Audio-Haptic Relationships as Compositional and Performance Strategies

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Abstract

As a performer of firstly acoustic and latterly electronic and electro-instrumental music, I constantly seek to improve my mode of interaction with the digital realm: that is, to achieve a high level of sensitivity and expression. This thesis illustrates reasons why making use of haptic interfaces—which offer physical feedback and resistance to the performer—may be viewed as an important approach in addressing the shortcomings of some the standard systems used to mediate the performer's engagement with various sorts of digital musical information.

By examining the links between sound and touch, and the performer-instrument relationship, various new compositional and performance strategies start to emerge. I explore these through a portfolio of original musical works, which span the continuum of composition and improvisation, largely based around performance paradigms for piano and live electronics. I implement new haptic technologies, using vibrotactile feedback and resistant interfaces, as well as exploring more metaphorical connections between sound and touch. I demonstrate the impact that the research brings to the creative musical outcomes, along with the implications that these techniques have on the wider field of live electronic musical performance.

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(Lauren Sarah Hayes)

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List of Media Examples

Files are located in `/dissertation/media` *on the accompanying DVD.*

Hearing is a way of touching at a distance and the intimacy of the first sense (touching) is fused with sociability whenever people gather together to hear something special.

(Schafer, 1977, 11)

Chapter 1

Introduction

This thesis, the writings offered and the practice described within, presents my continuing exploration of various aspects of musical boundaries and continuums: the boundary between sound and sensation; the blurring of composition and improvisation; the meeting point of acoustic and electronic; the threshold between man and machine; and the liminality between performer, instrument and environment. It concerns a practice that sits, at least in certain respects, amongst current technological thinking regarding interaction design for instruments of digital or electronic music, touching on areas such as machine-listening, sensors, augmented instruments, and *hardware hacking* (Collins, 2009). Yet, it demands a reconsidered approach through phenomenological inquiry into the nature of our relationships with instruments and computers. But the essence of this work is not technological, nor is it philosophical, but rather it is fundamentally *musical*. It is the creation of new music and new musical experiences that I wish to elicit through this research and development.

1.1 Losing *Touch*?

In the current climate of musical human-computer interaction (HCI) development, there exists an ever expanding number of new (or novel) interfaces (or instruments) for musical expression (NIMEs)[1]. These may be truly unconventional creations, drawing on the technology of other fields such as medicine[2], or adapted and *augmented* traditional acoustic instruments. The richness and breadth of innovation within the field means that the results are highly diverse, and are in many cases extremely sophisticated and customised. In this paper, I describe the development of various performance environments and new technologies, which are indeed bespoke and created specifically within the context of my own creative practice. But rather than searching for the optimised NIME or attempting to prescribe a universally applicable methodology, I am seeking to examine the links between the sonic and the tangible and to readdress the rela-

[1]The acronym NIME employed in this way as a noun, was commonly in use at the International Conference on New Interfaces for Musical Expression, 2011, which I attended, and has been derived from the title of the conference series.

[2]An example would be the use of EEG devices which allow biofeedback to control musical parameters on a computer, such as those offered by BioControl Systems: http://www.biocontrol.com [accessed 16th May 2013].

tionships between the physical and the virtual in order to understand the musical implications that such enquiry might hold.

A fundamental change in the way that musicians engage with instruments occurred with the emergence of the first electronic musical inventions, which appeared at around the end of the nineteenth, and early twentieth centuries. The actual source of the non incidental musical sound being produced began to shift from within resonating physical materials to the electromagnetic circuitry of these new devices. For example, Thaddeus Cahill's Telharmonium (1897) produced tones by sending electrical signals over telephone wires (Weidenaar, 1995). Necessarily, the electronically produced sounds had to be transmitted over loudspeakers—or in the case of the Telharmonium: telephone receivers and, later, paper cones and horns—in order to be sufficiently made audible. One inevitable consequence of this was that the physical or tangible connection between the sonic output and the performer's action was increasingly reduced. These sounds were no longer the direct result of, for example, breath through a column of wood, or the bowing of a taught string, but were instead the product of amplification of electrical processes, mediated via a series of interactions which would produce the desired voltage. Moreover, the theremin's appearance in the early twentieth century—facilitated by its eponymous inventor Léon Theremin—paved the way for a whole breed of instruments designed to *liberate* performers from actually having to hold, or even make physical contact with the device in order to engage with it (Rovan & Hayward, 2000).

Cut to the present day, with Wii Remotes[3] strapped onto limbs, and more recently with the emergence of Microsoft's voice, gesture and movement recognition technology—the Kinect—and musicians may take on, with apparent ease, the roles of *dancer*, *conductor*, or perhaps more generically *performance artist*, so as to wave, waggle, gesticulate, or flail their way through a performance. The threshold between man and machine has been elegantly disintegrated through seamless technology (see Chapter 5), paving the way for the rapid emergence of systems comprising sensors, biofeedback, motion capture, and whole body interaction. In *Being and Time*, Martin Heidegger (2000) describes two modes of engaging with *instrumental* objects: firstly where the tool is transparent, or *ready-at-hand*, where the user is engaged in a sense of *flow* and is not continuously aware of the tool's presence; and the other state in which the tool again makes its existence known, being *present-at-hand*, when it obtrudes or distracts us from the task at hand when, for example, it breaks. Thor Magnusson and Enrike Hurtado (2008) suggest that while working with computer-based musical tools or instruments, we constantly fluctuate between these two modes of engagement. But when the instrument that we

[3]Wii Remotes are the controller most widely associated with the Nintendo Wii: http://www.nintendo.com/wii/what-is-wii/#/controls [accessed 16th May 2013].

are playing is removed from within the grip of our hands and the physiological constraints of our bodies, this fluctuation, friction, or *resistance* between the physical and virtual worlds becomes somewhat removed. As Microsoft's emphatic tagline for the Kinect suggests: "YOU ARE THE CONTROLLER. NO GADGETS, NO GIZMOS, JUST YOU!" (Microsoft, 2011).

Certainly, these *hands-free* systems are all fruitful and important developments within the field of HCI as a whole. Concerning *musical* applications, however, it cannot be denied that this *unchaining* (Rovan & Hayward, 2000) process breaks one of the most crucial feedback systems that has been embedded in musicians for centuries: that of tactile response. As Joseph Rovan and Vincent Hayward succinctly put it:

> But in the electronic world of synthesis algorithms and control rate data, open-air controllers are both divorced from the actual sound producing mechanisms, as well as from the body itself. Simply put, the computer music performer loses touch. (Rovan & Hayward, 2000, 299)

It is precisely this *losing of touch* that I experienced firsthand as I began incorporating computers and electronic instruments into my own musical practice that has led to this body of research. If indeed touch is the most highly developed of the senses, as some would claim (see Jütte, 2008, 5, for a discussion of the variable ranking of the importance of touch throughout history, beginning with Aristotle), why has the importance of touch been so often erroneously (I will argue) overlooked in the development of NIMEs? And in readdressing this sensory balance, what might the musical implications be for performance paradigms of live electronic musical practice? Simon Emmerson has questioned whether in the rupturing of bodily action and sonic gesture the performer is "Losing Touch?" (Emmerson, 2000, 194); I will specifically focus on the relationships between sound and touch *itself* as being key to understanding some of the current areas of contention in live electroacoustic and electro-instrumental performance practice.

1.2 Creative Practice: Reflexivity and Reflection

> With regard to epistemological issues the practitioner is the researcher; from this informed perspective, they identify researchable problems raised in practice, and respond through practice. The role is multifaceted - sometimes generator of the research material - art/design works, and participant in the creative process; sometimes self-observer through reflection on action and in action, and through discussion with others; sometimes observer of others for placing the research in context, and gaining other perspectives; sometimes co-researcher, facilitator and research manager, especially of a collaborative project. (Gray, 1996, 13)

The methodology of this research sits very much within that of creative practice, as described by artist and researcher, Carole Gray above. The questions that were being raised within my own practice became the very basis for undertaking further enquiry from a research perspective. It is perhaps not surprising that my training as a classical pianist, which began formally at the age of four, has led to an exploration of musical HCI that is largely focused around the expressive capacities of the fingers. I can clearly recall some of the frustrated feelings of separation and disconnect that I experienced from both my instrument, as well as the musical world that we were inhabiting together during my first attempts at regularly creating music with computers, commencing in 2007. One particular instance of this occurred when performing in a small laptop and electronic instrument ensemble with some colleagues from within the University of Edinburgh Music Department[4].

We are attempting to rehearse and perform a composition by one member of the group, and my role is to trigger a series of prominent, low frequency bass sounds, as notated in the graphic score that we are working from. The score had initially been created as a listening guide to the piece, and we are attempting to perform it as a live ensemble. As is the nature of the particular Max/MSP patch that I am using, which has been cobbled together from tutorial exercises and snippets of code that I am picking up as I learn the software, all that I have to do in order to achieve these sounds is to click a button (a Max/MSP *bang* object) on the screen, using the trackpad of my laptop. This will trigger an enveloped sine wave oscillator. I click as required, producing the desired rumbles through the speakers and subwoofer, but I do not feel that I am in any way *performing* the music. The performance gesture—achieved by sweeping my finger over the trackpad, a few centimeters at most to find the button on the screen, followed by a small amount of pressure from my thumb to execute the click, all over within around a second—contains none of the effort, struggle, or physicality that I am used to engaging with, within a piano performance. My actions are, of course, in *real-time*, but they do not necessarily feel *live*. Am I really providing something additional by my presence as a performer that could not have been achieved by triggering these sounds via some form of automation within the software, or indeed a mechanical device? How can my expressive capacities as a musician really come into play here, other than through the temporally accurate triggering required?

Aside from feeling unfulfilled as a musician, these types of scenarios led me to question what it was that I was missing in my experience as a performer engaging with digital technology, in order to adequately communicate a musical idea. How could I translate an intention, either preformed or conceived in the moment, through bodily action into an expressive and articulated

[4]The piece being rehearsed for a performance at City University, London, was *Mute|Solo* (2009) by Jules Rawlinson. The performance can be viewed online at http://vimeo.com/8742634 [accessed 17th May 2013].

sonic result? It has been through my own personal history of musical performance that I have been prompted to examine the relationship between sound and touch. The confused feelings of the disconnect between intention and result, and almost *meaninglessness* in my action as described above, urged me to explore more deeply the link between action and perception, specifically for the performer. Emmerson discusses the distinction between the terms *live* and *real-time* extensively (Emmerson, 1994), and suggests that it is the "loss of appreciation of human agency" (Emmerson, 2000, 206) by the audience that can allow a piece of music to transpire in real-time without it being strictly live. I will go on to further this idea by arguing that with much live electroacoustic music, this breakdown often occurs at a much earlier stage in the process, within the performer-instrument relationship itself.

1.2.1 Reflexive Non-Linear Research

This work is necessarily reflexive, in that as I chisel away along a certain path within my creative practice, the small and often multidirectional headway that I make is directed back into my own practice itself. By addressing the problems described above *through* the doing of music, which I mean to include the acts of composing, performing and improvising, my very *doing* of music becomes inevitably changed. And importantly, this is an account of a personal process, where my trajectory is continuously being shaped by my own musical background, experiences, aesthetic preferences, as well as social interactions. As Brad Haseman and Daniel Mafe summarise:

> For the creative practitioner emergence and reflexivity are much more than distracting variables in the research which need controlling. Instead they are both foundational and constituting, operating at practically every level of the research, and it is this which makes it a difficult, messy and at times a frustrating endeavour for the creative researcher. (Haseman & Mafe, 2009, 218)

Once a particular tool or technique has been developed, perhaps in an attempt to overcome a certain obstacle or forge a new compositional path, it is then assimilated back into my *practitioner's toolbox* and becomes part of the enquiry itself. This means that, for example, the technology I develop as part of this process may be pushed in many directions and used to fulfil different roles and explore multiple themes. Moreover, it may only be when a piece of technology has been actually realised and tested that I conceive of new potential uses for it.

