequently inspired the notions of 'casual' and 'focused' interactions with mobile devices in HCI (Pohl & Murray-Smith, 2013).

Our focus on autonomy is somewhat different from much of this previous work. Our interest lies in the various ways in which humans experience autonomy, especially in how they relinquish control when engaging a computer system that is in turn directly controlling their body. Thus, we do not focus so much on what it means for a system to be autonomous (indeed the systems that we present are hardly autonomous in the sense meant by artificial intelligence research), but rather, we consider what it means for a human to contest their personal autonomy with an autonomous system as part of an embodied interactive loop, recognizing that this may involve negotiating with their own autonomic bodily responses as well as with a system.

3. Methodology

Recent decades have seen the field of Human–Computer Interaction take something of a 'turn to the cultural,' exploring applications of computers in domains such as games, music, museum visiting, film, television, interactive art, and performance. This, in turn, has led to approaches, concepts, and methods from these domains finding their way back into mainstream HCI thinking. Notions such as the deliberate use of ambiguity in interaction design (Gaver et al., 2003), for example, emerged from early reflections on cultural applications to become a more widely recognized concept in HCI.

In this paper, we adopt the approach of Performance–Led Research in the Wild that has emerged from HCI's engagement with artistic and cultural experiences (Benford et al., 2013). This involves collaborating with artists to create, tour, study and then reflect on live public performances that employ emerging interactive technologies. We have three broad motivations for pursuing such an approach. First, we believe cultural applications of computing (and performance specifically) to be valuable human activities that can benefit from new digital technologies and that consequently deserve attention from HCI – including the use of methods that respect the nature of practice within this particular domain. Following this motivation, we are interested in understanding new artistic, often playful, interactions that are appropriate to the design of future cultural experiences. Second, we value the inherent, often professionally trained and honed, creativity of artists that, in our experience, frequently opens up previously unforeseen uses of new technologies while also pushing them to their limits. Third, public performance provides a valuable crucible within which to engage the public with emerging HCI technologies in a meaningful, contextually grounded, and safe way. Thus, we hope that our findings may speak to the wider challenges of designing deeply embodied interactions in applications beyond the cultural.

Whatever combination of motivations is at play, the approach generally involves three interleaved activities. The first is an artistic practice in which artists conceive of new performances while HCI researchers as technologists help realize them, sometimes innovating new interaction techniques along the way. Second, are studies of performances as they 'go live,' often following the first few public outings as the new work is gradually stabilized, documenting the artist's rationale as well as audiences' experiences through observation and interviews, sometimes supported by system data. Third, is a reflection, in which (typically several) projects inspire and illustrate new interaction design concepts, leading to various forms of 'intermediate design knowledge' (Höök & Löwgren, 2012) that seek to bridge between theory and practice, for example, guidelines, heuristics, design patterns, strong concepts, and in the case of this paper, taxonomies.

This particular paper is an example of the latter activity, reflecting across three artistic projects that have each been realized as public performances and also studied, as reported in earlier publications (Kallionpää et al., 2017; Marshall et al., 2011; Pike et al., 2016). Here, we revisit these works and studies (briefly summarizing them along the way) so as to establish a conceptual framework that captures their essence and distils it into a form intended to guide the design of future performances, other cultural experiences, and potentially interactive experiences in other domains. The three case studies were all created and performed by professional artists. They share a common concern with highly embodied forms of interaction and yet also address quite different styles of 'performance' – an interactive ride, a brain-controlled film, and a musical performance as we now discuss.

3.1. *Thrill laboratory*

Our first case study focuses on the setting of the amusement park as a site for playful, thrilling, and also performative interactions with technology. Specifically, we reflect on a series of performance-led engagements to explore how physiological sensing – specifically breath-control – could be used to create interactive rides. Thrill Laboratory is the collective name for a series of projects conceived and delivered by the artist Brendan Walker over a period of more than 10 years. Early projects explored the use of wearable sensors (heart-rate, galvanic skin response, accelerometers, and cameras) to capture the experience of riders on roller coasters and other thrill rides and then transmit this back to spectators (especially friends and loved ones) so that they might be able to vicariously follow the riders' experience (Schnädelbach et al., 2008).

Subsequent explorations turned their attention to the question of how such sensors might be used to actually control a ride, creating an actuated experience in which a human rider would control the ride through their embodied interactions that, in turn, would be affected by the actions of the ride. This was realized in the design and deployment of the *Broncomatic* (Marshall et al., 2011), a breath-controlled rodeo-bull ride, shown in Figure 1. Conventional mechanical rodeo-bulls take the form of mechanical motion platforms that are controlled by a human operator who dynamically manipulates the pitch, roll, and yaw movements of the ride to create a bucking sensation, with the rider initially attempting to retain control before (usually) being thrown off onto a soft landing area, delivering entertainment for both rider and spectators. In some cases, the human controller may be replaced with a predefined 'ride programme.' The ride in the *Broncomatic* is automated, but instead of being a predefined programme, it is controlled by the rider's breathing.

Figure 1. Riding the *Broncomatic*.

The ride programme progresses through three levels: (relatively) easy, moderate, and difficult. In each level, the rider's breathing – estimated from the signals generated by an elasticated chest strap monitor – serves to generate movements through a simple mapping. Breathing controls the yaw motion of the ride, with 'breathing in' turning the Bronco to the left and 'breathing out' turning it to the right. This effect is stronger on higher levels, and toward the end of the final level is accompanied with a continuous forwards-backwards 'bucking' motion which greatly increases the difficulty. Testing during the design phase revealed that even this simple mapping was sufficient to generate significant challenge while also being clear and comprehensible to riders and quick to teach and learn. Finally, the overall ride experience was framed as a game in which the rider had to breathe more in order to score more points, establishing the core tension of wishing to breathe to score points while simultaneously trying to avoid breathing so as to placate the 'bucking' motion in an attempt to stay on the ride.

Over the course of its active life the *Broncomatic* was deployed at multiple venues, including as a public exhibit at the UK's National Videogame Arcade, during which time it proved to be a popular experience, being ridden by thousands of visitors. In the previously published study of the ride, Marshall et al. (Marshall et al., 2011) focused on 43 participants who consented to be observed and interviewed, and also to have their breathing data captured and discussed during this process. This revealed a variety of different experiences of the ride as well as tactics for controlling it that we briefly summarize here with reference to the breathing data traces shown in Figure 2. Each trace shows movements of the chest strap corresponding to breathing on the vertical axis (upwards for inhale and downwards for exhale) plotted against the duration of the ride, with the boundaries between Level 1/Level 2 and Level 2/Level 3 shown as dashed lines.

Several riders tried to control their breathing, with some claiming to draw on breath-control techniques that they had learned from yoga, martial arts, and shooting: *Because I used to do a lot of martial arts, and of course from that, we focus on how to calm your breathing down to a point, so I mainly just tried to focus on that, just calm it down, keep it level and steady* . By way of illustration, Figure 2a shows a pattern of relatively steady and regulated breathing, especially later on as the rider becomes more familiar with the experience, even though the ride is intense by this time.

A different and common tactic as shown in Figure 2b was to try and hold one's breath at key moments, such as the transitions between levels, so as to keep the ride under control while getting used to the new intensity of movement. However, it is only possible to hold one's breath for so long before becoming light-headed or acutely aware of the need to breathe, at which point the body's autonomic system takes control: *I guess I thought that if I held my breath when I was about to fall off,*

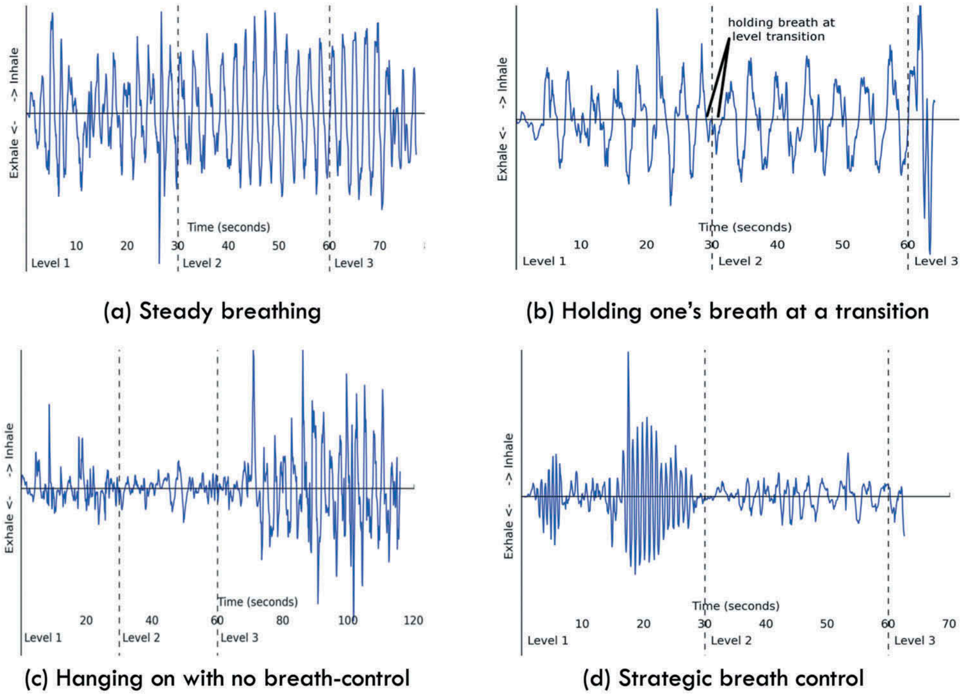

Figure 2. Graphs of breathing data revealing riders' tactics.

it might be okay, and that worked for a few seconds, but then I found myself like going, losing blood, you know, needing a breath. Rather than being problematic, however, such moments were often experienced as being thrilling, with riders suddenly becoming acutely aware of their own bodily sensations, the imminent loss of control, and its likely consequences as they perched precariously on top of the ride, often in front of their friends and other spectators.

Figure 2c reveals an alternative tactic of forgetting to try to control the ride by breathing, and simply hanging on for dear life, with breathing becoming wilder and wilder due to the physical exertion of being thrown around while clinging on: … *Level 3, like near the end; I was just concentrating on holding on with my legs and arms as tightly as possibly* .

Finally, some riders developed clear strategies for playing the game, especially after repeated rides. Figure 2d shows a case of breathing heavily in the early levels to try and score points while building up a supply of oxygen, before then breathing less in subsequent levels so as to stay on for a long time: *First time I tried long slow breaths, to sort of pace it and then I realized that you need to score quite highly in the lower levels, so I think it's a case of exploitation of the system a little bit*.

The point is not whether any of these tactics were better than others, but rather the realization that the key dynamic behind the success of the *Broncomatic* was that it set up a tension between controlling the ride and controlling one's own body – which was also being affected by the ride. At its best, the *Broncomatic* created moments of heightened self-awareness followed by moments of wild movement and loss of control. These insights were carried forward by the artist into the design of subsequent experiences, including a breath-controlled swing in which riders wore rubberized gas masks (with breathing measured through a respiration sensor) as a way of making them even more aware of their own breathing, later cited as an example of the deliberate use of discomfort to create entertaining experiences (Benford et al., 2012).