While the practice feeds back into itself in a reflexive manner, a symbiosis also exists between the theory and praxis of this research, in that they evolve through a mutual dependence. If my own experiences as a performer have sparked the initial lines of enquiry, it must also be acknowledged that the investigation and research themselves have inspired developments within the practice that would not have otherwise occurred: the ideas put forth here in writing have both emerged through, and helped to shape, the musical practice. And conversely, I would not have arrived at the performance practice I am engaged in today, nor would I have been able to produce the body of work presented in the portfolio, had I not critically tested and developed theories surrounding the relationships between the performer and her instrument, and between the sonic and the haptic within a contextualised discourse. Nevertheless, it is important to state that while there are numerous supporting media examples referred to throughout this dissertation, the body of music included as the portfolio is presented not as a collection of sketches or experiments, but as a selection of high quality recordings and videos of complete musical works, which attempt to illustrate the broad range of my practice, as well as being the prominent outcomes of this body of research.

1.2.2 Reflective Thinking

This practice-based research uses the creative acts of composing, performing and improvising live electroacoustic and electro-instrumental music as an aesthetic basis through which to postulate and develop theoretical constructs, these ideas themselves reciprocally shaping the musical output. In his work on *technical* versus *artistic* inquiry, Donald Schön describes two types of reflective thinking. The notion of *reflecting-on-action* (Schön, 1983), suggests composing one's next move based on a reflection of what one has already done, and what results were achieved. I might begin a new composition based around a certain idea that I wish to explore, such as the notion of resistance, which may have become illuminated through, but not fully addressed in a previous work or performance. Similarly, as I reflect on recent practice, I may start to theorise or develop new lines of inquiry based around the results of what I have already done: what worked well, what did not, and what needed further clarification. This is contrasted with a reflection of only the *present* action, where the *ongoing* process can still influence the current state of affairs.

> When someone reflects-in-action, he becomes a researcher in the practice context. He is not dependent on the categories of established theory and technique, but constructs a new theory of the unique case. His inquiry is not limited to a deliberation about means which depends on a prior agreement about ends. He does not keep means and ends separate,but defines them interactively as he frames a problematic situation. He does not separate thinking from doing, ratiocinating his way to a decision which he must later convert to action. Because his experimenting is a kind of action, implementation is built into his inquiry. (Schön, 1983, 68)

This suggests a distinctly exploratory process, which often provides the more accidental or unexpected discoveries: those that could not otherwise have been uncovered, and those that were not necessarily planned for through a verification process. The practical component of this research involves a range of *musicking* (Small, 1998) in many forms, and addresses performance *of* composition, and *as* improvisation. Analogously, I arrive at my theoretical position by way of both contextualisation amidst current thinking and technical innovation, as well as through experimentation, conjecture and play. While the existence of the text cannot be divorced from this reflective process, the writing is not intended to be merely *a* reflection on the musical works presented in the portfolio, but a rigorous discussion of how through addressing the links between sound and touch, perception and action, performer, performance environment and instrument, as well as composition and improvisation, we can start to unpick and address some of the problems, pitfalls and successes of live electronic performance.

1.3 The Stage as Laboratory, Technology as Tool

This research examines many possible advantages in exploring the audio-haptic link for practitioners of digital music. An assessment is presented of what has been lost, in terms of interaction and embodiment, in the move from traditional acoustic instruments to current standard interfaces for digital music performance. This is followed by a discourse on the different possible approaches to reinstating audio-tactile relationships within this advancing medium, and why this might be beneficial to artists working within the field of digital or electronic music. Themes of haptics, vibrotactile feedback, and the more metaphorical links between sound and touch are explored through theory and practice. The practical work is undertaken through the creation of new musical works, which are predominately, although not exclusively, related to the field of piano and live electronics performance practice, as this is where a large amount of my engagement with computers within music lies. My compositions also include pieces for small ensembles; and as an improvisor I have developed a range of performance systems that include combinations of analogue synthesizers, acoustic and augmented pianos, repurposed game controllers and bespoke software. However, many of the axioms that I derive from the research are applicable to the field of live electronic music performance practice in general.

> Research material may not necessarily be replicated, but can be made accessible, communicated and understood. This requires the methodology to be explicit and transparent (documentation is essential) and transferable in principle (if not specifics). (Gray, 1996, 13)

As Gray suggests, it is not the specifics of the technological implementations which I undertake that I am proposing be utilised by digital music practitioners *en masse*, but rather that through presenting and discussing my work, I will show how this investigative enquiry can offer a contribution into the much wider field of musical research through its more general implications. Yet, simultaneously, I have produced an extensive body of new musical works, and several personalised, yet replicable performance environments. Code, technical information, and performance scores have been documented along with audio and video recordings, supporting additional media examples, and descriptive analysis where required.

A discussion of the role of haptics within digital musical instrument (DMI) design must be examined beyond merely the technical perspective, in order to ascertain why such innovations may help us to more easily negotiate the potentially elusive terrain of performer-instrument relationships. As such, I discuss the relevance of this work within the field of embodied music cognition, in particular, looking at *enactive* approaches to DMI interaction. I offer my perspective as the *performer* as being the departure point for a discussion of action and perception loops. As Marc Leman elaborates:

> The starting point is the performer, who has in mind a musical goal or idea (possibly provided by a composer). This goal is realized as sound energy, using the human body and a mediation technology. More specifically, the musical goal is realized through corporeal articulations, whose biomechanical energy is transferred to the music mediation technology (the music instrument). This device in turn translates part of the biomechanical energy of the performer into sound energy, while another part of the biomechanical energy is bounced back as haptic energy (energy related to the sense of touch). The control of the musical instrument is realized in a closed loop with haptic, sonic, and perhaps visual feedback. In the mind of the performer, this physical interaction can be enhanced by corporeal imitation processes that translate the sensed energy back into the action-oriented ontology, giving meaning to the interaction. Thus, haptic energy may largely contribute to the perceptual disambiguation of the particular relationship between gestural control and sonic output. (Leman, 2007, 13)

Rather than simply describing methods for encoding physical action into various parameters within the virtual or digital realm, the mediation with the system itself may allow one to create or communicate musical ideas and meaning. *Doing* music, as performance, is more than merely the control and alteration of sonic material, but rather involves ongoing negotiations between performer, audience, instrument, space, and environment (see Chapter 3 and (Waters, 2007)).

Two main technological routes are explored and developed in tandem with the portfolio of music. The first involves the use of creating artificial vibrotactile feedback to aid the musician during the performance of live electroacoustic music. The second approach looks at implementing haptic controllers as NIMEs. But the technology here is merely the tool which allows me to expand my artistic practice, probe the areas that I wish to examine, and solve problems that I encounter along the way. It is the *stage* itself that can be thought of—in some senses—as the laboratory, where the instruments and musical systems are iterated through numerous performances in different spaces and venues, and where the musical works emerge *through* their actual performance. The stage, or perhaps more accurately the *performance space* becomes itself key in each individual performance. One corollary of this, which will be discussed in Chapter 5, is that the versions and iterations of the works presented in the portfolio are in some instances just one potential realisation, and in other cases are presented as multiple versions.

1.4 Structure of the Thesis

This section describes the structure of the thesis and notes the particular research questions that are addressed in each chapter.

1: Introduction describes the motivations for this research, as well as some of the claims that it makes. It also lists the specific musical works that are included as part of this thesis, and their performance history (see Section 1.6 below).

2: Sound and Touch expounds phenomenological approaches to musical practice, through which a theory of sound and touch is developed. This chapter also gives a contextual overview of the history of haptics within music. It presents a selection of some of the current developments that are related to this research, as well as introducing the notion of perceptually guided performance. It asks what role touch might play within electronic music performance practice.

3: The Instrument-Performer Relationship provides a description of how this work fits into current research into embodied music cognition within the field of HCI, and introduces the enactive view, compounding the theoretical framework for the practice-based research. It questions the importance of the relationship between performer and instrument, as well as asking how we might consider the notion of performance environments for electronic music. It describes the development of the hybrid piano, one of the most prominent instruments within my practice.

4: Feedback and Communication addresses ways in which employing vibrotactile feedback can help both within the performance of compositional works, as well as in systems for improvisation, at the same time asking whether it is indeed useful to draw a distinction between the two practices. It looks at case studies where artificial vibrotactile feedback is added to the body of the performer, to send information from the laptop as a performance aid. On one hand, this is employed as a score and triggering notification system within compositions. Elsewhere, this technique is used for improvisational suggestion using NeVIS (Networked Vibrotactile Improvisation System), which was developed in collaboration with Christos Michalakos. It questions whether the technology can be used not only as a pragmatic tool but also as a creative means.

5: Effort and Struggles: Resisting the Paths of Least Resistance discusses how engaging with physical forces and resistances are crucial for musical expression and articulation. It looks at case studies where specific technologies which allow for force feedback and tangible interaction are used as performance tools. It asks whether employing resistance and haptic technology can lead to more expressive, dynamic live electronic performance.

6: Conclusion evaluates the processes and outcomes of this body of work in relation to my creative practice, as well as with regard to wider implications for digital music performance. This section also gives some suggestion for further development in the field.

1.5 Glossary

This section contains terms which may be unfamiliar to the reader, or concepts which are specialised within the field of this work. I have included this section within the chapter rather than at the end of this document as many of the terms are crucial to the understanding of this text.

Cutaneous means of or pertaining to the skin.

Enaction describes the process of organising knowledge through our interaction with the physical world. We acquire enactive knowledge by *doing*, and by using our motor skills.

Haptic means relating to the sense of touch.

Haptic Technology is used herein to refer to devices that employ physical forces, such as resistance, within their design. However, it is occasionally used as an umbrella term encompassing interfaces that make use of haptic, cutaneous or kinaesthetic sensory experiences in general.

Kinaesthesia refers to the movement and sensation of our joints and muscles.

Machine Listening refers to the process whereby a computer *listens to* or analyses audio with a complexity similar to, or at least drawing on, those perceptual mechanisms which take place within humans.

Phenomenology is the study of the structures of consciousness, as experienced subjectively about things, objects, or *phenomena* in the world.

Proprioception is similar to and interchangeable with kinaesthesia, but is more concerned about the relation between parts of the body in space, rather than their movement in space.

Somatosensory refers to the sensory system which comprises those sensations felt in the skin and deep tissues. It encompasses the modalities of touch, pain, temperature and proprioception.

Vestibular Senses are concerned with our movement in space and balance.

Vibrotactile means relating to the perception of vibration through touch.

1.6 Portfolio and Publications

This section describes the musical works that have been included in support of this document. The original audio recordings, videos and software referred to herein are listed in the document `disk_contents.pdf` on the accompanying DVD. These works are discussed as case studies and examples within the text. Media examples are linked to throughout the text. Portfolio works are marked in **bold** font, indicating when they should be listened to. They are located in */portfolio* on the accompanying DVD. This section also lists the papers that have been published during the course of this research.

1.6.1 Main Works

1. *kontroll* (2010) for prepared piano, live electronics and self-playing snare.

    - First performed at the Roxy Arthouse, Edinburgh, Sunday 16th May, 2010.
    - Performance at the Reid Hall, Edinburgh, Thursday 15th July, 2010.
    - Selected for performance at the Electroacoustic Music Studies Network, New York, Thursday 16th June, 2011.
    - Selected for performance at the International Computer Music Conference, Huddersfield, Thursday 4th August, 2011.
    - Invited for live radio broadcast on Sveriges Radio P2, in Malmö, Sweden, Wednesday 23rd November, 2011.
    - Selected for performance at the BEAM Festival, Brunel University, Sunday 24th June, 2012.
    - Invited for performance at Norberg Festival, Sweden, Thursday 26th July, 2012.

2. *multifingeredbodyparts* (2010) for generic game controller, laptop and vibrotactile feedback device.

    - Recorded August, 2010.

3. *Running Backwards, Uphill* (2011) for piano, violin, cello and live electronics.

    - First performed by the Artisan Trio and guests at the Reid Hall, Edinburgh, Saturday 23rd April, 2011.
    - Selected for performance at the International Computer Music Conference, Ljubljana, Monday 10th September, 2012.

4. *Socks and Ammo* (2011) for piano, percussion and live electronics. Created in collaboration with Christos Michalakos.