3.2. *The disadvantages of time travel*

Our second case study turns to the medium of cinema and also involves the use of physiological sensing, but in this case a head-worn electroencephalogram (EEG) sensor to control an interactive film. Despite some occasions where cinema audiences dress up, shout out, or even sing along with films (McCulloch & Crisp, 2016), watching a film is usually intended to be a deeply immersive experience in which the viewer sits in a purpose-built, comfortable, and darkened theater environment so as to become engrossed in a compelling audio-visual narrative. While the film industry has often sought to achieve interactivity, it has proven difficult to marry this up with the immersive aspects of movie watching. In this context, brain–computer interfaces are an interesting approach to explore as they potentially allow for 'passive' control while quietly sitting and concentrating (or otherwise) on a film.

Filmmaker Richard Ramchurn has created an interactive film called *The Disadvantages of Time Travel* that is controlled by the electrical activity of a viewer's brain as sensed by a wearable EEG device (Pike et al., 2016). The device, in this case, is a commercial sensor called a NeuroSky MindWave[1] that captures single-channel EEG and also the wearer's blinking, using a dry electrode, and that is intended for commercial use (Luo & Sullivan, 2010). Previous projects have explored the potential of this particular device to support cultural applications including interactive music (Leslie & Mullen, 2011), games (Grierson & Kiefer, 2011), and live cinema (Zioga et al., 2017).

In this project, the viewer enters a small cinema space, dons the NeuroSky MindWave, and sits and watches a film that lasts for 17 minutes (Figure 3). The narrative of the film is generally dark and challenging, addressing experiences of childhood bullying. The duration and plot are the same for each screening, but the cutting between different aligned visual layers is controlled in real-time by blinking, while the mixing of video and audio layers is controlled by the EEG, such that each viewer gets their own distinct experience of the film and becomes, in the words of the filmmaker, a 'co-creator.'

Figure 4 shows how the film was shot as four distinct layers of video. Two of these portray an objective reality as experienced by the film's protagonist, while the other two portray a dream-like view of the same events from the protagonist's internal point of view. Inspired by the filmmaker Walter Murch (2001), who likened a cut in a film to a blink, each time the EEG sensor recognizes the

Figure 3. Watching *The Disadvantages of Time Travel.*

[1]http://store.neurosky.com/products/mindwave-mobile.

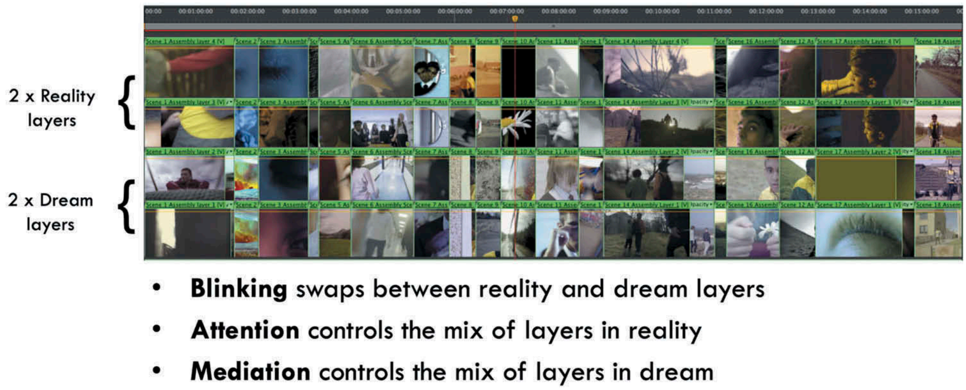

Figure 4. The four video layers in *The Disadvantages of Time Travel.*

viewer blinking, the film cuts between these layers, i.e., each time they open their eyes the perspective has switched from reality to dream, or vice versa. When within the reality state, the level of ‘attention’ reported by the sensor’s in-built algorithm controls the mixing of the two reality video layers, while in the dream state, the reported level of ‘meditation’ controls the mix of the two dream video layers. The net result is a film experience that is constantly shifting – dream-like in its format and experience as well as its content – with video layers being dynamically mixed and cut while the underlying narrative continues along its scripted path.

The film toured to various public venues in a specially adapted caravan, including being open to the public for a week at the Foundation for Art and Creative Technology (FACT) in Liverpool. This afforded an opportunity to conduct an HCI-oriented study of interactive control in which 24 viewers consented to watch the film, be interviewed, and have their EEG data analyzed. The full study has been published in (Pike et al., 2016) and just the key findings are briefly summarized here. Participants came with varying backgrounds and prior expectations, ranging from members of the public who turned up with no prior knowledge but were keen to try it out, to individuals who were invited by friends and given some level of explanation beforehand (though not necessarily an accurate one). Perhaps unsurprisingly, people emerged with very different experiences and understandings of the film and especially of their ability to control it. This said, there were some interesting commonalities (and also notable similarities to the *Broncomatic*) that helped shape our emerging understanding of control.

Blinking was clearly something that it was possible to use to directly control the experience. Many participants reported being able to use blinking to control the film, and a few appeared to have figured this out for themselves. The average rate of blinking was 5 blinks per minute, which is broadly consistent with normal rates of blinking while using a computer screen or watching TV (Patel et al., 1991). However, there were notable exceptions as participants endeavored to control their blinking so as to control the film, with two common cases being either to prolong the viewing of a scene that was interesting or alternatively, to cut away from a scene that was felt to be too uncomfortable. By way of example, Figure 5 shows the measures of blinking, attention, and meditation for one participant (P2) over the course of the film. The graph shows the intensity of attention (0 to 100) above the horizontal and meditation (0 to −100) below the horizontal, with each vertical intersection with the horizontal line signifying a blink. P2 only blinked 28 times during the entire film and at one point in the middle, refrained from blinking for 2 min in order to try to prolong a scene.

However, while it was at times possible to control the film in this way, blinking – like breathing – is not fully under the control of participants who reported having to blink as their eyes became tired and dry, or who blinked in response to noises and other sudden distractions. Moreover, some

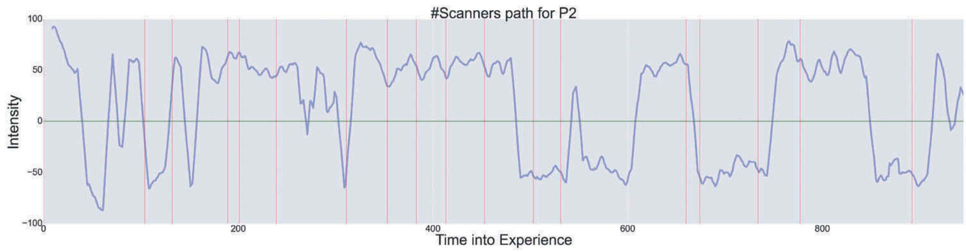

Figure 5. An example of controlled blinking from *The Disadvantages of Time Travel.*

participants reported a tendency to forget about their blinking as they became immersed in the film, although some noted how they might suddenly remember their blinking as a result of a cut between layers in the film. The net result was that participants would often tip back-and-forth between being in control or not, and also remembering or not that they were in control. These changes happened throughout the course of the film, driven in part by events within the film itself, but also by external events and their own state and responses.

In contrast, attention and meditation were far more difficult to comprehend and control. Pike et al. (2016) report that attention varied significantly between scenes while meditation did not. In particular, scenes 3 and 4, during which the primary character in the film experiences an intense and anxious nightmare, drew the highest levels of attention. Some participants reported deliberately trying to attend or relax during the film in order to control it and some claimed success. Many others, however, did not feel that they were able to consistently control the film in this way, while others remained unaware of the control mechanisms or forgot about it as the film progressed.

3.3. *Climb! and muzicodes*

Our final case study turns to a third creative domain, that of musical performance. Muzicodes is a technology that enables musicians to control interactive performances directly through their playing (Greenhalgh et al., 2016). The system can be instructed to listen out for, recognize, and respond to musical codes – fragments of music expressed as sequences of pitches and/or durations – and to trigger various actions as a consequence, for example, driving audio effects, samples, sequences, visuals, and lighting. Rather than pressing buttons, using pedals or gestural controllers, or indeed relying on technicians, the musician can control their performance technologies directly through the notes they choose to play at an instrument. The presence of the codes in the music may be more or less hidden, ranging from the musician carefully crafting their own codes, to them playing a score that someone else has composed with no prior knowledge of where the codes are, or even that they are present at all.

While not employing the kinds of wearable physiological sensing systems considered in our first two case studies, this example is relevant here because it addresses a deeply embodied and playful human practice – that of musical performance – while also involving complex sensing systems, in this case a combination of audio signal processing to sense a stream of notes being played (although MIDI can be used where instruments can generate it) alongside a series of rules to match this stream of notes against musical codes.

Muzicodes was developed through an iterative design process that involved over 20 musicians trying out successive versions of the technology and providing feedback. As reported in (Greenhalgh et al., 2017), these musicians ranged from amateurs to professionals and they played a wide variety of instruments including guitars, keyboards, pianos, banjos, whistles, and percussion. A key lesson learned was the need to support the cyclic process of attunement, shown in Figure 6, through which the musician could gradually align the system to their instrument and personal style while also

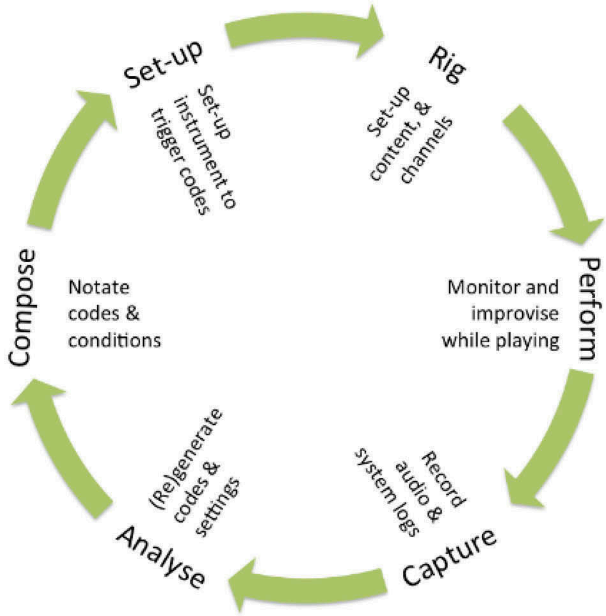

Figure 6. The cyclic process of attunement in muzicodes.

adapting their own playing to the characteristics of the system. This involved providing facilities in the technology to allow musicians to: notate codes with trigger conditions during composition, filter out false positives when matching their instrument to the note recognition system during set-up, monitor feedback from the system during a live performance, and regenerate codes from recordings of their performance. One key facility was the ability to set a customizable 'error distance' for each code, which expressed the number of permissible differences between the notes specified in advanced and those recognized in performance. Our musicians employed various combinations of these facilities according to their desire to either tightly control the system, optimally matching its recognition to their playing and instrument, or to let it run more loosely and then improvising around its (sometimes surprising) responses.

One of these musicians, the professional composer and pianist Maria Kallionpää, used muzicodes to create a full-scale performance called *Climb!* (Kallionpää et al., 2017). This is a non-linear piece of classical music composed for Disklavier piano, a mechanically actuated piano that can also play itself, playing back prerecorded MIDI sequences by physically moving its keys and striking its strings. In *Climb!*, the capability of the piano to physically play itself rapidly, without tiring, and with spans and combinations of notes that even the most highly proficient human cannot achieve, is used to create a game-like duet in which human and piano duet together in what, at times, feels like a contest of skill. Metaphorically, in *Climb!*, the pianist undertakes a journey up a mountain, choosing to follow one of three paths and encountering various objects, animals, weather conditions, and obstacles on the way. Each encounter on the path triggers a different section of the overall composition, so each performance of the work may be unique depending on the route the performer follows. This route is determined by whether they successfully play particular muzicodes that are embedded in the score, which also control audio effects and projected visuals (see Figure 7), as well as the piano that physically duets with them. The codes are defined with differing degrees of tolerance, with those that determine the route up the mountain being more precise (as failure to complete a code has interesting consequences of changing path) while those that introduce essential effects have greater tolerance so that they can be reliably triggered. Finally, while the composer herself is highly aware of the presence of the codes when she performs the piece, this need not be the case for other pianists

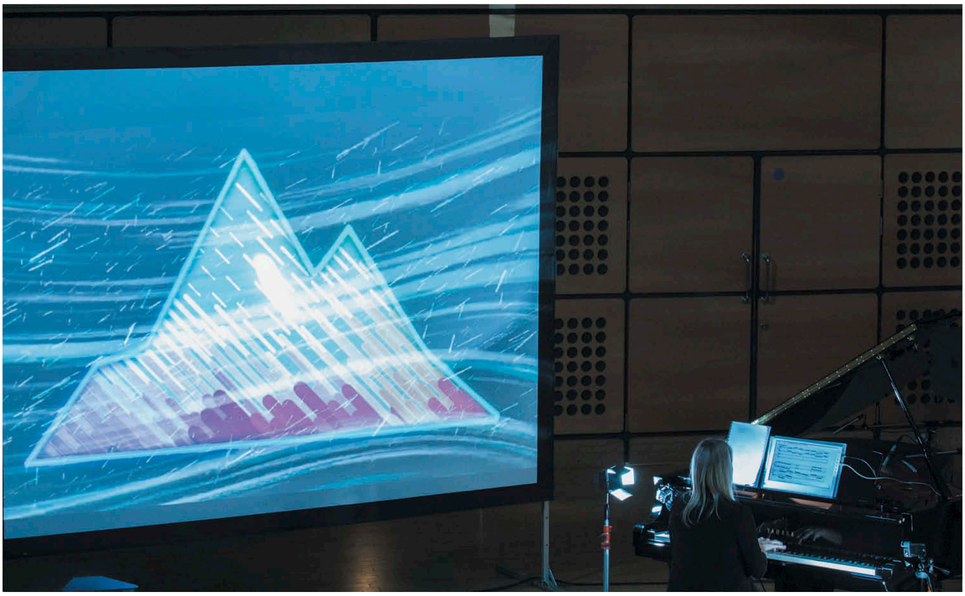

Figure 7. The interactive musical performance *Climb!* plays with music recognition technologies.

who might simply be given the score as part of an invitation to play. A study reported by Hazzard et al. (2019) revealed how professional pianists adopted differing approaches to performing *Climb!*. One concert pianist, who had been recruited to play the piece, invested great effort into figuring out the precise details of how the muzicodes worked so as to be able to control the performance (including being able to choose their route). They also became attuned to the system's response to them, for examplepredicting when the system appeared to be suffered from its own technical performance problems and was in danger of failing. In contrast, a second recruited pianist remained unaware of how the codes worked and where they were located in the score, instead interpreting the paper score as they normally would and following wherever the system led them.

4. A conceptual framework for contesting control

We now reflect on our three case studies to generalize a conceptual framework that is intended to help analyze and design control in deeply embodied interactive experiences. While distinct in many ways, our three case studies are united by a common thread – the notion of contesting control. At its core, each experience requires the user to battle for control of the interaction, which typically involves them battling both the system and sometimes also their own body. This latter point is especially significant to what follows, as the use of physiological sensing technologies means that the user's autonomic bodily responses increasingly come into play, leading them to probe the limits of their ability to control themselves. However, this inherent lack of self-control is also a feature of human cognition, for example, a person's ability to sustain a level of attention or focus. This simultaneous contest with oneself and a physically actuated system that is pushing back at one's body and mind is ongoing, shifting over time as the experience unfolds. Rather than control reaching a fixed equilibrium, the user is constantly wrestling with it as part of a playful, sometimes inwardly reflexive and even uncomfortably thrilling experience.

In what follows, we attempt to capture the distinctive and playful sense in which control is contested in our examples by considering the idea of journeys through a 'space' of control. This space is defined by three key dimensions, different facets of control that may be contested: the surrender of control, self-awareness of control, and looseness of control. In identifying these dimensions, we have adopted the perspective of the human in the interaction, encouraging experience designers to focus on how contesting control is experienced from the human point of view (rather than adopting a system perspective as has often been the case in work on autonomous systems, as we discuss below). We begin by introducing each of our three dimensions individually, before considering how they define an overall space of control and possible journeys through this.

4.1. *Surrender of control*

We believe that the feeling of loss of control – or at least of battling to stay in control – of both the system but also of oneself – is a vital aspect of our case studies. Our first dimension, therefore, reflects the extent to which the user surrenders control of the interaction. In physiologically coupled interactive loops such as the *Broncomatic, The Disadvantages of Time Travel* and to some extent *Climb!* (given the actuation of the piano keys that physically push back at the player), this involves surrendering control both to one's own internal autonomic bodily processes as well as to the computer. The modalities of breathing and blinking are especially interesting in this regard as they can at times be brought under fine voluntary control (e.g., breath control when speaking or playing a flute) while at others are involuntary (one cannot refrain from breathing, or indeed blinking, for long).

As shown in Figure 8, the dimension of surrender of control reflects the important sensation of relinquishing control, ranging from 'voluntary' at one extreme in which the user retains control over their body and/or the system, to 'involuntary' at the other in which they relinquish control of both (as body and system are coupled in an interactive loop so that surrendering control to one typically leads to surrendering control of the other).

Our case studies illustrate how surrender of control varies over time, with the user being in voluntary control of the interaction at one moment before then losing control at others and then sometimes regaining it. Control in the *Broncomatic* ranges from being largely voluntary in lower levels of the game, depending upon your skill at both riding and breathing, to being involuntary as riders lose control at the end of the game, as everybody ultimately does. Control in *The Disadvantages of Time Travel* ranges from directly controlling the cutting of scenes through blinking, to being unable to refrain from blinking due to dry or tired eyes, or being unable to maintain attention or meditation. Control in muzicodes depends upon a musician's levels of musical and motor skills, the complexity of the codes they must play, and how the instrument may play back against them.

4.2. *Self-awareness of control*

Our second dimension considers the user's awareness of the extent to which they are in control. As shown in Figure 9, the extent to which one is self-aware of one's level of control over the system, or

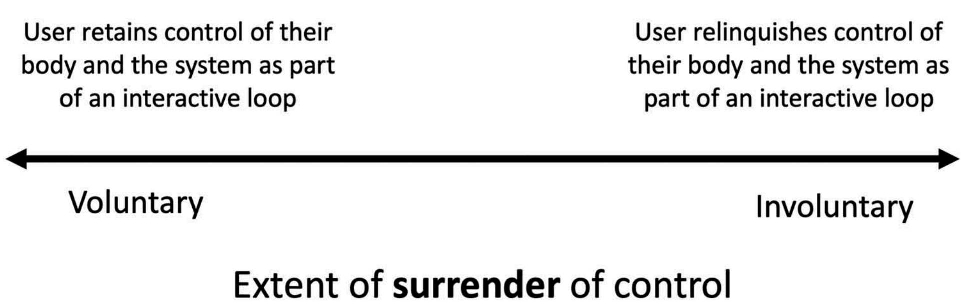

Figure 8. Extent of the surrender of control.

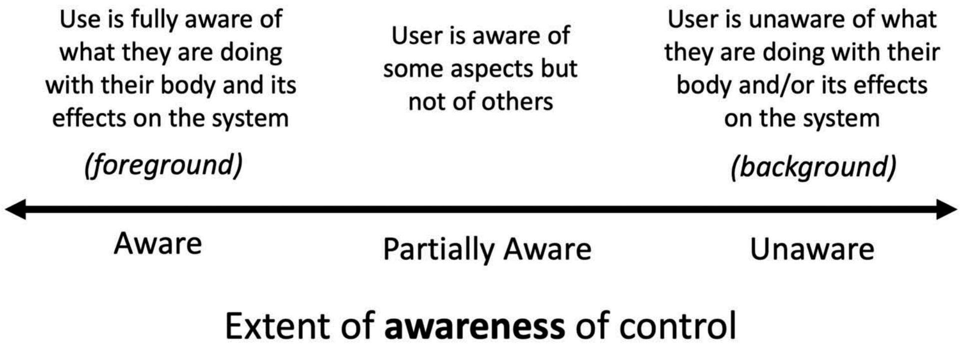

Figure 9. Extent of self-awareness of control.

of oneself, may vary greatly, and for a variety of reasons. The user may be fully aware of their cognitive-motor actions such as pressing a button or a piano key, and yet even these can fade into the background of awareness with practice and expertise. For example, when in a flow-state (Csikszentmihalyi, 1991) proficiently playing a musical instrument or computer game, riding a bicycle, driving a car (or even typing at the keyboard as I write this document – except at this precise moment when I am suddenly minded to think about how I am pressing the keys). In an ethnography of self-learning to improvise Jazz piano, Sudnow (1993) describes how his self-awareness gradually shifted across different aspects of his own playing, from the mechanics of pressing keys and positioning his hands early on in his learning, to thinking more about musical structures, forms, and expression later on. Interestingly, the tendency to sometimes re-focus back on the mechanics of playing correctly can appear to trigger more errors, for example, when experiencing performance nerves in music or sport (see, for example, Bawden and Maynard's (2001) study of why cricketers experience the so-called 'yips'). More generally, users may be unaware of how to control the system, a common situation with artistic and playful experiences where mappings are often not revealed in advance, or are sufficiently complex and unclear in their detail, that playful discovery of the nature of the interactivity is a core part of the experience.

Returning to our three case studies, it was obvious in the experience of the *Broncomatic*, especially through the 'kitting up' process and instructions given beforehand, that the machine was at least partially controlled by breathing. The mapping from breathing to the movement was also straightforward (breathing in to turn left, and out to turn right). On the other hand, the intense difficultly of staying on the ride and intensity of the physical experience appeared to cause some to forget about their breathing and in some cases about trying to control the ride at all, and resorting to just 'clinging on for dear life.' Perhaps the biggest 'payoff' moment on the ride, however, was for those riders who, having held their breath to try and control the ride, then experienced an increasing awareness of their imminent loss of control as they figured out that their breath would run out soon and they would have to take a deep breath at which point the ride would 'kick off.' Thus, as noted earlier, the *Broncomatic* can give rise to moments of heightened self-awareness of control, and an inward focusing on one's own physiological state as part of a playful and thrilling experience, much like the impending sense of 'the drop' on a roller coaster.