    - First performance at Sonorities Festival of Contemporary Music, the Sonic Lab, SARC, Queen's University Belfast, Saturday 9th April, 2011.
    - Selected for performance at New Interfaces for Musical Expression, Oslo, Wednesday 1st June, 2011.
    - Invited for performance (with John Pope, upright bass) at Soundings Annual Festival of Sonic Art, Reid Hall, Edinburgh, Friday 13th May, 2011.
    - Selected for performance at Sound Festival, Aberdeen, Sunday 23rd October, 2011.
    - Invited for performance as part of the lunchtime concert series, SARC, Queen's University Belfast, Thursday 23rd March, 2012.
    - Studio album released 3rd April, 2013 (see below).

5. *Signal Powder* (2011) studio album with Christos Michalakos and John Pope.

    - Lauren Sarah Hayes: piano, celeste, analogue synths and computer
    - Christos Michalakos: percussion and computer
    - John Pope: double bass
    - Released 23rd December, 2011 on Reid label[5].
    - Recording, mixing and mastering by Můstek.

    1. Forêt Noire

    2. Leave it Alone (Leave it Alone)

[5] http://sites.ace.ed.ac.uk/reidstudio/reid-label/ [accessed 1st September 2013]

3. Signal Powder

4. Werewolf Whim Wham

5. Goofooyoo

6. Jein

7. Space Jockey

6. *Figurine-Operated String* (2012) for piano and live electronics.

   - First performed as featured artist at INTER/actions, Bangor University, Wednesday 11th April, 2012.
   - Invited for performance at Sonic Interactions III, Liverpool Hope University, Monday 22nd October, 2012.
   - Selected for performance at RMA Interactive Keyboard Symposium, Goldsmiths, University of London, 11th November, 2012.
   - Invited for performance at Sonorities Festival of Contemporary Music, SARC, Queen's University Belfast, 25th April, 2013.
   - Performed at Reid Hall, University of Edinburgh, 29th May, 2013.

7. *Sungazing* (2012) for bass clarinet, trombone and live electronics.

   - First performed by the Red Note Ensemble at the Inventor Composer Coaction, Edinburgh, Wednesday 9th May, 2012.

8. *Node/Antinode* (2012) studio album with Christos Michalakos.

   - Lauren Sarah Hayes: analogue synthesizers, controllers, laptop
   - Christos Michalakos:electronically augmented drum kit, laptop
   - Released 18th December, 2012.
   - Mastering by Můstek.
   - Mixing by Christos Michalakos

1. Antistrophe

2. Node

3. Derelict

4. Antinode

9. *subspace* (2013) for string quartet and live electronics

    - Selected and workshopped as part of the McFall's Chamber *Electronics* project, 5th February, 2013.

10. *Socks and Ammo* (2012) live album with Christos Michalakos.

    - Lauren Sarah Hayes: hybrid piano, laptop
    - Christos Michalakos: augmented drum-kit, laptop
    - Released 3rd April, 2013
    - Mastering by Můstek.
    - Mixing by Christos Michalakos

1. Socks and Ammo: SARC lunchtime concert series, Belfast

2. Socks and Ammo: SOUND festival, Aberdeen

3. Socks and Ammo: Sonorities Festival of Contemporary Music

1.6.2 Publications

The following papers have been published during the course of this research, and have been included in Appendix H.

1. Hayes, L. (2011). Vibrotactile Feedback-Assisted Performance. In Proceedings of the International Conference on New Interfaces for Musical Expression (pp. 72-75). Oslo, Norway. http://www.nime2011.org/proceedings/papers/B12-Hayes.pdf [accessed 23rd August 2013]

2. Hayes, L & Michalakos, C. (2012). Imposing a Networked Vibrotactile Communication System for Improvisational Suggestion. Organised Sound, 17 (pp. 36-44). Cambridge Journals Online. http://journals.cambridge.org/abstract_S1355771811000495 [accessed 24th August 2013]

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Chapter 2

Sound and Touch

2.1 Introduction

The link between sound and touch is inherent: hearing is, essentially, “a specialized form of touch” (Glennie, 1993, 1). Profoundly deaf musician, Evelyn Glennie asserts a view that is the grounding premise for this entire body of work. Her statement could be explained in physical terms by the fact that sound is the rapid vibration of molecules in the air, or oscillations of pressure, which excite the membranes, hair and fluid inside of our ears, allowing us to hear. Moreover, as Simon Waters emphasises, our perception of sound goes beyond just the penetration of the auditory canal, and in fact is felt by our whole body, through vibrations within the organs and the bones (Waters, 2007). When a subway train travels through a tunnel, we not only hear its passing, but *feel* it as a strong rumbling sensation that stimulates our bones through our feet, which are in connection with the ground. We also feel it in a different way through the skin of our hand that clutches onto a rail in the station.

This engagement with the somatosensory system is something that Glennie affirms, claiming that she can perceive, as vibrations, even those *higher* frequency sounds, which we may not have considered to be tangibly perceivable (Glennie, 1993). Of course, it is well known that below around 20 hertz, sound passes out of audible range, into palpable sensation (Schafer, 1977; Roads, 1996), and while many of us are familiar with the physical thumping of a bass line in a nightclub, we are not necessarily aware of our body’s ability to haptically perceive higher pitched sounds. Glennie claims that is this simply because the auditory modality is more efficient in such ranges, and so becomes more prominent:

> If you are standing by the road and a large truck goes by, do you hear or feel the vibration? The answer is both. With very low frequency vibration the ear starts becoming inefficient and the rest of the body’s sense of touch starts to take over. For some reason we tend to make a distinction between hearing a sound and feeling a vibration, in reality they are the same thing. It is interesting to note that in the Italian language this distinction does not exist. The verb ‘sentire’ means to hear and the same verb in the reflexive form ‘sentirsi’ means to feel. Deafness does not mean that you can’t hear, only that there is something wrong with the ears. Even someone who is totally deaf can still hear/feel sounds. (Glennie, 1993, 1)

While Glennie's account is a purely subjective phenomenological one, as described from the unique perspective of a profoundly deaf virtuosic musician, we should not disregard her lifetime of experience and heightened awareness of a finely tuned sensory system. The idea of hearing through physical *sensation* is a sentiment that is echoed by other deaf musicians (Roebuck, 2007), as well as elsewhere in formal literature (see Ingold, 2000, 273, for further discussion). We might start to wonder to what extent the body makes use of this sensory information in building up our impression of the world around us without our active awareness.

Sound is also *touching*, in the sense that a piece of music can touch us, or *move* us in an emotional manner. The mass hysteria, screaming and fainting of young girls at The Beatles' concerts repeats itself in the pop concerts of today—although this perhaps has more to do with the spectacle of the *stars* than the actual music. Recent studies in neuroscience confirm that dopamine is released in the pleasure centres of the brain at peak emotional arousal during listening (Salimpoor, Benovoy, Larcher, Dagher & Zatorre, 2011). A piece of music can move us to tears, to anger, or spur us on with work, or exercise. The touching effect of sound is not just emotional: it can entrain the body and provide it a means of synchronising with the environment (DeNora, 2003); or indeed it can be used to produce physical discomfort (see Goodman, 2009). Of course these are examples of a different type of *movement*, and being touched by music in this way perhaps has less to do with the kind of touching that R. Murray Schafer refers to when he describes hearing as "touching at a distance" (Schafer, 1977, 11). While we may reach out and physically touch something that is in close proximity, Schafer suggests that we may extend our touch out of the body, and touch that which is not spatially immediate, through the act of hearing. Mark Paterson argues that touch can "bring distant objects and people into proximity" (Paterson, 2007, 1), and is thus crucial in terms of communication, in so far as it is "receptive, expressive, can communicate empathy" (Paterson, 2007, 1). Here we can see that sound and touch are both inherently necessary for communication across social boundaries and also physical distances. Waters highlights how this phenomenon relates to Edward Hall's notion of *proxemics* (Waters, 2007). Waters argues that sound has the ability to reach into a variety of different social spaces, from the highly intimate to more public territories (Waters, 2013).

Touching or feeling can bring about a sense of realism or truth, this sentiment being expressed in the idiom, "seeing is believing, but feeling's the truth" (Thomas Fuller, quoted in Paterson, 2007, 73). However, it is interesting to note that only the first part of this dictum is commonly used. Paterson seems to highlight such phenomena as evidence to support his claim that popular media has an "infatuation with visuality", and that we live in an "academic climate that celebrates visual cultures" (Paterson, 2007, 1). Indeed, it is only within the last hundred years, or so, that theories of sound and audio culture have started to emerge. On the other hand, Tim Ingold provides a rejection of "the thesis that attributes the dominance of objective thinking in the West to an obsession with the eye" (Ingold, 2000, 245). Ingold suggests that the problem with such criticism lies fundamentally in the "reduction of vision... to its construal as a sensory modality specialised in the appropriation and manipulation of an objectified world" (Ingold, 2000, 287), rather than embracing the commonalities between the *actual practices* of looking, hearing, and so on. I believe this objectified world is exemplified within the field of HCI, where interaction is based around *graphical* user interfaces and onscreen icons: the visual representation of the metaphorical *desktop*. Yet touch brings us into direct contact with the objects that are within our visual field. Touching can also renew our relationship with a person or object, and if we haven't picked up or practiced our instrument for a significant length of time, we may say that we are "out of touch". But the role of touch within musical practice, I believe, goes much deeper than this. In the remainder of this chapter, I outline a theory of sound and touch, which is then explored through my creative practice in the subsequent chapters with respect to four recurring themes: materiality, feedback, communication, and resistance. I begin with an investigation into the role of haptics within music making, where I reveal that while the many potentials are well documented, there is a clear lack of practice-led musical exploration in this field.

2.2 Haptic Sensation

Hungarian psychologist Révész first introduced the word haptic, from the Greek *haptesta* (to touch), in 1931[1] (Davidson, 1976). It was used to describe the process of actively exploring a shape, or spatial dimension, with the hands, discussed in the context of his research into blindness and its profound effects on the other senses. He contrasts this process with the sensation of indirectly perceiving something via the skin (Davidson, 1976), such as experiencing differences in temperature, or feeling a feather brush against one's arm. However, when discussed in terms of HCI, the phrase *haptic sensation* is often used as an umbrella term, encompassing both the active information gathering that Révész describes, as well as the passive tactile sensations that he classes separately. It is also sometimes used to refer to *kinaesthetic* sensory information, which makes sense of the relationship between parts of the body in space (Rovan & Hayward, 2000). Within the following body of work, the term *haptic* will used in relation to both the somatosensory system—dealing with the perception of sensations on the surface of the skin—as

[1] Although the Oxford English Dictionary reports usage from 1890 (http://www.oed.com/viewdictionaryentry/Entry/84082 [accessed 24th August 13]), Révész could be credited with giving the word a wider usage.

well as in relation to the proprioceptive system—involving intentional or *active* touching, and the actions and movements of the hands and body.

2.2.1 Haptic Technology

Haptic devices are specially designed interfaces that usually involve some type of actuator or mechanical device, such as small motors or pins, which either move back and forth, vibrate at perceivable frequencies, or provide applied force back to the user. One of their purposes is to improve the translation of gesture from the physical world into the digital realm, and to allow for the perception and control of virtual objects or spaces. Another related implementation of haptic technology is to *enhance* existing modes of digital interaction for the user, rather than to create new ones. For example, the recent addition of vibrotactile feedback to mobile phones is not necessarily an integral part of the interaction system that detects the gestural information from a key press in order to carry out a particular task on the phone, but rather signals the user—through a vibration—that the key has indeed been pressed. This, of course, can greatly speed up the operation of the device, in that we may not need to rely so much on visual feedback to affirm that an action has been correctly sensed by the equipment.

Much commercial research into haptics focuses on creating simulators with which to perfect real-world skills, such as sophisticated haptic medical systems, which are used to practice keyhole surgical techniques. The benefits are clear: procedures can be repeated until they have been perfected, and furthermore, surgical gestures can be tracked, and the data used for analysis, and replayed in the future. Small studies and demonstrations have been devised to enable similar scenarios for musicians working with traditional instruments, where haptics can be employed to assist the execution of a particular gesture or instrumental technique (O'Modhrain, 2001; Berdahl, Niemey & Smith, 2009). While these studies have yielded varying results, they generally conclude that including at least *some* form of haptic feedback produces more positive results than having none at all. As with haptic research in general, these case studies suggest that learning processes are sped up with the addition of this physical feedback. Nevertheless, the motivation for such technical intervention does not seem as imperative as in the cases involving the living, breathing human subjects of the medical world: a musician can, of course, hone their technique with less urgency! Furthermore, as I will unfold below, the audio-haptic connection has significant importance within performance practice that endures beyond the various stages of instrumental skill acquisition.

More relevant to my own practice, are the growing clusters of practitioners in the creative community who work in the *opposite* direction, utilising tacit knowledge of the physical world to improve interaction with the virtual realm. Haptic technology is already established as a tool within the visual arts, to some degree, with programs such as the Tacitus[2] project at Edinburgh College of Art (2001-4). It is now beginning to gain slightly more prominence within digital music fields. Here the focus is not to intervene with the established practice of acoustic instrumental performance, but to use the new technological possibilities to open up expressive embodied interactions within the realm of digital signal processing. Leading research hubs include the Tangible Media[3] group at MIT Media Lab, and its European research partner, Media Lab Europe, where Sile O'Modhrain led the Palpable Machines[4] project. However, as I will argue in Chapter 5, my own focus on musical performance practice necessitates a departure from some of the key themes that are the impetus for much of this current research, namely the strong adherence to providing *seamless* interaction between humans and computers (see Ishii & Ullmer, 1997, for an exemplary case of seamless interaction design).

2.3 Instruments and Physicality

2.3.1 The Importance of Instrumental Feedback

The skin's sensing nerves are most densely collected in the lips and hands (Rovan & Hayward, 2000; O'Modhrain, 2001); since most acoustic instruments are constructed to be played with the mouth or fingertips, this distribution of sensors in the skin allows for the maximum amount of information exchange. Acoustic instrumental performance involves the use of specific and refined sensory-motor skills, such as plucking, bowing, blowing, and so on. These actions must be practiced over a long period of time in order to achieve the ability to accurately articulate the desired timbres and nuances of a sound. During engagement with the instrument, the performer receives physical feedback in the form of various forces, such as resistance, pressure, friction, or more subtle phenomena, such as quivering. Vibrations are felt—almost subconsciously—through a pianist's hands and arms from the keys, and through the legs from contact with the pedals, and perhaps even floor. These carry the physical oscillations of the resonating body of the instrument, and inform the performer about, for example, the dynamic, timbre or shape of the sound that is being produced. Additionally, kinaesthetic information—which includes the position of the instrument in relation to the body, the movement of the arms, and so on—is constantly being processed by the performer.

This haptic information supports the auditory feedback received through the ears as sound is made. Hence a closed feedback loop is created (see Figure 2.1): the performer makes a

[2]http://www.eca.ac.uk/tacitus [accessed 26th August 2013]
[3]http://www.media.mit.edu/research/groups/tangible-media [accessed 26th August 2013]
[4]http://www.sarc.qub.ac.uk/~somodhrain/palpable/projects.html [accessed 26th August 2013]

sound, which is heard and also perceived physically, and then judged and considered before—and whilst—the next sound is made. This process occurs in a very short space of time and is constantly ongoing throughout musical play. The auditory and haptic feedback is immediate, with the latter information received perhaps almost subconsciously. Certainly while the amount of force used to strike the keys while playing the piano is a decisive consideration, vibrations received through the feet may not be consciously perceived, but are no doubt significant in creating the necessary collective feedback. As Claude Cadoz, Leszek Lisowski and Jean-Loup Florens claim, this bidirectional information exchange, between instrument and performer, “provides us with manipulation possibilities and even signals the nature of the sound phenomenon itself” (Cadoz, Lisowski & Florens, 1990, 47). Furthermore, this entire process is uniquely private to the performer, creating sense of intimacy between musician and instrument.

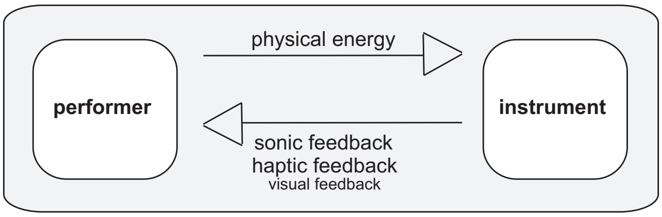


Figure 2.1: Closed interaction feedback loops in musical performance.

It could be argued, however, that it is the forces and resistances of the instrument itself, rather than the vibrotactile feedback produced through resonances and frictions, that are more immediately useful to the musician. After assessing the forcefulness or lightness of touch with which to press down a piano key, does the pianist really make use of the ensuing vibration felt from the sound produced? A study of the vibrotactile feedback received from a cello, undertaken by Chris Chafe (1993), indicates that while much of the haptic vibration that travels through the bow is of a frequency too high to be detected, the more unstable oscillations such as bow direction changes or slips *are* felt, and moreover, can provide cues to the musician. Chafe’s experiments confirm that “fingertip vibration (or lack of vibration) can be used to gauge the time and length of articulation” (Chafe, 1993, 78). In Chapter 4, I explore several different potential uses of this vibrotactile feedback, both as cues and otherwise.

As O’Modhrain explains, evidence suggests that different types of movements engage with different motor control processes and sensory information:

> slow movements and movements that require fine control closely track sensory feedback, while rapid and learned movements are executed essentially open-loop, rely-

> ing on motor programs initiated by a central control mechanism. Because motor programs are structured in advance, they are executed without reference to sensory feedback. (O'Modhrain, 2001, 25)

Furthermore, these various processes are employed differently by experts and novices, the latter of whom may be learning an instrument, or a new skill, which requires the assimilation of new embodied knowledge (Dreyfus & Dreyfus, 1999; O'Modhrain, 2001). This would seem to support my concern made in Section 2.2.1 above, that implementing haptic technology for the development of instrumental technique may have limited lasting benefits, except, perhaps in that it would allow the relationship between performer and instrument to develop at a much faster rate than without this feedback present. What seems clear is that, at least at some point during the course of any instrumental performance, the two types of haptic feedback will be utilised by the musician—both the active engagement with physical forces, as well as the passive perception of vibration. And while we must not discount the importance of previously acquired motor programs that are activated without necessarily engaging sensory feedback at all, this haptic feedback is useful and clearly necessary for the musical processes of articulation and expression. In addition to my own conclusions drawn from my experience as a pianist, it seems that there is strong evidence to confirm that this duality of physical perception is a substantively important element within the process of performing live instrumental music. This will be explored in more detail in Chapter 3, although it is interesting to note that I did not start to properly appreciate the role of haptic feedback within musical performance until I began creating music in an environment—the realm of digital signal processing (DSP)—where it was wholly absent.

2.3.2 Electronics and the Decoupling of the Physical

As Filippo Tommaso Marinetti led the Futurists into a celebration of speed, power and technology, Luigi Russolo's Intonarumori instruments emphasised "the infinite variety of tones of noises, reproduced with appropriate mechanisms" (Russolo, 1913). These mechanised machines and automatons were operated by performers who would pull levers back and forth, or push buttons to stop and start the sound. "Varying degrees of amplification" were also called for. This paradigm shift of viewing the machine as instrument—or instrument as machine—goes hand in hand with the developments of the early electronic instruments at the start of the twentieth century. Both the Ondes Martenot and the theremin exhibit an important fundamental change in sound production with the separation of musical parameters into different control functions: the former instrument requires the left hand to operate controls within the *tiroir* drawer to vary dynamics, as well as the articulation from *staccato* to *legato*. Similarly, the theremin's volume is controlled by the left hand loop antenna, with the pitch controlled, separately, by the right hand. And of course both instruments require amplification through a loudspeaker, which removes some of the direct sensation of the physical vibrations that are produced when sounds are made. As Russolo's instruments engaged in a mechanisation process, transforming the labour spent of "twenty men furiously bent on redoubling the mewing of a violin" (Russolo, 1913), the electronic era reinforced this lack of direct physicality through the emergence of sounds not audible except via supplementary amplification, and also through the dissection of sonic elements into distinct control parameters.

In general, digital musical instruments (DMIs) have emerged out of this system of distinct parameter-control mapping, and have not taken into account the advantages of the fundamental human proficiencies involved in learned motor skills. Keyboard controlled synthesizers and MIDI keyboards do, of course, model *some* of the physical properties of piano playing, but as with most commercial DMIs, gestural data must be mapped to a specific process within the software or hardware being controlled. Perhaps, due to a lack of sophisticated exploration on the part of the programmer, or as a direct result of the affordances of the particular software being used, these mappings are usually one-to-one. As Andy Hunt and Marcelo Wanderley explain, "There is a temptation for engineers to directly connect each element of the interfaces to a synthesis parameter in one-to-one relationships (e.g. slider position = volume control)" (Hunt & Wanderley, 2002, 98). This implies that such mapping choices are a result of not a great deal of thought going into this aspect of the design. However, we must remember that in some cases the inventor may be both engineer and software designer, composer and performer. With so many roles being assumed, it is perhaps easy to see why this aspect of design can often be neglected.

On the other hand, this could be merely a result of the continuation of this separation of parameters, which began with the early electronic instruments, and was expanded through the modular design of analogue synthesizers. Within the hardware of these instruments, not only are sound-producing-action and sound-producing-source distinct, but the production of sound is constructed through a chaining of different signal processing units. Perry Cook argues that this decoupling of total sound from action has resulted in a significant loss of intimacy between performer and instrument:

> From the advent of electronic music, and even from early organ consoles and other remote manipulated instruments, much of the design and research of new musical interfaces has focused on abstracting (both physically and in the design process) the "controller" from the "synthesizer" and then investigating how to best interface those two classes of hardware with each other and the player. Yet, many of the striking lessons from our history of intimate expressive musical instruments lie

> in the blurred boundaries between player, controller, and sound producing object. (Cook, 2004, 315)

Current music software, such as Ableton Live[5] actively encourages this type of one-to-one mapping, where the user will first construct a chain of various modular effects and instruments, and subsequently enter into the MIDI or controller mapping menu of the software to assign control data to different parameter values within the DSP.

In traditional acoustic instruments, which are complex physical systems, sound production and sonic result are tightly coupled. Furthermore, this relationship may often be non-linear. In the case of a piano, for example, depressing the sustain pedal, holding down a number of keys with one hand, *and* strumming the strings inside the piano with the other hand may *all* be necessary to produce the desired sound; a long note played on the recorder requires a controlled and steady stream of breath, along with a combination of fingers covering the holes of the tube. Conversely, similar sounds can be produced in multiple ways: the same pitch can be produced (albeit with slightly different timbral qualities) at different positions on the guitar fretboard, or trombone slide. Within electronic instrument design, Hunt and Wanderley (2002) distinguish between *one-to-many* strategies, where one control parameter may affect numerous synthesis values; and *many-to-one* mappings, where more than one input parameter is used to affect a single aspect of the sound. They suggest that the behaviours of the complex dynamic systems that comprise acoustic instruments are combinations of these convergent, divergent, and *one-to-one* mappings, which could be termed together as *many-to-many*. Their findings indicated that when DMIs tried to imitate certain aspects of acoustic instrument design, they tended to have a more enjoyable, embodied and long-term appeal: complex mappings were used; more than one hand or limb was required to play the instrument; energy had to be injected into the system in order to make sound and determine its amplitude level (Hunt & Wanderley, 2002).

Hunt's notion of injecting energy into a musical system seems to suggest a need for physicality or the presence of resistant force to play off. For example, MIDI faders usually move smoothly up and down, yet there are certainly crucial times where a slow and controlled trajectory is required, such as a fade in amplitude at the end of a piece. This could certainly be assisted by the addition of resistance. The implementation of various exponential curves within the software can help to give the illusion of, for example, moving finely through a data set; but still the actual tangible sensation remains the same. As mentioned above, there have been some attempts to create instrument-based controllers, the most obvious example being the ubiquitous MIDI keyboard. MIDI wind controllers and electronic drum pads offer alternative

[5] https://www.ableton.com/en/live/ [accessed 26th August 2013]

affordances such as blowing and striking. Nonetheless, musical human-computer interfaces are still, in part, based on the studio paradigm of the mixing desk, consisting largely of knobs and faders. These devices all attempt to transform human gesture into parametric numerical data for manipulating digital audio processing. However, no matter how sensitive a MIDI device may be, it will usually fail to deliver the whole picture, in terms of gestural performance data, to the software instrument being controlled. This is due to the limited bandwidth of information available (Rovan & Hayward, 2000), and the general lack of interaction between a too-small parameter set, whereby only a few control parameters (perhaps key number and velocity) are mapped to those sonic parameters seen to be critical (usually pitch, amplitude, and duration). Encouraging, at least in this respect, are the numerous new creations presented yearly at the International Conference on New Interfaces for Musical Expression (NIME), which make use of new sensor technology and higher resolution protocols, such as CNMAT's Open Sound Control (OSC)[6]. Unfortunately, the commercial sector is much slower to move in this direction.