Self-awareness of control appeared to be far more varied and fluid in *The Disadvantages of Time Travel*, with some viewers, never realizing what was going on, some being told in advance, and some learning as they went. Some became more self-aware as they learned but then lapsed into less awareness as they became immersed in the film, only to become more aware again as something changed in its content (a sudden cut between video layers) or their own body (eyes drying out). Self-awareness of control was also affected by the varying complexities of the different control mechanisms. The direct mapping of blinking to cuts was relatively comprehensible compared to the less direct effects of attention and meditation on the mixing of video layers.

As with the other examples, muzicodes, and especially its use in *Climb!*, raises varying possibilities for self-awareness. Firstly, the codes may be created by a composer but then performed separately by another musician. The performer might be fully aware of them, practice to them, and then use a live monitoring interface on stage to help them trigger them, or alternatively might just approach the piece as a conventional score, playing the piece as written with no knowledge of the presence of hidden codes. Moreover, as discussed above, the player might have different levels of awareness of their own physical actions while playing according to their level of skill and/or flow or immersion in the experience.

4.3. *Looseness of control*

Our third dimension concerns the extent of looseness of control of the interaction as depicted by Figure 10. A tight relationship strives to ensure a more direct response to an accurate performance by the human, encouraging the precise, predictable, reliable, and synchronized rendition of actions with few errors. In contrast, a degree of looseness introduces flexibility into the interaction with regard to its predictability, accuracy, or synchronization.

Looseness may arise from several aspects of the relationship between human and computer. From the computer's point of view, it may arise from imprecise recognition of the user's actions, for example, noise in sensors, or from unpredictable mappings within the system, for example, random or pseudo-random mappings on inputs to outputs, or non-linear mappings where outputs are sensitive to initial conditions. However, looseness may also arise from the human, for example, through poor execution of actions or alternatively, through highly expert interactions that enable them to introduce their own personal expressive touch or feel. As with our previous two dimensions, we also need to consider the impact of the human autonomic systems. The body's internal systems that regulate breathing, heart rate, sweating, and similar physiological responses exhibit a degree of looseness in terms of the combinations of stimuli they may respond to (one may sweat when anxious, hot or exerting oneself) and the timescale over which they take effect.

While tightness may be seen as a virtue in traditional interaction paradigms such as Direct Manipulation (Shneiderman, 1993), there are situations in which looseness can be a desirable feature. One example of this is art and performance in which it is a rich concept that encompasses elements of personal style, and variations of tempo and rhythm among players. A degree of looseness in music, for example, may establish "feel" or "swing" or encourage improvisation, all of which can be desirable aspects of self-expression with an interface. This looseness of control in music performance is what separates a human performance from a computer-controlled one – it is the 'live' aspect that allows the same piece to reflect each individual's performance style in a situated context. A second benefit of looseness lies in control over autonomous systems where interaction has been

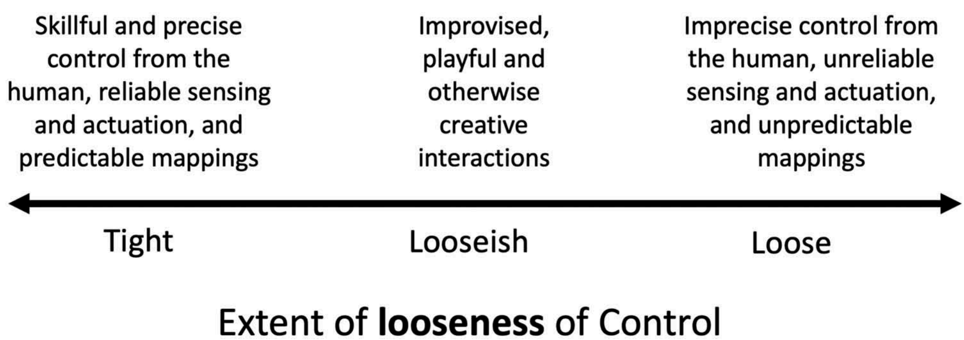

Figure 10. Extent of looseness of control.

likened to the tightening and loosening of the reins of control of a horse as in Goodrich et al.'s (2006) H-metaphor reviewed above.

Each of our three case studies demonstrates looseness of control in different ways and to varying extents. Control in the *Broncomatic* is mostly tight with the chest strap often sensing 'breathing' (actually the in and out motion of the chest) quite accurately and connecting this to the movement of the ride through a simple linear mapping as noted above. However, extreme twisting movements later on in the ride, as the body is thrown around, introduce more noise into the sensing while the increasing bucking of the ride serves to confuse the mapping, leading to an increasing degree of looseness. *The Disadvantages of Time Travel* employs multiple sensing modalities with different degrees of looseness. Like breathing, blinking can be sensed accurately – indeed blinking, even more so than breathing, is a relatively discrete event – while attention and meditation appear to be far less clear cut and far looser ways of interacting.

However, it is muzicodes and its use in *Climb!* that most directly and systematically address looseness of control. Several of the features of the muzicodes system are direct responses to the need for tighter or looser codes, and enable a composer or performer to position themselves and their instrument along this dimension. A musician's control over the triggering of codes can be made tighter by employing longer codes or matching codes on rhythm as well as pitch. Alternatively, control can be made looser by using wildcards or inexact matching (Greenhalgh et al., 2017). From the human perspective, the musician may become tighter with the instrument by playing slowly, simply and precisely, following a fixed score in tempo, using a muted style to avoid confusing overtones or sticking to known and recognizable instruments. Alternatively, they may choose to play loosely with their instrument by varying, relaxing, and embellishing their playing or generally improvising. At the tight end of the spectrum, we find a 'strict' musical relationship in which the musician is able to play skillfully as required by the instrument and the score, or where the instrument is finely tuned to respond to the fine nuances of their playing style. It should be noted that looseness and tightness are not necessarily good or bad qualities of a musical performance in and of themselves. Looseness can be virtuosic and tightness pedestrian, but tightness can be highly skilled and fine-tuned, while looseness may be sloppy and under-rehearsed. In the case of muzicodes, the key is to be able to tailor tightness and looseness to a particular situation, that is to a combination of musician, instrument, system, and work.

4.4. The space of contested control

Having introduced each of our three dimensions individually, we now consider how their combination defines an overall design space that helps map out the diverse possibilities for contesting control of interactive systems. We begin by considering the design space that exists between the first two dimensions before then introducing the third. Figure 11 represents the space of possible relationships between surrender and self-awareness. Some areas of this are familiar territory for HCI. At the bottom left we find familiar paradigms such as Direct Manipulation where the user is largely in voluntary control of the interface and of their own body and is aware of it. At the top-right, we find examples of ubiquitous systems in which the user gives up direct control and becomes unaware of the system that operates on its own in the background, for example, smart energy management systems that regulate heating in buildings according to the presence of humans. Such systems are involuntary in the sense that users are compelled to engage with them (e.g., being present in the building to work) and also because they control the body's autonomic responses to ambient temperature, while their operation is generally hidden from those users. A second example might be implanted devices that regulate or medicate the body with no direct user control or ongoing awareness.

The other two corners of the space can be directly related to playful situations. Toward the bottom-right, becoming aware of involuntary control can be found in all three of our case studies. As a positive aspect of the experience, it can be seen in the heightened awareness of holding one's breath

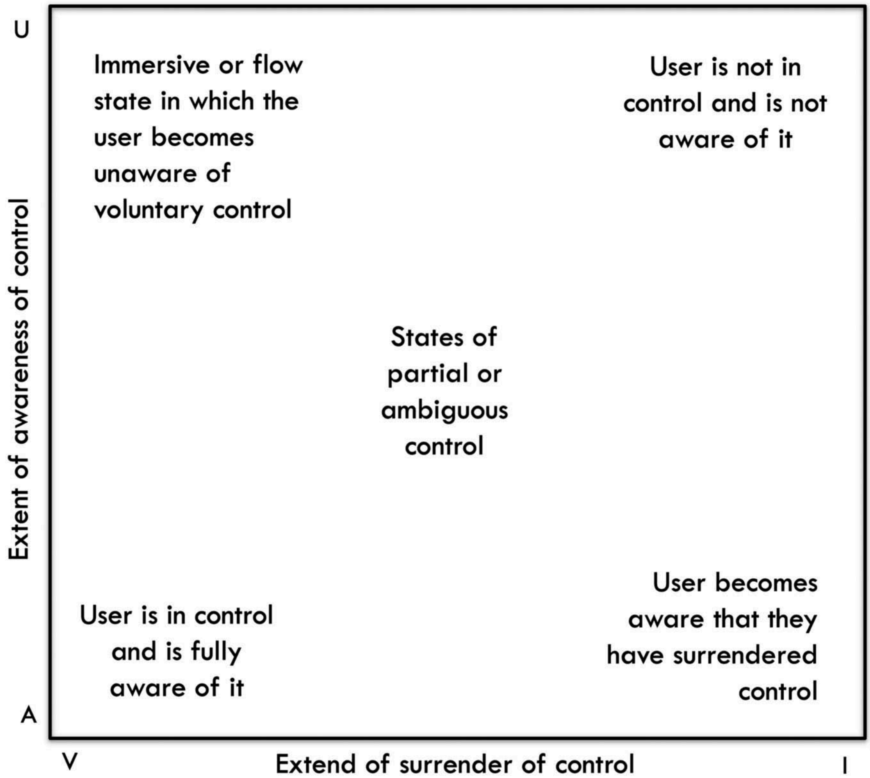

Figure 11. Comparing the surrender of control and self-awareness of control.

in the *Broncomatic* ride in anticipation of coming excitement, or the suspenseful struggle to hold onto a scene by refraining from blinking in *The Disadvantages of Time Travel*. More negatively, in *Climb!*, this arrangement can be found in the self-awareness of a musician who, perhaps affected by performance nerves, lacks the skill to correctly control their muzicodes-enabled instrument.

The zone at the top-left is perhaps the most counter-intuitive of the four extremities. How can a user be unaware that they are exerting voluntary control? Surely, being voluntary requires awareness of what one is doing? The answer lies in the subtleties of how awareness, and indeed volunteering, are experienced in the 'flow' of many creative activities. The psychological concept of flow expresses an energized state of deep immersion, involvement, and enjoyment in an activity during which one becomes less conscious of one's detailed mechanical actions in performing the task and more immersed in the overall sensation in the moment (Csikszentmihalyi, 1991). While flow might apply to all manner of tasks, it has proved particularly popular for describing the experiences of repetitive, highly-practiced, and often enjoyable experiences, from playing music to computer games. Flow – or indeed other kinds of deep immersion in an experience such as the experience of reading a book or watching a film – is an example of a control that is both voluntary but also unaware, at least in terms of the loss of awareness of the fine mechanisms of control. The skilled musician may be thinking about the broader interpretation of the music, delivering an expressive performance, or the activities of fellow musicians – without attending to each and every keypress or string pluck. The reader or player may be focused on the narrative rather than the mechanics of turning the pages or pressing keys.

We now introduce our third dimension of looseness into the picture to form an overall design space in which these various combinations of surrender and self-awareness can also be further combined with different degrees of looseness of the relationship between human and system, yielding the three-dimensional taxonomy of contesting control as shown in Figure 12.

As with the two-dimensional case, it may be illuminating to consider the extreme corners. What possibilities do they represent for forms of control? Can we find existing examples to populate them? Do they suggest new possibilities? Or do we believe them to be impossible and if so, why? Figure 13 therefore relates each of the eight corners of Figure 12 to examples of interactions from our case studies. Those in the bold case were observed in the studies while those in italics are offered as speculative cases that might be explored in future designs.

4.5. *Journeys through control*

The final idea that we introduce in this analysis of our case studies is that of journeys through control. A key feature of all of our case studies is that the nature of control is not fixed. Participants do not remain in one control state (one location within our taxonomy) throughout an experience but rather, undertake a journey – or trajectory (Benford et al., 2009) – through various kinds of control. Moreover, designing this journey is integral to designing the overall experience – especially where play, exploration, and learning are concerned. Control is, therefore, something that is explored, learned, acquired, then challenged, experimented with, and ultimately reflected on. Humans may also undertake these journeys through the space of contesting control within a single experience or over a series of repeated experiences.

Figure 14 summarizes our key observations of how people rode the *Broncomatic* in terms of two typical and contrasting journeys through control. Journey 1 involved trying to control one's breathing. Following an explanation prior to the ride that established some initial level of awareness of how to control the machine, riders would learn how to exert control, but would then gradually but inexorably surrender voluntary control over the ride and ultimately their own breathing as it became more intense. The key payoff moment for some was a crucial tipping point in this journey at which

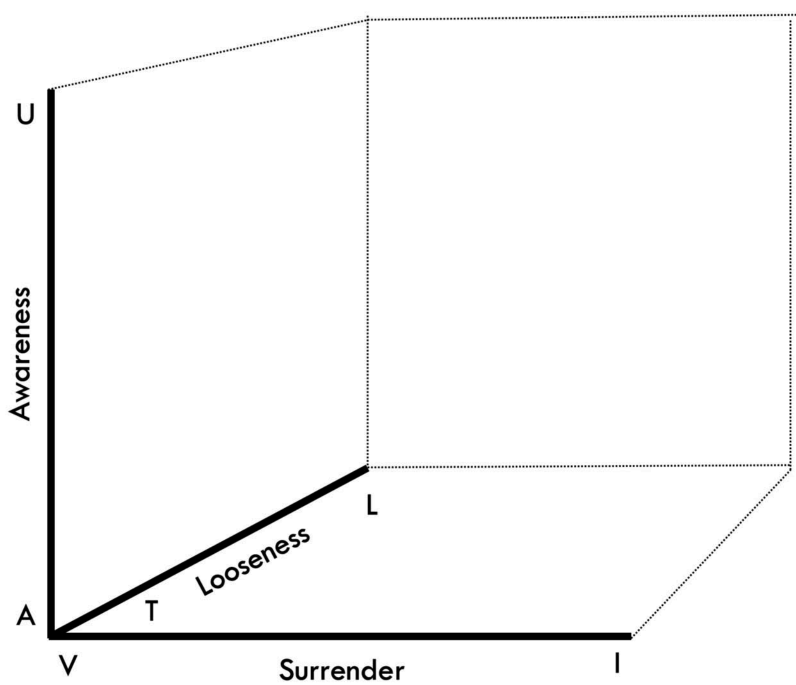

Figure 12. The three-dimensional design taxonomy for contesting control.

Corner	*Broncomatic*	*The Disadvantages of Time Travel*	Muzicodes
Voluntary, Aware, Tight	**Controlled breathing at the start of the ride (when control is tight)**	**Deliberate use of blinking to cut away from or hold a scene**	**Deliberately and successfully executing tightly defined codes on a MIDI instrument**
Voluntary, Unaware, Tight	*Flow state of controlled breathing near start of the ride*	*Entering a state of immersion in the film while still systematically controlling it using blinking*	*A new performer executes tight codes on a MIDI instrument by playing the score without knowing the codes are present*
Voluntary, Aware, Loose	**Controlled breathing later in the ride (when control is looser)**	*Using attention or meditation to exert some control over the video mix*	**Deliberately and successfully executing loosely defined codes using audio recognition**
Voluntary, Unaware, Loose	*Flow state of controlled breathing later in the ride*	*Entering a state of immersion in the film while still systematically controlling it using attention or meditation*	*Successfully executing loosely defined codes using audio recognition by following the score without knowing that the codes are present*
Involuntary, Aware, Tight	**Aware that one cannot keep holding one's breath at the start when control is tight**	**Aware of inability to refrain from blinking as eyes dry**	*Being aware of triggering a wrong code on a MIDI instrument due to not being able to play the score correctly*
Involuntary, Unaware, Tight	**Riding the *Broncomatic* as normal near the start of the ride**	**Unaware of how one's autonomic blinking is controlling the film**	*Being unaware of triggering wrong codes on a MIDI instrument due to not being able to play the score correctly*
Involuntary, Aware, Loose	*Becoming aware that one has lost control of breathing later on in the ride.*	*Becoming aware of one's changes in attention of mediation that arise in response to and also affect the film*	*Being aware of triggering a wrong code with audio recognition due to not being able to play the music correctly or inaccurate system response*
Involuntary, Unaware, Loose	**Focusing on hanging on for dear life later in the *Broncomatic* ride**	**Being unaware of how measures of attention and meditation are affecting the film**	*Being unaware of triggering a wrong code with audio recognition due to not being able to play the music correctly or inaccurate system response*

Figure 13. Populating the design space with examples from the case studies (bold text shows examples observed in studies while italic text shows hypothetical examples).

they experienced a heightened awareness of their own breathing and imminent lack of control as they held their breath to try and control the ride, before losing control and being rapidly thrown off. Journey 2 is quite different, representing the strategy of "holding on for dear life." While the rider may well begin with some awareness of the nature of control from the initial explanation, this is quickly lost as they focus on physically staying on the ride rather than trying to control it. Control of the ride then rapidly becomes involuntary, although they may succeed in retaining control over their own bodily actions and responses a long way into the ride, before eventually losing this too as they are thrown off. These two journeys broadly reflect the two quite different skills involved in riding the *Broncomatic* – the ability to control one's breathing (Journey 1) versus the ability to physically hang onto the ride (Journey 2). They also mirror Jäger et al.'s (2017) observation of how bodily synchronization with a breath-controlled tent (a biofeedback device that encouraged relaxation) appeared to involve two distinct mechanisms; interbodily resonance between two communicating parties (human and tent), or secondary control involving the adjustment of one's expectations so as to maintain the pretense of control.

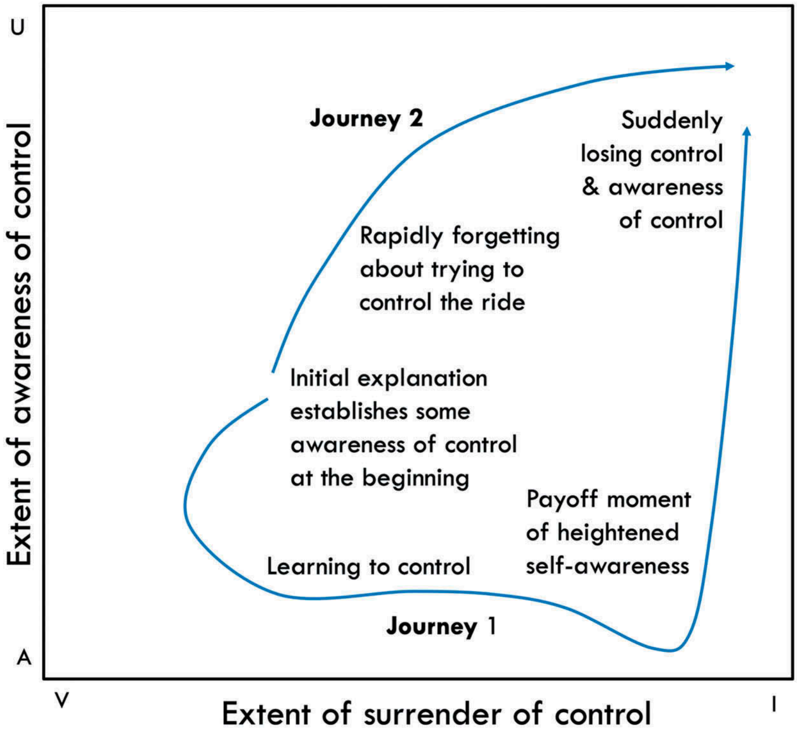

Figure 14. Journeys through control for the *Broncomatic*.

Journeys through control in *The Disadvantages of Time Travel* appear to be more complex with viewers potentially cycling around the space of control in various ways. Figure 15 summarizes the various kinds of steps around the space that we observed in our study, synthesized into an overall hypothetical journey through the experience. A common first step (1) was a realization that there is some form of interactive control, which may take place prior to engaging, for example, on the recommendation of a friend, or sometimes during the early stages of the experience itself. Humans might then experiment with the system (2), developing an internal model (though not always an accurate or complete one) and learning to exercise a degree of control. Becoming immersed in the film (3) might then cause the viewer to become less aware of their own direct control, potentially even experiencing a state of flow. However, various other events might then trigger other transitions around the space of control, potentially tipping them back-and-forth between being more or less voluntary and more or less aware. A change in the film might serve to remind them of control (4). They might surrender control, for example, through drying eyes (5) or due to an external distraction (8). They might consciously increase their level of voluntary control, for example, by refraining from blinking to prolong a scene (6), or a new scene might grab their attention (7). While no single participant may have taken the exact journey depicted, the general form is typical of the journeys of control that were experienced by viewers and serves to summarize key factors that an interaction designer (in this case filmmaker) might wish to consider in trying to shape the experience.

Finally, we can extend this idea of journeys through control to include the dimension of looseness. Taking muzicodes as our example, a musician may achieve a looser or tighter relationship with their instrument and wider performance system over the course of a single performance, many performances, or indeed a whole lifetime of perfecting their art. As summarized in Figure 16, a beginner may start with a very loose relationship with their instrument, as well as a lack of voluntary control and even awareness of control in large part due to their own lack of skill (1) – both knowledge and bodily control. Learning to master the instrument – and often also investing in superior instruments along the way – may eventually lead to a situation in which they have acquired a far higher degree of voluntary control over their