As mentioned in Chapter 1, the shift from the purely acoustic world to the emergence of electronic instruments has generally meant that significantly less physical feedback is available: a MIDI keyboard may feature weighted keys but cannot reveal any other information to the *performer* about the physicality of the sound being produced. Indeed Richard Moore argues that MIDI introduces a lack of control intimacy in that gestures are reduced to mere "trigger rates and values" (Moore, 1988, 27), this being a crude representation of the physical reality. Moore claims that for live performance, the way in which musicians interact with sound must be "tightly coupled to both what they are hearing and what they are doing" (Moore, 1988, 27). On comparing a MIDI wind controller with a clarinet, Cadoz and Wanderley (2000) illustrate that numerous gestures that are available on the clarinet are lost on its synthetic counterpart. These include the ability to create glissandi by partially covering holes, or being able to create vibrato with breath control. In fact, some scholars have gone as far as to suggest that actions such as pushing a button or pressing a key on a computer keyboard cannot be considered to be musical gestures since the only significance of such actions is the binary data transmitted (Wanderley, 1999): nothing contained within the motion of the finger to its target is significant or observable. Of course, this could still be considered to be a musical *decision*, and while this is potentially a controversial claim, it would seem that manufacturers of DMIs agree in some respect, as seen in the growing number of pad-based controllers, which make use of velocity or pressure sensors. On promoting their MPC series velocity and pressure-sensitive pads, AKAI use

[6]See http://opensoundcontrol.org/what-difference-between-osc-and-midi [accessed 26th August 2013] for a comparison between OSC and MIDI.

wording such as “expressive and intuitive instrument... unmistakably human feel”[7], suggesting that more is required—and desired—than just binary interactions. I will discuss the different types of gesture further in Section 3.2.3.

2.3.3 Tactile Feedback Principle

Research into embodied interaction has questioned the haste with which new instruments are designed and built. This often occurs without consideration of these key problematic areas of physicality, the feel of an instrument, mapping design, and this divergence from the intrinsically embodied modes of action of traditional acoustic instruments (Leman, 2007). In 1978, Cadoz proposed the *tactile feedback principle*, in conjunction with his work at ACROE[8], where along with Lisowski and Florens, he developed the first *Retroactive Gestural Transducers*, or haptic devices. Their aim was to provide new insights into music creation by focusing on the instrument-performer relationship as fundamental to both the learning of the instrument, and the development of the music itself, rather than solely providing improved ergonomics and gestural control in sound synthesis (Cadoz et al., 1990).

Cadoz argues that any DMI must succeed on three levels: the gesture used to manipulate the device must be *genuine* in that the performer must be familiar with the type of movements being used. Secondly, the device must be able to accurately sense the characteristic behaviour of the gesture, and information must not be lost. Finally, he suggests that the device must offer some *resistance* to the performer, this being in some way correlated with the nature of the simulated gesture process (Cadoz et al., 1990). He calls this final aspect feedback, and deems it necessary to achieve mastery of the instrument, and perform with deftness. Cadoz’ manifesto is perhaps one of the earliest acknowledgements of the importance of the physicality of DMIs. While my own practice diverges from his work in that I do not employ the strict physical modelling techniques that he advocates, I believe that his ideas are key to the development of embodied interactions.

2.4 Haptic, Tangible, Tactile

In this section I outline the recent developments within the field of haptic technology and DMIs. In doing so I aim to illustrate the particular approaches that have influenced my own lines of exploration and their relevance within this discourse.

[7] http://www.akaipro.com/mpd18 [accessed 26th August 2013]
[8] Association pour la Création et la Recherche sur les Outils d’Expression, Grenoble, France

2.4.1 Haptics and Instruments

Human-computer haptic interfaces may be described as any device that incorporates an element of force feedback through actuators, which are mechanical systems, such as motors, that offer a wide range of accurate motion. Rovan and Hayward distinguish these devices from what they call "tactile stimulators" (Rovan & Hayward, 2000, 10), which consist of small groups of pins that tap at the skin, vibrating at controllable frequencies and intensities. This would also include vibrotactile feedback received from small vibrating motors. Thus Révész's distinction between active and passive perception, discussed above in Section 2.2, manifests in these contrasting approaches. The force feedback haptic devices allow the user to navigate through a virtual space within which they may encounter obstacles of different shapes, sizes and textures, around or through which they can pass, bump into, bounce off, or engage with in another way. On the other hand, vibrotactile systems allow the user to *passively* experience sensations; an example of this is the introduction of the vibration setting on mobile phones to indicate an incoming call. But both these types of technology spoke to me as being relevant and useful in my design of performance systems for live electronic music: force feedback devices offer the potential to manifest some of the resistances of acoustic instruments, while tactile stimulators in the form of vibrations could potentially reintroduce some of the other sensory information that has been lost with electronic instruments.

Edgar Berdahl et al. suggest that when considering the creation of NIMEs, a gesture will be genuine if the included haptic feedback in some way reflects that of traditional instruments (Berdahl, Verplank, O. Smith III & Niemeyer, 2007), giving the sense of familiarity that Cadoz demands. This would encompass a large range of actions that may include hitting, blowing, plucking, and so on. They claim that by making these new interfaces physically intuitive in this way, performers will be much more able to play them, as they will have already learned the required motor skills from their acoustic instruments. Of course, an intuitive instrument could also be built by utilising the motor skills of everyday familiar actions, rather than existing musical skill. Nevertheless, Berdahl et al. (2007) claim that by modelling these haptic devices on *familiar* musical gestures, the complex task of mapping gesture to sound parameter becomes significantly easier in that the programming possibilities will be to some extent reduced and predefined. They illustrate this point with the Haptic Drumstick, a device which can behave in the same way as a normal percussion-based instrument according to laws of physics and gravity, but can also be gradually haptically augmented. Initially the drummer may play standard two-handed double stroke rolls using the device as a substitute for one of the drum sticks. More interestingly, by altering the bounce-back force of the drum stick, these rolls can be achieved single-handedly, but without a wholly alien form of interaction being required, and with the gesture feeling “somewhat like holding a stick against the spokes of a rotating bicycle wheel” (Berdahl et al., 2007, 365). The authors are careful to note that while many other methods of varying the physical dynamics of the interaction could have been implemented, these are less likely to occur in nature and are therefore less likely to feel intuitive.

One of the most powerful and well-designed examples of a force-feedback haptic interface is Cadoz’s Modular Feedback Keyboard, offering up to 80 newtons of transitory force (Cadoz et al., 1990). Comparatively, a piano key is usually struck with a force between 3 N and 60 N (Kinoshita, Furuya, Aoki & Altenmuller, 2007). The keyboard paradigm was selected by Cadoz as this design has remained unchanged for hundreds of years and is claimed to be the fundamental link to our instrumental legacy[9]. However, the device is completely modular in that number of keys, and indeed the function of keys can be defined, utilising up to three degrees of freedom. Thus, an instrument that would still contain the basic characteristics of the traditional piano keyboard could be assembled; or the device may be used as an entirely new interface whereby, for example, black and white keys are arranged arbitrarily, or the rest position height of each key varies. The aim of the project was to create “not only a synthesis of the sound but also of the instrument” (Cadoz et al., 1990, 47). This would not only allow experimentation and play, but also successfully couple the performer and instrument. Musical engagement is more than a simple model of *performer-gesture-input* resulting in *instrument-sound-output*. The musician is also affected by the instrument throughout the performance and her role is not to simply control a piece of technology. This idea will be discussed in further detail in Chapter 3.

2.4.2 Embodied Experience of the World

While transferring the potential for using learned instrumental motor skills onto haptic-based system serves as a good initial basis for their construction, it does not seem necessary that the haptic instrument should model only the established acoustic instrument paradigm, as suggested by Berdahl et al. The knowledge required need not come from our involvement with acoustic instruments, but from our lived embodied experience of the physical world as a whole. As discussed in Section 2.4.3 below, for the average practitioner wishing to delve into the world of haptics, this will indeed be a fruitful path to follow. By utilising simple electronic or mechanical devices such as motors, or inexpensive game controllers that already make use of haptic feedback, those without instrumental training are welcomed more easily into the world of mu-

[9] This is understandable, but certainly debatable, with the drum certainly having a much longer place in our musical history.

sical creation, allowing for expression of musical ideas that they may not otherwise be able to render. However, this is not to say that new DMIs should necessarily be *easy* to play, a point that I will expand through further discussion in Chapter 5. Furthermore, the technology need not be complex in order to work with the physics of everyday action: by actually incorporating interactions between objects and hand movements that are tacit and familiar, the need for sophisticated mediating technology can often be removed.

A good example of a simple interface that makes use of this embodied tacit knowledge is the PebbleBox. PebbleBox is a collaboration between O'Modhrain and Georg Essl (2004) in which they explore the types of sounds that emerge specifically from our interactions with physical objects in the real world. The interface consists of a wooden box full of pebbles, on the bottom of which is placed a contact microphone, connected to a computer. The sound of collisions between the pebbles is used to control the granular synthesis of various sounds. Of course, the acoustic sound of the pebbles bouncing off each other cannot be removed, but this does not need to be amplified along with the synthesis produced, as the actual acoustic sound is being used purely for control data, rather than a sonic result. In this way, the pebbles can sonify other *grains*, such as ice cubes or water droplets. Indeed this is not a haptic device involving force feedback, but an alternative type of interface, relying on our tacit knowledge of physical interactions as the control surface. Our experience tells us that bumping pebbles together will produce a sensory experience with particular forces and frictions, accompanied by an audible attack. This work decouples the physical encounter from the sound source, but then imposes a new sonic experience, which is still based around the original physical energy: granular synthesis is used, and pebbles themselves represent a sort of granular physicality.

2.4.3 DIY Haptics

Unfortunately many digital music practitioners do not have access to the technology required to create devices like the Modular Feedback Keyboard, nor the funds required to purchase even the most low-end haptic devices available: leading marketer of haptic devices, SensAble offers the PHANTOM Omni, with prices beginning at over £1000 at the time of writing, and increasing to over ten times that amount, depending on the model[10]. Nevertheless, as with the PebbleBox, designs have emerged of simple but inventive new interfaces, which successfully engage with these haptic properties. Berdahl, Hans-Christoph Steiner, and Collin Oldham (2008) have presented a further percussion-based haptic instrument called the Haptic Drum, which exerts different forces back onto a drumstick from the drum membrane, enabling the performer to play drum rolls at speeds faster than humanly possible, and moreover, single-handedly. Unlike

[10]http://www.worldviz.com/purchase/pricelist.php [accessed 26th August 2013]

the previously mentioned Haptic Drumstick, which uses a drumstick attached to a PHANTOM Omni, this newer device is created from a speaker, piezoelectric microphones, and an Arduino[11] circuit board: all cheap components, requiring only a small amount of technical expertise. The device enables types of expression and performance not otherwise possible. Berdahl et al. note that the motivation for such relatively low-tech development is to make the addition of haptic feedback more accessible to musicians who might wish to implement it, with an emphasis on low-cost and practicality. My own motivation for this type of approach was the desire to prototype various ideas, often using only the materials that I could acquire easily, rather than to render a polished, commercially available product.

2.4.4 Embedding Vibrotactile Feedback

The second type of haptic feedback involves the passive perception of sensations that are felt cutaneously through the body itself, but *indirectly*, and not as the result of actively touching. Mark Marshall and Wanderley (2006) describe the Viblotar and the Vibloslide, two NIMEs which each use small inbuilt loudspeakers to produce vibration in addition to sound as feedback for the performer. As with acoustic instruments, in both these examples the sound source is located within the body of the physical instrument itself[12], and not dislocated in the loudspeakers; thus, the physical feedback emulates concurrently with the auditory feedback. The aim of using the vibration of the loudspeakers is to create vibrotactile feedback in the DMI that is akin to that felt in an acoustic instrument, as a physical sensation directly related to the sound being produced. Certainly this approach is an important one, in that it uses the paradigm of traditional instruments as a starting point for introducing haptic information to new digital instruments. This echoes the ideas of Berdahl et al. in Section 2.4.1. However, in Chapter 4, I offer an alternative approach in which the vibrotactile feedback is not intended to necessarily emulate the feel of playing an acoustic instrument, but rather as a signalling and suggestion system for the performer.