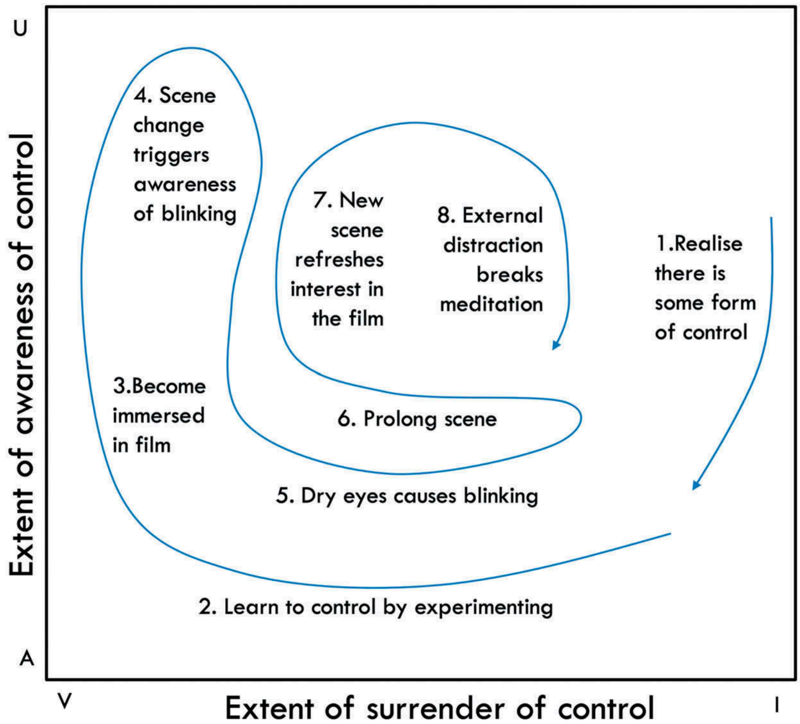

Figure 15. Journeys through control for the *The Disadvantages of Time Travel.*

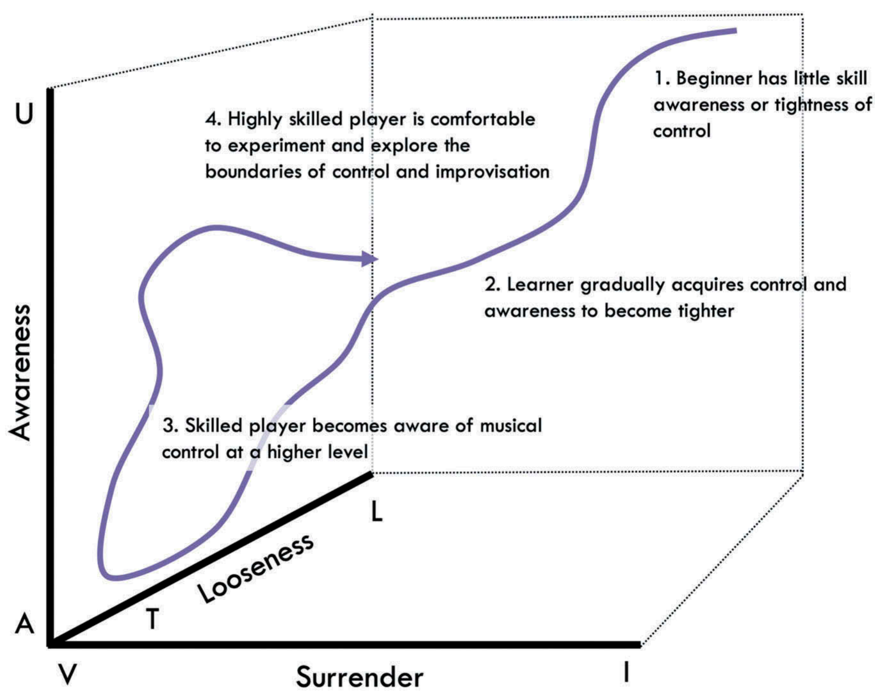

Figure 16. Journeys through control for the muzicodes.

instrument, with a high self-awareness of their own playing and greater control over how the instrument responds to their actions. A key part of this may be the process of *attunement* that we saw with muzicodes where the musician gradually learns how to tune the software to their instrument and personalized style of playing (2), using various filters and parameters to achieve a tighter mapping between their actions and its responses. However, becoming even more skilled and experienced may then actually involve some relaxation of control (3). Their awareness of direct control may reduce as they begin to focus attention on other matters – higher-level interpretation of the music or engagement with the audience – or they may experiment with unusual looser set-ups and mappings or be willing to improvise around unpredictable system responses (4).

5. Discussion

Having introduced our framework, we now consider its wider implications, returning to the two themes highlighted in our earlier review of related work – embodied interaction and autonomy.

5.1. *Embodied interaction revisited*

Our paper directly addresses calls for HCI to focus on the role of the body in embodied interaction, and in particular to adopt a more holistic approach toward designing for both mind and body (Höök et al., 2016; Klemmer et al., 2006). While we concur with the need for such an approach, we recognize that the mind and body can also be in tension and that this can provide a resource for design as well as a challenge to be addressed. Our dimension of self-awareness considers how people may become more or less aware of their own bodily control over the course of an experience. In our case studies, and consequent framework, mind, and body are not always in perfect synchronization, but rather people pass through different states of self-awareness of their bodily experience. Thus, while users may engage in implicit (Ju & Leifer, 2008) or unconscious (Wakkary et al., 2016) interactions, moments of consciousness and attention to the body are certainly present, including the possibility for heightened self-awareness of one's own state. But so are moments in which one is immersed in the content of a film or lost in the flow of a musical performance. Similarly, our experiences provide examples of how users may move back-and-forth between mindful and more 'mindless' or subconscious interactions, i.e., between System 1 and System 2 thinking as discussed earlier (Gawronski & Creighton, 2013), sometimes directly reacting to stimuli and at other times reflecting on planning their interactions with the system. This was especially evident in *The Disadvantages of Time Travel* in which some viewers tipped back-and-forth between the two modes in a highly fluid manner. We, therefore, recognize that multiple states of mind-body connection and separation are possible, often inevitable and even desirable as part of embodied experiences. This latter point about potential desirability is important here. While moments of mind-body separation can be problematic, removing users from immersion, flow, or mindfulness, this can also be beneficial, creating moments of introspection, reflection, and heightened self-awareness as a way of provoking interpretation. There is an ambiguity in the somewhat slippery nature of the relationship between mind and body that demands interpretation, reflecting the argument by Gaver et al. (2003) and Sengers and Gaver (2006) about how ambiguity in interactive artworks (and potentially other kinds of experience too) can serve to provoke interpretation and meaning-making.

Somaesthetic approaches to designing embodied interactions appear to lean toward the design of mindful, relaxed, and broadly comfortable interactions, at least as practiced so far, though this is perhaps not inherent to the approach. However, as our experience with the *Broncomatic* reveals, creatively engaging the tension between mind and body can also contribute to the visceral aspects of the uncomfortable interactions (Benford et al., 2012) that underlie many playful and thrilling experiences. It may be that the mind-body separation is not the only dualism that we are confronting here – but that HCI also needs to further explore the dualism between the comfortable and uncomfortable – between the wholesome and the provocative – as being closely related aspects of bodily experience that are in a potentially productive tension. Looking beyond thrilling experiences such as rides, this tension can be also found in the challenge of negotiating the limits of comfort and discomfort and physical and mental capabilities in sports, for example, in exergames within HCI. We suggest that it might potentially also play a role in rehabilitation and pain management in health care for example.

An important aspect of our framework is the idea of shaping journeys through experiences that both introduce and resolve tensions between mind and body. This reflects previous arguments about designing journeys that both setup but also resolve uncomfortable interactions (Benford et al., 2012) based on Gustav Freytag's (1862) five-act structure of theatrical performance (exposition, rising action, climax, falling action, and dénouement), which can be seen as a specific example of the wider approach of designing trajectories through so-called 'hybrid' experiences that mix digital interactions with physically embodied experience (Benford et al., 2009).

Thus, while we agree with calls for more holistic approaches to mind-body experiences in embodied interaction, we suggest that more attention be paid to the inherent tension between mind and body and argue for a broad range of strategies that encourage mindful and meditative reflections, skilled flow and playful exertion. Our conceptual framework reveals new possibilities and strategies to help broaden the palette of options available to designers.

5.2. *Autonomy revisited*

While our case studies are not directly of autonomous systems (typically involving quite simple interaction algorithms rather than the overt use of artificial intelligence, and in which systems are tightly coupled to humans rather than being independent of them), both *Broncomatic* and *Climb!* exhibit robot-like features in the manner in which they engage humans with physically actuated systems that push back at the human bodily experience, and that engender something of the feeling of being a partner in the interaction. Our findings raise three implications for how humans might experience such systems in the future.

5.2.1. *Considering the human experience of autonomy*

First, our framework emphasizes the *human perspective* on interaction with autonomous systems. Previous frameworks and concepts have tended to view autonomy from a system point of view: what does it mean for a system to become increasingly autonomous and what forms or levels of autonomy might be at play? In contrast, we consider how it feels from a human point of view to contest control with such systems and to relinquish one's autonomy. We highlight how, by carefully considering unfolding journeys through surrender, self-awareness, and looseness of control, designers might shape experiences in which humans experience the sensation of losing control and ultimately may learn to control such systems. Our argument for emphasizing the human experience of autonomy speaks to the psychological concept of 'locus of control' (Lefcourt, 2014), which broadly reflects whether humans see themselves (internal locus) or external forces (external locus) as controlling a given situation. This concept has found its way into HCI in the form of one of Shneiderman's eight golden rules for the design of Direct Manipulation Interfaces – that the of locus control should remain with the user (Shneiderman, 1993; Shneiderman & Plaisant, 2010). Our paper emphasizes that the sense of being in control (or otherwise) is indeed important to interact with autonomous systems, but that it is important to recognize and even emphasize the inherently contested nature of such control, and the powerful experience of yielding control from a human point of view.

5.2.2. *Engaging autonomic responses*

We emphasize that interactions that rely on sensing and actuating partially autonomic bodily functions such as breathing, blinking, gaze, heart rate, sweating, and others need to consider that the user is increasingly battling for control of their internal autonomic as well as external autonomous systems, which opens up new possibilities for how one can lose control. Whereas previous discussions of 'initiative' in implicit interactions (Ju & Leifer, 2008) and of mixed-initiative interactions in general

(Horvitz, 1999) have viewed control as shifting between human and system, we emphasize the sensation of loss of control, to both computer systems but also human (internal autonomic) systems that arises when physiological sensors and actuators closely couple the two. And whereas Ju and Leifer's notion of 'attentional demand' considers how much an external system demands our attention, our dimension of self-awareness shifts the focus to consider how the human's attention may vary throughout the interaction, which may be due to the system demanding their attention but also due to their own internal thoughts and feelings. Thus, our framework encourages designers to consider how contesting control is experienced by the human in an interactive loop and how this involves a negotiation with their own thoughts and bodily systems, as well as with an external system.

This perspective on autonomy perhaps speaks most strongly to a class of autonomous system that may emerge in the future in which the role of computer systems is to directly help us control our own bodies. Technologies such as prosthetics, orthotics, implants (pacemakers and drug release), electrical muscle stimulation (e.g., (Tamaki et al., 2011)) and transcranial magnetic stimulation (Chen, 1997) point toward future interactions that are directly coupled to human physiological systems, including autonomic ones, and so very directly raise questions about the extent to which can we control ourselves as well as an external system. The same might be argued of affective computing technologies (Picard, 2000) that attempt to recognize aspects of the visible manifestation of our emotions such as facial expressions and tone of voice that may at times 'leak' from humans in spite of their attempts to control themselves.

5.2.3. *Play and improvisation*

Third, we have called attention to the potentially playful nature of contesting control. While much of the focus on the design of autonomous systems has, quite rightly, been on matters of safety, comfort, and the ethics of taking control away from humans, we note that contesting control also speaks to a sense of playfulness, thrill, and excitement that may arise from the possibility and experience of losing control; this is after all, one of the reasons that many people elect to ride rollercoasters (Benford et al., 2012) or enjoy the challenge of playing games that test the limits of their mental or physical capabilities. Our framework also speaks to important questions around what it means to improvise with autonomous systems. Previous research into interactive music technologies has, for example, explored the design of autonomous robot musicians that perform on stage alongside humans as part of human-robot ensembles (Bretan & Weinberg, 2016). In testing the limits of our own control, such systems might push our limits as human performers, leading us to improvise new responses and ultimately extend our repertoire of creative interactions. Our own work has recently explored the idea of how failure can be an esthetically vital aspect of interactive performance, showing how humans may adopt strategies toward 'capable systems' such as taming, gaming, riding, or even becoming them (Hazzard et al., 2019). The framework for contesting control introduced in this paper highlights ways in which control may tip back-and-forth between human and system as being key aspects of improvisation. Of course, as Suchman (1987) pointed out, plans, in general, serve as resources to support situated action, by which we mean that human-system improvisation will no doubt be an important issue in our interactions will all kinds of autonomous systems, even those that emphasize values of comfort and safety such as autonomous vehicles.

6. Conclusion

We have introduced a conceptual framework for understanding and designing for contesting control as part of embodied interactions. Our framework is primarily targeted at the use of physiological interfaces to support bodily forms of interaction. It is also intended to be relevant to situations in which a physically actuated system pushes back at the human body, which in turn influences its responses as part of a tightly coupled human-in-the-loop system.

Our framework is grounded in the practice-led experience of designing and studying cultural applications such as rides, games, and performances. We suggest that applications such as these can benefit from playful forms of interaction in which the degree of ambiguity (Gaver et al., 2003) involved in contesting control may contribute to the design goals of curiosity, playful discovery, and provoking interpretation (Sengers & Gaver, 2006), while engendering a degree of discomfort may support the broader pursuit of entertainment, enlightenment, or sociality (Benford et al., 2012). This said, we anticipate that our framework might also speak to the design of more 'serious' applications that involve bodily interactions, for example, computer-controlled prosthetics and orthotics – which also raise new opportunities and challenges due to interactions not being entirely under the control of humans, including them not being able to control their own bodily actions. We, therefore, close our argument by proposing three potential uses of our framework.

(1) **Sensitizing HCI to new ways of seeing interaction**. First and foremost, it is an attempt to persuade HCI to expand how it views bodily interaction. This is necessary as HCI engages with new technologies that behave differently to conventional ones. Physiological interfaces may involve sensing and actuating bodily functions that users cannot fully control for themselves. It is also necessary as HCI engages with new domains such as the arts that may value different styles of interaction that are inherently ambiguous, unpredictable, and uncontrollable. As a taxonomy, our framework tries to generalize the essence of how (at least some) artists are approaching such technologies and interfaces, 'bringing it back' from the art world and explaining it in a way that should make sense to HCI researchers and practitioners. Of course, this may not be the way that the artists themselves would think of or explain it – though we hope they would at least recognize it.
(2) At a more detailed level, the design space and its constituent concepts (the dimensions and journeys that emerge from comparing them) might guide the analysis of future examples, providing **sensitizing concepts** (Bowen, 2006) to guide the grounded analysis of qualitative data gathered during studies.
(3) The framework might also potentially guide practice, distilling the (perhaps tacit) craft knowledge of artistic practitioners into a form that is reusable by others. In this case, the framework can be seen as a form of **intermediate design knowledge** (Höök & Löwgren, 2012) that bridges between the abstract world of theories, often from disciplines outside of HCI (the psychological notion of flow, for example) and specific design instances (our three case studies). Such intermediate design knowledge can take many forms, including design patterns, heuristics, guidelines, strong concepts and in this case, taxonomies.

We anticipate that the framework set out in this paper will at least serve our first purpose here – inspiring HCI to reconsider the design of artistic and playful interfaces – but perhaps other interfaces too – that employ embodied interaction and physiological sensing.

Acknowledgments

We would like to thank Patrick Brundell for taking some of the photograph images at events.

Background

This article draws upon the insights gained from three separate performance-led research-in-the-wild projects to reflect on the emergent, contested, and ambiguous nature of interaction with responsive technology.

Data access statement

Following ethical review, consent was not gained from participants to release personal data and interview transcripts online, and so datasets from the case studies are not openly available.

Funding

This work was supported by the Engineering and Physical Sciences Research Council through the Horizon Centre for Doctoral Training [grant number EP/G037574/1] and the FAST Project [grant number EP/L019981/1].

Notes on contributors

Steve Benford (steve.benford@nottingham.ac.uk, https://nottingham.ac.uk/computerscience/people/steve.benford) is a Computer Scientist with an interest in Mixed Reality and performance-led research in the wild; he is a Dunford Professor in the Mixed Reality Lab at the University of Nottingham.

Richard Ramchurn (richard.ramchurn@nottingham.ac.uk, https://nottingham.ac.uk/research/groups/mixedrealitylab/people/richard.ramchurn) is a filmmaker and researcher with an interest in brain-controlled cinema; he is a PhD Student in the Mixed Reality Lab at the University of Nottingham.

Joe Marshall (joe.marshall@nottingham.ac.uk, https://nottingham.ac.uk/computerscience/people/joe.marshall) is a Computer Scientist with an interest in creating full body interactive experiences; he is an Assistant Professor in the Mixed Reality Lab at the University of Nottingham.

Max L. Wilson (max.wilson@nottingham.ac.uk, https://nottingham.ac.uk/computerscience/people/max.wilson) is a Computer Scientist with an interest in Brain-based Human-Computer Interaction as a form of personal data; he is an Associate Professor in the Mixed Reality Lab at the University of Nottingham.

Matthew Pike (matthew.pike@nottingham.edu.cn, https://www.nottingham.edu.cn/en/science-engineering/staffprofile/matthew-pike.aspx) is a Computer Scientist with an interest in Brain-Computer Interaction and Digital Wellbeing; he is an Assistant Professor of Computer Science in the School of Computer Science at the University of Nottingham in Ningbo China.

Sarah Martindale (Sarah.Martindale@nottingham.ac.uk, https://nottingham.ac.uk/clas/departments/culturalmediaandvisualstudies/people/sarah.martindale) is an audience researcher with an interest in how people attach meaning and value to digital interactions and new media; she is a Nottingham Research Fellow in the Department of Cultural, Media and Visual Studies at the University of Nottingham.

Adrian Hazzard (Adrian.Hazzard@nottingham.ac.uk, https://nottingham.ac.uk/computerscience/people/adrian.hazzard) is a Musician, Composer, and Researcher with an interest in the intersection between human computer interaction (HCI), music and performance; he is a Research Fellow in the Mixed Reality Lab at the University of Nottingham.

Chris Greenhalgh (chris.greenhalgh@nottingham.ac.uk, https://nottingham.ac.uk/computerscience/people/chris.greenhalgh) is a Computer Scientist with an interest in interactive and multi-user applications and the technical platforms and tools that support them; he is a Professor in the Mixed Reality Lab at the University of Nottingham.

Maria Kallionpää (makallio@hkbu.edu.hk, http://mus.hkbu.edu.hk/Maria_Kallionpaa.html) is a composer and pianist, with an interest in designing a music engine that uses gamification as a composition technique; she is an Assistant Professor in the Department of Music at the Hong Kong Baptist University.

Paul Tennent (paul.tennent@nottingham.ac.uk, https://nottingham.ac.uk/computerscience/people/paul.tennent) is a Computer Scientist with an interest in interdisciplinary working with artists on creative applications of a range of technologies; he is an Assistant Professor in the Mixed Reality Lab at the University of Nottingham.

Brendan Walker (brendan@studiogogo.ltd, http://www.studiogogo.ltd) is an artist, thrill engineer, television presenter and founder-director of Studio Go Go Limited. He currently holds the post of Professor of Creative Industries at Middlesex University, and has previously held posts as Deputy Head of Design Interactions at the Royal College of Art, and Senior Research Fellow in Computer Science at the University of Nottingham.

ORCID

Steve Benford http://orcid.org/0000-0001-8041-2520
Richard Ramchurn http://orcid.org/0000-0002-5510-1840
Joe Marshall http://orcid.org/0000-0001-9666-786X
Max L. Wilson http://orcid.org/0000-0002-3515-6633
Matthew Pike http://orcid.org/0000-0002-1543-0148

Sarah Martindale http://orcid.org/0000-0002-0427-5672
Adrian Hazzard http://orcid.org/0000-0003-0286-960X
Chris Greenhalgh http://orcid.org/0000-0003-3483-2422
Maria Kallionpää http://orcid.org/0000-0002-2709-3193
Paul Tennent http://orcid.org/0000-0001-6391-0835
Brendan Walker http://orcid.org/0000-0002-7217-3950

References

Adams, A. T., Costa, J., Jung, M. F., & Choudhury, T. (2015). Mindless computing: Designing technologies to subtly influence behavior. In *Proceedings of the 2015 acm international joint conference on pervasive and ubiquitous computing* (p. 719–730). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/2750858.2805843

Allen, J. E., Guinn, C. I., & Horvtz, E. (1999, September). Mixed-initiative interaction. *IEEE Intelligent Systems and Their Applications*, *14*(5), 14–23. https://doi.org/10.1109/5254.796083

Bartneck, C., & Forlizzi, J. (2004, September). A design-centred framework for social human-robot interaction. In *Roman 2004. 13th ieee international workshop on robot and human interactive communication (ieee catalog no.04th8759), Kurashiki, Okayama, Japan* (p. 591–594). https://doi.org/10.1109/ROMAN.2004.1374827

Bawden, M., & Maynard, I. (2001). Towards an understanding of the personal experience of the 'yips' in cricketers. *Journal of Sports Sciences*, *19*(12), 937–953. https://doi.org/10.1080/026404101317108444 (PMID: 11820688)

Beavers, G., & Hexmoor, H. (2004). Types and limits of agent autonomy. In: Nickles M., Rovatsos M., Weiss G. (eds) *Agents and Computational Autonomy. AUTONOMY 2003*. Lecture Notes in Computer Science, vol 2969. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-25928-2_8

Benford, S., Giannachi, G., Koleva, B., & Rodden, T. (2009). From interaction to trajectories: Designing coherent journeys through user experiences. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 709–718). New York, NY: Association for Computing Machinery. https://doi.org/10.1145/1518701.1518812

Benford, S., Greenhalgh, C., Crabtree, A., Flintham, M., Walker, B., Marshall, J., … Adams, M. (2013, July). Performance-led research in the wild. *ACM Transactions on Computer-Human Interaction*, *20*(3), 1–22. https://doi.org/10.1145/2491500.2491502

Benford, S., Greenhalgh, C., Giannachi, G., Walker, B., Marshall, J., & Rodden, T. (2012). Uncomfortable interactions. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 2005–2014). New York, NY, USA. Association for Computing Machinery. https://doi.org/10.1145/2207676.2208347

Bowen, G. A. (2006). Grounded theory and sensitizing concepts. *International Journal of Qualitative Methods*, *5*(3), 12–23. https://doi.org/10.1177/160940690600500304

Bradshaw, J. M., Feltovich, P. J., Jung, H., Kulkarni, S., Taysom, W., & Uszok, A. (2004). Dimensions of adjustable autonomy and mixed-initiative interaction. In M. Nickles, M. Rovatsos, & G. Weiss (Eds.), *Agents and computational autonomy* (pp. 17–39). Springer Berlin Heidelberg.