In a similar vein, Tychonas Michailidis has worked with the contemporary music pianist Sebastian Berweck to develop a system for introducing vibrotactile feedback through a foot pedal to signal successful triggering of cues during performances of works for piano and electronics (Michailidis & Berweck, 2011). They claim that this will give the pianist more security in their performance, where foot pedals can often be problematic. In certain works, a sound file may contain several seconds of silence at the start, and therefore the performer will not get immediate aural feedback to confirm whether triggering has been successful or not. They assert that

[11] An open-source electronics prototyping platform board: http://www.arduino.cc/ [accessed 24th August 13].
[12] External amplification is also permitted to increase sound quality.

"This leaves the performer with little to no confidence in creating a dynamic system between the controller and the audible result" (Michailidis & Berweck, 2011, 661). Fortunately, the haptic feedback from the foot pedal can provide this information, where listening alone cannot. Furthermore, they reference the example of Hans Tutschku's *Zellen-Linien* (2007), for piano and live electronics, which uses the foot pedal to start recording a live audio signal. Again, a vibration sent to the performer signals success where no other feedback may be available to indicate that the recording process has actually commenced. A further useful application would be where multiple pedal-presses were required in quick succession. While there has been no specific piece dedicated to this approach, Berweck has performed various compositions for piano and electronics using this device as an additional hardware component, and has indicated his desire that this technology be more widely available and incorporated into standard performance practice of live electronic works[13]. Interestingly, this work was published shortly after my own research[14] on using vibrotactile feedback had been presented at NIME 2011; yet we had come to a similar technological approach without being aware of each other's developments. Berweck has expressed interest in the technology that I have developed in this field, while noting that so far it has only been employed within my personal practice (Berweck, 2012).

2.5 Haptics within Musical Works

There has been a very limited number of actual performances that make use of haptic feedback within DMIs. Collin Oldham's cellomobo (Berdahl et al., 2008) is perhaps one of the more established NIMEs that features vibrotactile feedback. A speaker driver is used to create a *shaker* which in combination with a resistive ribbon controller makes up a virtual bowed string. When the player bows the device they are provided with a physical representation of the slip-stick motion of a bowed string, while they concurrently provide gestural input data for controlling sound synthesis. Oldman performs regularly using his haptic DMI both as an improviser (Antosca, 2008), and on commercial musical releases (Fontaine, 2011). Nevertheless, the area remains relatively unexplored by practitioners. As Marshall demonstrates in his survey of feedback present in DMIs at the NIME conferences between 2001 and 2008, less than 6% of the DMIs presented featured any implementation of vibrotactile feedback, despite its importance having been recognised by many scholars (see Marshall, 2008). While this statistic shows that there is at least some acknowledgement among the computer music community of the significance of haptic feedback and the feel of an instrument, most of the NIME literature offers only

[13] In conversation at ICMC 2011 and through personal email correspondence.
[14] As will be discussed in Chapter 4.

a technical perspective. Musical examples are usually provided in the form of demonstrations, and there are little to no detailed practice-based accounts of working with haptic technologies by performers, nor composers. I hope to address this gap within the current research with my contribution that follows in the subsequent chapters.

2.6 Perceptually Guided Performance

2.6.1 Schaeffer and Phenomenology

> For years, we often did phenomenology without knowing it, which is much better than talking about phenomenology without practicing it.
>
> (Schaeffer as quoted in Kane, 2007, 15)

Recent shifts in the understanding of human cognition, which suggest that mental processing is grounded in the body, have led to an increased discourse on the role of the body within systematic musicology, and particularly computer-based musical research. Nevertheless, this is only a recent change, and most musical research up until around the 1970s focused on what might be described as *disembodied* practices, such as approaches for analysis of the notated score, or performance practices based around the history of instruments and the interpretation of notation systems. In the 1960s, Pierre Schaeffer (1910–1995) proposed a phenomenological framework for the experience of sound (Schaeffer, 1966), which was based around the *acousmatic situation* and the idea of *reduced listening* (Chion, 2009). This encouraged an abandoning of the attempted interpretation of the causal origins of sounds, replaced instead by the formation of musical meaning purely through what is heard: the sound itself. Despite what Brian Kane describes as "the lack of consensus amongst phenomenological thinkers over what constitutes phenomenology proper" (Kane, 2007, 15), phenomenological ontology focuses on structures of consciousness and the subjective experience, and is the philosophical basis on which theories of embodied cognition are built. Schaeffer echoes Husserl's theory of *intentionality* by claiming that the sound object is an *intentional* object, "synthesised together from a continuum of auditory perceptions" (Kane, 2007, 17), this synthesis being more than simply what is experienced at any single perceptual moment.

While the larger part of Schaeffer's work focused around music as perceived by the listener, he also comments astutely on the role of the performer, clarifying the importance of the performer's position within the execution of a piece of music. He suggests that the performer is more than simply a mediator between the intentions of the composer and the reception of the listener (Schaeffer, 1966). However, despite his acknowledgement of the sensuous possibilities offered by new technology, Schaeffer seems to fall short of actually capitalising on the potential affordances of such developments. As Kane (2007) suggests, he instead employs the loudspeaker simply to replicate the ancient acousmatic curtain of Pythagoras. Nevertheless, Schaeffer's theories provide an important shift in musical thought in his attempt to find a way to describe both how music is perceived, while at the same describing sound in a scientific manner.

2.6.2 Embodied Action

I quote Schaeffer at the start of Section 2.6.1, reflecting on being unaware of *doing* phenomenology. In a similar vein, as I reflected on my musicking while developing my own performance practice, it became clear that I was making choices in accordance with a philosophy of *enaction* long before I could formulate exactly what it was that was informing my design tactics for performance environments. It is perhaps interesting to note that such choices came about initially purely through practice and the unfolding of what *felt* genuine and instinctive. Yet, it was only through deeper investigation, and the influence of the ideas that I have presented in this chapter that I was able to formalise these empirical hypotheses.

As Marc Leman, who argues for the importance of an embodied approach with respect to mediation technology, suggests:

> A way to proceed is based on the idea that action may play a key role in mediation processes between the mental and the physical worlds. The concept of action allows sufficient room for taking into account subjective experience and cultural contextualization, as well as biological and physical processes. Actions indeed are subjective: they can be learned, they often have a cultural signification, and they are based on the biomechanics of the human body. In that sense, actions may form a link between the mental and the physical worlds. (Leman, 2007, 14)

Schaeffer's theories focused on the phenomenological experience of the perceiver of sound, usually taken to be concerning the listener. Indeed the majority of research into the psychology of music performance have focused on the experience of the listener (Geeves & McIlwain, 2009). The idea of embodied music cognition is also commonly applied to the multimodal perceptions of musicians who are actually creating or performing music, in addition to those partaking in listening. In fact, in certain cultures where there is no clear divide between perceiving and performing music, an embodied approach may be a necessary model for understanding music (Jensenius, 2007). James J. Gibson's (1904–1979) *ecological psychology* (Gibson, 1979) is an important precursor to theories of embodied cognition. Gibson suggests that the mind, body and environment are all bound together as part of an ecological system, and that the affordances of physical objects within our environment are directly perceived and acted on, rather than being constructed via mental models. These ideas have gradually started to permeate the field of digital instrument design, especially in relation to haptic and tangible technology where the emphasis on the interdependent relationships between body and mind is taken as key to suggesting improved ways in which novel DMIs might be conceived, in order to create more potential for expression, and a more engaged performance both from the point of view of the performer, and consequently, of the audience. Thus there is a potential three-fold benefit, encompassing interaction, cognition, and appreciation. The concept of performance environments will be addressed further in Chapter 3.

An *enactive* (Varela, Thompson & Rosch, 1991) approach to understanding and creating music, closely related to embodied music cognition, would be to further build on this phenomenological perspective by suggesting that our cognitive processes have their root within the multimodal capacities of the body as a whole, and that meaning can be elicited through our bodily interactions with the world. Of particular note are the distinct methodologies that have been proposed by Cadoz (1988, 2009) and Essl & O'Modhrain (2006)—whose work I have already touched upon in this chapter—as well as that of Newton Armstrong (2006). These proponents all provide theoretical frameworks, as well as quite different practical approaches to DMI design, yet are all strongly influenced by themes of multimodality, and the close coupling of action and perception. These methodologies will be analysed in more detail in Section 3.2.

Despite the obviously different, yet related, practical outcomes, these approaches all acknowledge the importance of the enactive view, which was formulated by cognitive scientists Francisco Varela, Evan Thompson, and Eleanor Rosch (1991). It entails that "(1) perception consists in perceptually guided action and (2) cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided" (Varela et al., 1991, 173). This non-symbolic approach attempts to redefine cognition as embodied action, or *enaction*. Although born out of the study of the organisation of living systems, enaction was largely inspired by the phenomenology of French philosopher Maurice Merleau-Ponty (1908 - 1961). Specifically, enaction develops Merleau-Ponty's (1962) notion of the body as both biological (outer) and phenomenological (inner), in that we constantly oscillate between these states whilst perceiving and acting (Varela et al., 1991). As Armstrong explains, "the enactive perspective takes the repeated sensorimotor interactions between the agent and the environment as the fundamental locus of cognitive development" (Armstrong, 2006, 11). Despite initial skepticism and controversy surrounding these phenomenological developments, recent advancements within cognitive neuroscience have provided empirical support for this interdependency between action and perception. Specifically, scientific experiments have confirmed the existence of *mirror neurons*, which suggest that as we carry out or observe physical actions, we concurrently activate mental simulations of these very scenarios (Leman, 2007; Jensenius, 2007).

2.6.3 Embodied Interaction

Armstrong (2006) suggests that his encountering of an often negative critical reception of computer music in general may in part be due the fact that many DMIs have failed to provide the potential for an embodied relationship between performer and instrument, due to a lack of fully developed technical and, moreover, *theoretical* frameworks. As a result, he argues, the performer often feels disengaged from the instrument, and therefore also from the musical content. As a consequence, the audience also perceives this disconnect, and the performance suffers as a whole.

> Unlike the apologists for the currently predominant modes of computer music performance practice, I'm going to suggest that the perceived disconnect, or "missing dimension," that certain people have been complaining about, is not due to a conditioned desire for spectacle, or an ingrained expectation that an explicitly causal relation is witnessed between performance gesture and sonic result. Rather, it seems to me that there is something more fundamental to the issue: that an engaged and embodied mode of performance leads to a more compelling, dynamic, and significant form of music making; for the performer, the audience, and for the social space that they co-construct through the performance ritual. If the attributes of the computer preclude such a mode of performance, then the medium deserves to be examined, in order to determine what can be done to engender the technical conditions from which an embodied performance practice might arise. (Armstrong, 2006, 5)

Here Armstrong is not blaming this perceived disconnect on the shortcomings of the audience, who, as Kim Cascone (2000) would suggest, have not yet evolved beyond their expectations of a *show*. Perhaps what is more important here is that neither does he blame this on the need for obvious and unambiguous causal relations between action and resulting sound.

So what might be this middle ground that can provide the audience with an engaging and dynamic musical experience of live computer-based or electroacoustic music? Echoing Armstrong and Leman, I would argue that it is by creating this very experience for the performer herself, through an embodied relationship with her instrument, that will lead to a compelling performance for the audience. Comparably, Essl and O'Modhrain suggest that we need to consider the various ways in which perceptually guided action might define "the 'feel' and playability of a musical instrument" (Essl & O'Modhrain, 2006, 294), in the quest to develop a design philosophy for new DMIs; but they warn that we are only "at the beginning of understanding when a sensorimotor experience is natural and believable for a performer" (Essl & O'Modhrain, 2006, 294). There seems to be an emerging sense of a demand for deeper thought and theoretical rigour with regard to DMI design, in the midst of increasingly inexpensive and ubiquitous technology. These concerns are similarly expressed in recent calls for more discussion into the nature of performance (Schroeder & Rebelo, 2009), and the relationship between the body and the instrument within a performance environment (Rebelo, 2006).