Bradshaw, J. M., Feltovich, P. J., & Johnson, M. (2011). Human–agent interaction. In Guy A. Boy (Ed.), *The handbook of human-machine interaction* (pp. 283–300). CRC Press.

Bretan, M., & Weinberg, G. (2016). A survey of robotic musicianship. *Communications of the ACM*, *59*(5), 100–109. https://doi.org/10.1145/2818994

Chen, R., Classen, J., Gerloff, C., Celnik, P., Wassermann, E. M., & Hallett, M., & Cohen, L.G. (1997). Depression of motor cortex excitability by low-frequency transcranial magnetic stimulation. Neurology 48 (5). doi:10.1212/WNL.48.5.1398

Csikszentmihalyi, M. (1991). *Flow, the psychology of optimal experience, steps towards enchancing the quality of life*. Harper & Row.

Dehaene, S., Changeux, J.-P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences*, *10*(5), 204–211. https://doi.org/10.1016/j.tics.2006.03.007

Descartes, R. (1641). Meditations on first philosophy. In S. R. J. Cottingham & D. Murdoch (Eds.), *The philosophical writings of rené descartes* (Vol. ii, pp. 1–62). Cambridge University Press.

Dourish, P. (2004). *Where the action is: The foundations of embodied interaction*. MIT press.

Gaver, W. W., Beaver, J., & Benford, S. (2003). Ambiguity as a resource for design. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 233–240). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/642611.642653

Gawronski, B., & Creighton, L. A. (2013). Dual-process theories. In D. Carlston (Ed.), *The Oxford handbook of social cognition* (pp. 282–312). Oxford University Press.

Goodrich, K. H., Schutte, P. C., Flemisch, F. O., & Williams, R. A. (2006). Application of the h-mode, a design and interaction concept for highly automated vehicles, to aircraft. In *25th digital avionics systems conference,* Portland, OR (pp. 1–13).

Goodrich, M. A., & Schultz, A. C. (2008). Human–robot interaction: A survey. *Foundations and Trends in Human–Computer Interaction*, *1*(3), 203–275. https://doi.org/10.1561/1100000005

Greenhalgh, C., Benford, S., & Hazzard, A. (2016). mˆ uzicode: Composing and performing musical codes. In *Proceedings of the audio mostly 2016* (p. 47–54). New York, NY Association for Computing Machinery. https://doi.org/10.1145/2986416.2986444

Greenhalgh, C., Benford, S., Hazzard, A., & Chamberlain, A. (2017). Playing fast and loose with music recognition. In *Proceedings of the 2017 chi conference on human factors in computing systems* (p. 4302–4313). New York, NY Association for Computing Machinery. https://doi.org/10.1145/3025453.3025900

Grierson, M., & Kiefer, C. (2011). Better brain interfacing for the masses: Progress in event-related potential detection using commercial brain computer interfaces. In *Chi '11 extended abstracts on human factors in computing systems* (p. 1681–1686). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/1979742.1979828

Hazzard, A., Greenhalgh, C., Kallionpää, M., Benford, S., Veinberg, A., Kanga, Z., & McPherson, A. (2019). Failing with style: Designing for aesthetic failure in interactive performance. In *Proceedings of the 2019 chi conference on human factors in computing systems*. New York, NY: Association for Computing Machinery. https://doi.org/10.1145/3290605.3300260

Hicks, R. D. (1907). *De anima: With translation, introduction and notes*. Cambridge University Press.

Höök, K. (2008). Affective loop experiences–what are they? In: Oinas-Kukkonen H., Hasle P., Harjumaa M., Segerståhl K., Øhrstrøm P. (eds) *Persuasive Technology. PERSUASIVE 2008* . Lecture Notes in Computer Science, vol 5033. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-68504-3_1

Höök, K., Jonsson, M. P., Sta°hl, A., & Mercurio, J. (2016). Somaesthetic appreciation design. In *Proceedings of the 2016 chi conference on human factors in computing systems* (p. 3131–3142). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/2858036.2858583

Höök, K., & Löwgren, J. (2012, October). Strong concepts: Intermediate-level knowledge in interaction design research. *ACM Transactions on Computer-Human Interaction*, *19*(3), 3. https://doi.org/10.1145/2362364.2362371

Horvitz, E. (1999). Principles of mixed-initiative user interfaces. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 159–166). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/302979.303030

Jäger, N., Schnädelbach, H., Hale, J., Kirk, D., & Glover, K. (2017, July). Reciprocal control in adaptive environments. *Interacting with Computers*, *29*(4), 512–529. https://doi.org/10.1093/iwc/iww037

Ju, W., & Leifer, L. (2008). The design of implicit interactions: Making interactive systems less obnoxious. *Design Issues*, *24*(3), 72–84. https://doi.org/10.1162/desi.2008.24.3.72

Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan.

Kallionpää, M., Greenhalgh, C., Hazzard, A., Weigl, D. M., Page, K. R., & Benford, S. (2017). Composing and realising a game-like performance for disklavier and electronics. In *Proceedings of new interfaces for musical expression* (p. 464–469). New York, NY. Association for Computing Machinery.

Klemmer, S. R., Hartmann, B., & Takayama, L. (2006). How bodies matter: Five themes for interaction design. In *Proceedings of the 6th conference on Designing Interactive systems* (DIS '06) (p. 140–149). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/1142405.1142429

Klemmer, S. R., Hartmann, B., & Takayama, L. (2006). How bodies matter: Five themes for interaction design. In *Proceedings of the 6th conference on designing interactive systems* (p. 140–149). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/1142405.1142429

Langer, E. J. (2000). Mindful learning. *Current Directions in Psychological Science*, *9*(6), 220–223. https://doi.org/10.1111/1467-8721.00099

Lefcourt, H. M. (2014). *Locus of control: Current trends in theory & research*. Psychology Press.

Leslie, G., & Mullen, T. (2011). Moodmixer: Eeg-based collaborative sonification. In *Proceedings of the international conference on new interfaces for musical expression*, Oslo, Norway (pp. 296–299).

Luo, A., & Sullivan, T. J. (2010). A user-friendly ssvep-based brain–computer interface using a time-domain classifier. *Journal of Neural Engineering*, *7*(2), 2. https://doi.org/10.1088/1741-2560/7/2/026010

Marshall, J., Rowland, D., Rennick Egglestone, S., Benford, S., Walker, B., & McAuley, D. (2011). Breath control of amusement rides. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 73–82). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/1978942.1978955

McCulloch, R., & Crisp, V. (2016). 'watch like a grown up … enjoy like a child': Exhibition, authenticity, and film audiences at the prince charles cinema. *Participations: Journal of Audience & Reception Studies*, *13*(1), 188–217. https://www.participations.org/Volume%2013/Issue%201/S1/4.pdf

Mueller, F. F., Edge, D., Vetere, F., Gibbs, M. R., Agamanolis, S., Bongers, B., & Sheridan, J. G. (2011). Designing sports: A framework for exertion games. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 2651–2660). New York, NY, : Association for Computing Machinery. https://doi.org/10.1145/1978942.1979330

Murch, W. (2001). *In the blink of an eye* (Vol. 995). Silman-James Press Los Angeles.

Norman, D. A. (1986). Cognitive engineering. In D.A. Norman & S.W. Draper. (Eds), *User Centered System Design; New Perspectives on Human-Computer Interaction* L. Erlbaum Associates Inc., USA.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and cybernetics-Part A: Systems and Humans*, *30*(3), 286–297. https://doi.org/10.1109/3468.844354

Patel, S., Henderson, R., Bradley, L., Galloway, B., & Hunter, L. (1991). Effect of visual display unit use on blink rate and tear stability. *Optometry and Vision Science*, *68*(11), 888–892. https://doi.org/10.1097/00006324-199111000-00010

Picard, R. W. (2000). *Affective computing*. MIT press.

Pike, M., Ramchurn, R., Benford, S., & Wilson, M. L. (2016). scanners: Exploring the control of adaptive films using brain-computer interaction. In *Proceedings of the 2016 chi conference on human factors in computing systems* (p. 5385–5396). New York, NY. Association for Computing Machinery. https://doi.org/10.1145/2858036.2858276

Pinder, C., Vermeulen, J., Cowan, B. R., & Beale, R. (2018, June). Digital behaviour change interventions to break and form habits. *ACM Transactions on Computer-Human Interaction*, *25*(3), 1–66. https://doi.org/10.1145/3196830

Plato (390-347 BC). Platonis opera. In E. A. Duke, W. F. Hicken, W. S. M. Nicoll, D. B. Robinson, & J. C. G. Strachan (Eds.). *Euthyphro, apologia socratis, crito, phaedo, cratylus, theaetetus, sophistes, politicus* (Vol. 1). Clarendon Press.

Pohl, H., & Murray-Smith, R. (2013). Focused and casual interactions: Allowing users to vary their level of engagement. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 2223–2232). New York, NY, Association for Computing Machinery. https://doi.org/10.1145/2470654.2481307

Schnädelbach, H., Rennick Egglestone, S., Reeves, S., Benford, S., Walker, B., & Wright, M. (2008). Performing thrill: Designing telemetry systems and spectator interfaces for amusement rides. In *Proceedings of the sigchi conference on human factors in computing systems* (p. 1167–1176). New York, NY, Association for Computing Machinery. https://doi.org/10.1145/1357054.1357238

Sengers, P., & Gaver, B. (2006). Staying open to interpretation: Engaging multiple meanings in design and evaluation. In *Proceedings of the 6th conference on designing interactive systems* (p. 99–108). New York, NY, Association for Computing Machinery. https://doi.org/10.1145/1142405.1142422

Serim, B., & Jacucci, G. (2019). Explicating "implicit interaction": An examination of the concept and challenges for research. In *Proceedings of the 2019 chi conference on human factors in computing systems*. New York, NY, Association for Computing Machinery. https://doi.org/10.1145/3290605.3300647

Shneiderman, B. (1993). 1.1 direct manipulation: A step beyond programming languages. In B. Shneiderman (Ed.), *Sparks of innovation in human-computer interaction* (p. 17–38). Ablex Publishers.

Shneiderman, B., & Plaisant, C. (2010). *Designing the user interface: Strategies for effective human-computer interaction*. Pearson Education India.

Shusterman, R. (2008). *Body consciousness: A philosophy of mindfulness and somaesthetics*. Cambridge University Press.

Suchman, L. A. (1987). *Plans and situated actions: The problem of human-machine communication*. Cambridge University Press.

Sudnow, D. (1993). *Ways of the hand: The organization of improvised conduct*. MIT Press.

Tamaki, E., Miyaki, T., & Rekimoto, J. (2011). Possessed and: Techniques for controlling human hands using electrical muscles stimuli. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 543–552). New York, NY, Association for Computing Machinery. https://doi.org/10.1145/1978942.1979018

Wakkary, R., Desjardins, A., & Hauser, S. (2016). Unselfconscious interaction: A conceptual construct. *Interacting with Computers*, *28*(4), 501–520. https://doi.org/10.1093/iwc/iwv018

Zioga, P., Chapman, P., Ma, M., & Pollick, F. (2017). Enheduanna–a manifesto of falling: First demonstration of a live brain-computer cinema performance with multi-brain BCI interaction for one performer and two audience members. *Digital Creativity*, *28*(2), 103–122. https://doi.org/10.1080/14626268.2016.1260593