2.7 Summary

From the physical manifestation of sound as vibration to the ability of music to permeate distance and put people *in touch*, the links between sound and touch are evident. The role of our somatosensory system within traditional instrumental performance is well recognised. The idea of performance as perceptually guided action seems to suggest the importance of a multimodal approach to considering the design of digital musical instruments, and moreover understanding musical performance in general. Not only as listeners, but as performers we are continuously making use of multiple streams of sensory feedback as we make our way through a performance. The benefits of using haptic technology for improving certain aspects of instrumental performance are well documented, and it is evident that there are small pockets of researchers pursuing these ideas, and moreover, tackling some of the wider philosophical issues behind interaction design and embodied interaction. Nevertheless, research in this area tends to be focused around technical development. Where musical applications are documented, these are generally framed as small scale studies designed to produce qualitative and quantitive data in order to demonstrate the usefulness or improved ergonomics of such technology. This seems to suggest a lack of an in-depth, practice-based perspective in this field, which I hope to address in the subsequent chapters.

This chapter has outlined the main themes that formed the basis for my undertaking of this research. These can be summed up as follows:

- through our sense of touch we engage with instruments and the materials that we use to create music;
- we employ touch both through active engagement with an instrument, as well as through the passive perception of sensory feedback;
- the musical acts of listening and performing are multimodal affairs;
- musicians have always made use of haptic feedback, in addition to auditory and visual sensory information;

- the relationship between the physical energy injected into a system and the resulting sound should be meaningful;
- our engagement with instruments is dynamic and embodied;
- approaches to DMI design often fail to acknowledge the importance of many of these issues.

Chapter 3

The Instrument-Performer Relationship

3.1 Introduction

In the previous chapter I proposed that one of the most vital feedback systems that has been embedded in musicians for centuries is that of physical response, comprising the haptic and kinaesthetic somatosensory systems. I outlined how musicians will continuously reassess their playing by making use of not only their specialised sensorimotor skills, but also the tangible feedback that is relayed to them through the body of the instrument, in the same way that auditory information is available and used throughout a performance. In this chapter, I discuss the background and theoretical framework surrounding the development of an augmented instrument, the *hybrid piano*, which focuses on the notion of performance as *perceptually guided action*.

I look more deeply at the phenomenological basis for the development of haptic technology, and discuss the implications within my own practice, which often deals with augmenting acoustic instruments, as well as working with purely electronically produced sounds. As pointed out in Section 2.3, while the acoustic component of the sound energy of an augmented instrument is created within the real-world interactions—in the case of a piano, between hammers on resonating strings, the soundboard, and of course the performer's body—the digital sonic events cannot be located in a similar *palpable* source. I suggest that by exploring notions of multimodality and embodiment, and by looking at theories of enaction, the ongoing processes of human action and perception within instrumental performance can be maintained for the player, whilst arguably also enhancing the experience for the listener. I examine the instrument-performer relationship through the *hybrid piano*.

The hybrid piano is the instrument around which most of my creative portfolio is based, and reference to some aspects of the history and development of research within the field of piano and live electronic performance is required to provide a context for my own research. I assess current practices against the theories that are developed in this chapter, and observe differences in approaches, highlighting where my own work diverges from other methods. I present my creative practice as a practical phenomenology, with illustrative examples of the ongoing process of exploration and development.

3.2 Methodologies of Enaction

In what follows I will explore some of the methodologies related to instrument design that have emerged out of my practice as a performer of piano and live electronics, and have led to the haptically-augmented hybrid piano. It could certainly be claimed that the subset of DMIs known as augmented instruments are inherently suitable as potential candidates for offering engaging and embodied modes of performative activity, due to the established development both of the acoustic instruments around which they are built, and the corresponding history of performance practice. Indeed, the literature surrounding those DMI design philosophies in which the importance of tactility is emphasised includes a discussion of the favourable multimodal embodied engagement afforded by acoustic instruments, and an agreement of the tactile-kinaesthetic action-perception loops that arise during play as being crucial to performance (Vertegaal, Ungvary and Kieslinger, 1996; Rovan and Hayward, 2000; Cadoz, 2009). John Bowers, performer, improviser and interaction designer, on reflection of a concert where he moved from playing a complex electronic system to spontaneous percussive playing on a *found* ashtray, remarks on the tacit ease with which one may interact with a physical object:

> These sounds - with direct physical engagement at their source and inhabiting a quite different acoustic space than what was carried by the loudspeakers - proved most useful. The acoustic sounds were scaled to the bodily force I applied to them, and made for a refreshing contrast to the extremes of algorithmic mediation I had tried to find a home in before. Of course they were, of course they did. I was rediscovering a traditional instrumental technics (banging and scraping) and a concomitant phenomenology of playing (making music, not interpreting interfaces). I was not trudging through treacle. (Bowers, 2003, 38)

How can we start to augment an acoustic instrument, which affords embodied interaction, without losing these qualities which are so necessary for an expressive musical performance?

3.2.1 Structural Coupling

Emphasis on tactility and multimodality seems to support an understanding of performance as perceptually guided action. The concept of enaction is dependent upon embodied knowledge, the kind of knowledge that is derived from being and acting in the world, with all its physical properties and constraints; perceiving and acting are taken to be part of the same process (Varela et al., 1991). However, as we start to modify an instrument and construct relationships between gesture and real-time sound production, this intrinsic structural coupling between sound and touch, and between agent and environment can become fractured. Essl and O'Modhrain's (2006) approach to creating an embodied instrument-performer relationship takes as its basis an innovative solution to the problem of how to map input gesture to sound. This relies on the performer's tacit knowledge of the physical properties of real-world objects. By grouping together sets of actions that afford common types of behaviours, different audible responses, which arise from the similar types of interaction, can be substituted. For example, as discussed in Section 2.4.2, physical grains such as pebbles are used to make tangible a subset of the possibilities of granular synthesis. Moreover, the electronic sonic result may reflect the audible sound of stones themselves, or indeed could instead be substituted by the sound of colliding ice cubes. Here the *structural coupling* (Varela et al., 1991) between interaction and sonic result is compelling. The relationship between the performer and her instrument is both intimate and familiar: no awkward gestures are required and the physical qualities of the solid objects combined with the motor movements of the player will affect sonic parameters in a way that can be naturally anticipated. Thus, hitting pebbles together with a stronger force would produce a louder resulting sound. Interestingly, the mediating technology here is minimal: it is simply the sonic information derived via a contact microphone that is used for the control data.

Structural coupling of performer, instrument and environment suggests a state of affairs where the performer is not separate from the other elements but is connected to them in a way that creates a dynamic continuity between these different agents. Rather than a computational system where the performer creates input, which is subsequently processed and rendered as output by the musical system, this model of a performance environment suggests continuous shifting between the body of the performer and the space and system in which they act: the body is connected to the nervous system—via sensory inputs and motor outputs—in the same way that the body is connected to the environment in which it acts—through physical forces and constraints. As Varela, Thompson and Rosch suggest:

> It is precisely this emphasis on mutual specification that enables us to negotiate a middle path between the Scylla of cognition as the recovery of a pregiven outer world (realism) and the Charybdis of cognition as the projection of a pregiven inner world (idealism). These two extremes both take representation as their central notion: in the first case representation is used to recover what is outer; in the second case it is used to project what is inner. Our intention is to bypass entirely this logical geography of inner versus outer by studying cognition not as recovery or projection but as embodied action. (Varela et al., 1991, 172)

Waters similarly suggests that by dividing and separating performer, instrument and environment, we lose important notions such as the impact of the individual physicality of a particular performer, or the way in which an instrument might be thought of as extending back into the body. It is not simply the acoustic properties of the physical instrument that are crucial to creating music, but the "physiology of this particular body,... the algorithms which operate in this particular piece of warm wet meat, and... the many relationships between all of these and a particular acoustic and social environment" (Waters, 2007, 3). This statement expresses the reason why I am present, as a performer, in all the pieces included in this portfolio. The works and the "performance ecologies" (Bowers, 2003, 56) out of which they arise are exclusively build around my own physiology, and my own unique relationships with the materials and instruments that I employ.

3.2.2 Sustained Practice and Interdependency

Pedro Rebelo (2006) argues that when an instrument is thought of as an entity, rather than merely a functional *tool*, it carries its own cultural significance, created through the choices of the instrument-maker, and elicited through its relationship with the performer. It should follow, then, that when it is the performer who is also the instrument-maker, the resulting instrument can be deeply personalised through prolonged embodied practice. In developing the hybrid piano, the largest amount of time that I have spent on the project has been devoted simply to playing, feeling and listening, adjusting, and playing again. Hence, the development of the instrument itself is an embodied activity, and one which has continued over several years and evolved through many performances. As Atau Tanaka points out, this durational approach is necessary, and often difficult to achieve given the exponentially increasing pace of technological advancements:

> A relationship with an instrument is based on the time we spend living with it. In the accelerated pace of hi-technology development, we rarely have time to spend with any one given hardware or software configuration before it is replaced by a new version. This is quite contrary to the time needed to develop a deep relationship with an instrument. (Tanaka, 2000, 399)

Newton Armstrong (2006) takes an alternative approach to instrument development by looking towards creating adaptive and emergent performance environments through a combination of bespoke hardware and software, which exhibit various types of instrumental resistance to the performer, and which engage the rich and dynamic aspects of human behaviour. His first attempt at creating an enactive instrument, *Mr. Feely*, consists of physical features such as knobs, buttons and joysticks, along with a considered engagement of physical properties, such as the user's centre of gravity. However, most of the emergent and dynamic features of Armstrong's instrument can be found within the software design. It is important to notice that the musical goals here, as with the work of O'Modhrain and Essl, are concentrated around engagement, playability and interdependency, rather than control. In fact, the idea of exerting control over a system that displays emergent behaviours seems almost counter-intuitive, as both the system and the player must continually adapt to one another. This echoes Rebelo's notion of a "multimodal participatory space" (Rebelo, 2006, 29). Armstrong also notes the importance of a sustained and continued practice (see Figure 3.1 for an adapted illustration of Armstrong's model of enactive performance practice), where the musician's bodily adaptations are determined not only by "the resistance offered by the instrument, [but] are also determined by the musician's intentionality" (Armstrong, 2006, 47).

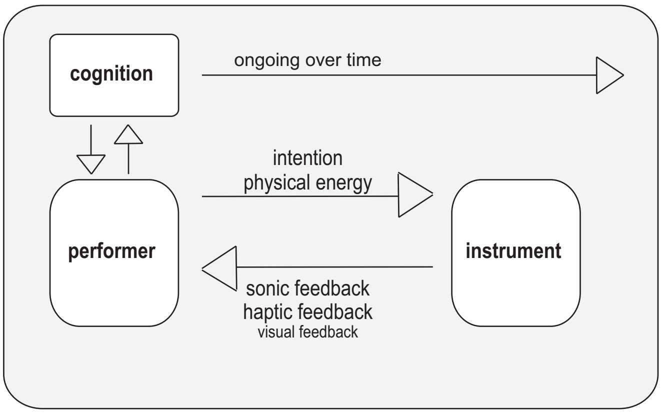


Figure 3.1: Cognition is formed through ongoing interaction loops over time.

3.2.3 Classification of Gesture

Cadoz (2009) warns against classifying every situation that maps gesture to real-time sound processing as *instrumental*. He starts by defining instruments as real-world objects that can give rise to both acoustic and visual phenomena through the physical energy exchange that takes place when a human interacts with the object, or with the environment *through* that object. He describes this type of interaction as *ergotic* (Cadoz, 2009). In a musical situation, only the performer experiences the direct tangible interaction with the object; the audience perceives the related visual (gestural) and auditory (musical) information. With regard to acoustic instruments, the interaction is clearly ergotic, in that the action and resultant sound are intrinsically coupled. Cadoz claims that the subtle variations in how we create and perceive the phenomena of these instrumental gestures "are of a primordial importance for the study and the understanding of the enactive conditions for the expressive and cognitive activities" (Cadoz, 2009, 219). The problem for Cadoz arises in DMIs, where the ergotic interaction of the gesture bears no physical relation to the resultant sound, even if performed in real-time. Here, even sophisticated mapping choices cannot remedy this as there is no real-world continuum of energy from input gesture to sound processing. Where, for example, is the transformation of energy from sliding up a fader to increase the speed of a played back sample? As a result, Cadoz advocates continued research into using force-feedback haptic devices, along with physical modelling techniques, as a way to *transduce* energy from gesture to sound.

It is quite clear that there is already an intrinsic potential for ergotic gestures within augmented instruments. Certainly, it would be extremely difficult to imagine an augmented instrument *without* this capacity, unless the gestural and sound-producing mechanisms were entirely decoupled. A possible, yet trivial case would be a performance where the body of the instrument was, for example, pressed by the performer, causing no acoustic sound, but triggering, by way of sensors, digital processes. Tanaka discusses the use of non-essential gesture as treading the same line as the "fine distinction between genuine physical exertion and gratuitous display" (Tanaka, 2000, 401). However, in the case of DMIs there may be gestures which are non-ergotic, but nevertheless functionally essential, rather than being theatrical displays. A common case might be the switching of preset modes within a software system using a MIDI foot pedal; similarly, buttons on a MIDI controller might be employed to turn on and off different processing modules. Neither of these gestures are ergotic, and nor are they even necessarily sound-producing, but may be necessary for a performance. I would suggest that while it may not be possible to completely eliminate the need for such gestures, a *more* engaging and intuitive system would be one in which these procedures were minimal. Such a system would, I am arguing, have more *potential* for embodiment. Certainly, within the domain of traditional instruments, a guitarist has the option to detune strings within a performance, and while the action of detuning *could* potentially be audible and built into the music, a performance in which multiple detuning occurred which had to be reconfigured in real-time without being part of the musical output would likely be distracting to both performer and audience.

Cadoz's engagement with ergotic gestures through physical modelling controlled by force feedback devices could be thought of as the instrumental *ideal*; a purist approach to creating embodied, enactive DMI performance systems where the interaction is based around the traditional acoustic instrument paradigm. This approach is manifest in his Modular Feedback Keyboard, which was discussed in Section 2.4.1. However, this ideal comes with its own limitations, for many of the possibilities provided by both electronic and digital audio developments are of course *not* representative models of physical instruments of the real world. If we were to limit ourselves to only acoustic-like interactions based on physical models, a vast amount of DSP/synthesis potential would be excluded. What sort of physics could be employed to engage with a phase vocoder? There is, of course, no analogous system that exists in the real world. Are we therefore to exclude all potential sound processes that are not built from physical modelling? Finding a middle ground between Cadoz's ideal and the multitude of possibilities offered to us by DSP could be a task worthy of more attention; this is somewhere that I have tried to situate my own research, as described below.

3.3 Augmenting the Piano: Performance Environments

Essl and O'Modhrain describe the notion of an augmented instrument as one which takes "traditional instruments and augments them by adding sensing technologies that offer access to aspects of the instrumental gesture" (Essl & O'Modhrain, 2006, 286). The particular way in which we gain access to this physical energy, and how we use the data that we cultivate from it must be carefully considered. The goal for my own practice is to create a performance environment that can facilitate a maximum potential for expression and an increased sense of engagement than would be achieved by operating discrete controllers while performing on a piano. The priorities arise not from creating something that can be easily mastered, but rather by ensuring that the performer's embodied experience of playing continually provides them with new knowledge and ability through this experience. As mentioned above in Section 3.2.2 the temporal aspect of a performance practice is also important, where "Over a sustained period of time, these negotiations lead to a more fully developed relationship with the instrument, and to a heightened sense of embodiment, or flow" (Armstrong, 2006, 6).

I am not concerned here with the practice of works for piano and fixed media. I am striving to create an instrument through which compositions can be realised, and with which I can also improvise in different situations. When John Cage (1960) pioneered the first works for piano and analogue processing, in the early 1960s, simple amplification of the acoustic sound was used, and there was no fracture between input energy and sonic result. Gordon Mumma furthered Cage's explorations of amplification with his *cybersonics* experiments in which electronic circuitry would self-organize according to the acoustic properties of the sounds. In *Medium Size Mograph* (1967) these cybersonics involved using an envelope follower to alter the natural attack and decay of the piano sound. The self-regulatory nature of the circuits involved in these processes has been a key influence for current concepts of emergent musical systems (see Di Scipio, 2003, for examples of such systems). Here, the inherent properties of the system itself are coupled with the environment, constantly updating and readjusting: the system not only observes and listens, but eventually becomes self-observing. While emergence has not been a key aspect of my own performance environments, this approach offers one of the perhaps rarer instances where an enactive and ecological system is the grounding basis for a piano-based system. Furthermore, I would follow Waters (2007) in suggesting that performance systems *necessarily* cannot be separated from the environment—the performance space, along with social and cultural contexts—in which they are performed. This point will be emphasised as I present examples of my own work, which vary and adapt on each performance.

Upon playing a note on the piano, sensory information is passed back to the performer through the haptic channels, and the slightest difference in the touch employed could noticeably affect the sound, or at least affect the character of the performance as a whole. This behaviour is learnt by the pianist over a long period of time with repeated and continual practice; yet it is always marginally adapted for each new piano that they play on, and in every different space. Waters argues that once computers are involved, "our sense of mutability between performer, instrument and environment is heightened" (Waters, 2007, 4), and that considering these roles using Agostino Di Scipio's notion of an *ecosystem*, or a "complex dynamical system" (Waters, 2007, 13), underscores the idea that involving digital or electronic elements should not be thought of any differently in regards to achieving what it is that we want musically. That is, we should not think of the computer as a supplementary tool for converting gestural input into sonic output, but should engage with the dynamics of the instrument or system as a whole, which also includes the sensory perceptions and motor skills of the performer.

3.3.1 Digital Augmentation

Having established some of the philosophy that continues to influence my own approach to building instruments, I will outline the two layers of development of the hybrid piano, starting with the original augmentation of the acoustic instrument. The hybrid piano has evolved over the last five years through my ongoing performance practice, which includes composition as well as solo and ensemble improvisation. I term the instrument a *hybrid* piano, to emphasise the integration and importance of both the acoustic and digital components, although, of course, it easily falls within the class of augmented instruments. The hybrid piano has been developed as a performance system that enables DSP through live sampling, synthesis, sample triggering, and so on, all of which are controlled by the performer alone. Whilst continuously evolving through a part-modular software approach, certain aspects of the sonic character of the instrument have remained constant over the years and, as such, it can be viewed as a developing system, and not a series of radically different experiments. For example, partial tracking has been used since inception, either to resynthesize sine waves, or, latterly, to generate resonances.

No additional performer is required to oversee the execution of the electronic aspect. Conversely, through my research and performances at various festivals and academic conferences over the last few years, it seems that much of the music composed for piano and electronics involves either multiple performers, or at least a team of collaborators consisting of technicians or programmers. Systems for the *single* performer are much more rare and often the result of many years research. Such an example is the body of work that comprises *Zellen Linien* (2007) for piano and live electronics, by Hans Tutschku. Tutschku claims that the work has arisen out of his prolonged engagement with the prepared piano[1]. Another thoroughly matured system is the *Piano+* environment, developed by Sebastian Lexer (2010). Lexer suggests that "a highly flexible and adaptive system minimizes direct operational computer control" and that "this has helped retain a pianism in sound production involving conventional, as well as extended, playing technique and electroacoustic real-time processes" (Lexer, 2010, 45). This need to improve flexibility through the minimisation of non-instrumental gestures seems to support my proposal made in Section 3.2.3 that such gestures should be kept to a minimum. As with Tutschku and Lexer, I wished to create a performance environment that would be suitable both for live treatments during improvisation, as well as being suitable for the performance of more repeatable compositions involving piano and live electronics.

3.3.2 Immersion and Intuitive Approaches

Particularly with respect to improvisation, many of the early performances with hybrid piano performance environments were unsatisfactory, both due to the instrument design, as well as external factors such as the layout of the stage and loudspeakers. This is illustrated in an early performance at the University of Edinburgh, 1st June, 2010, where I performed using a piano frame and electronics, with Christos Michalakos performing with percussion and electronics (see Media Example 3.1).

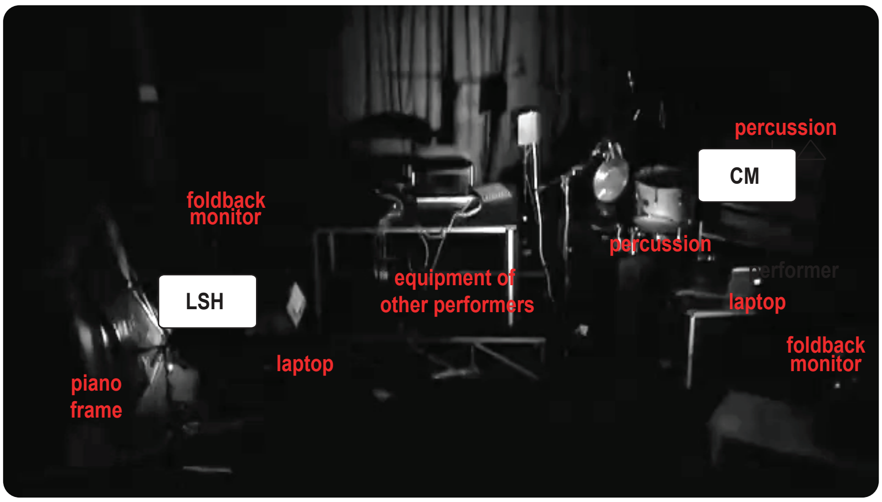


Figure 3.2: Awkward stage layouts and awkward instruments.

[1]See http://www.tutschku.com/content/works-Zellen-Linien.en.php [accessed 24th August 2013] for more information on the performance notes of the piece.

Christos Michalakos (CM) and I are going to perform an improvisation in the Atrium, a performance and lecture space within the Music Department at the University of Edinburgh. Instead of using an upright piano, I am going to play the frame: the sound board which has been salvaged from an old piano. CM is going to play an early version of his augmented drum kit. A variety of other performances involving laptops are going to take place in the same space. We start to set up, bringing through pieces of equipment, trying to figure out the best way to arrange them in the space. The piano frame needs to lie at a diagonal angle so that I can have access to the strings and pegs. We find that the only positions that works is to prop the bulky frame up on a pillar at one side of the stage (see Figure 3.2). The logistics of the laptop stations required for the other performers mean that the drum kit must be positioned on the other side of the stage. We've rehearsed for this concert thoroughly. We will start together rhythmically, and will gradually break into two alternating solo-led sections.

However, as the concert begins I suddenly get struck by the realisation that things are not going to go to plan. In the soundcheck, although my back was to CM, we could be casual enough in our movements to achieve, somehow, the required degree of communication necessary to negotiate the performance. I am facing away from CM, but now I cannot even glance over my shoulder as my performing demands that I absorb myself with the assembled instrument before me. I strike the strings and frame in a rhythmical conversation with CM's percussive playing. When the music moves on, I engage some of the electronic processing using the Behringer MIDI foot pedal, which I have laid on the floor in front of me. I pluck the strings with one hand, while regulating the level of the electronics with my other hand, on the loose expression pedal of the foot controller. It's a balancing act, not only between the acoustic and electronic sound palettes, but to literally stop from falling over in my squatting position on the floor. Our communication is limited both due to the logistics of the stage layout, but also because I feel unable to find any remaining cognitive space. My immediate attention is completely devoted to juggling both the sound making, and non-instrumental gestures required to play. I am not happy with my instrument as it does not feel whole. The correlation between the two separate sound-making mechanisms is not clear, or rather, not intuitive. One part feels instrumental, or musical, and the other feels primarily like a series of on-off switches and level controls. We get through the performance and listen back to it. It sounds better than we had anticipated, and more musical than we had imagined, but this feels more due to our familiarity with playing together, rather than coherent musical ideas.

Despite in some cases producing acceptable musical results, these early experiments involving the hybrid piano remained highly unsatisfactory to me as a performer and improviser. With my composer's head (heart) on, I felt uneasy about starting to write for an instrument with which I believed that neither myself, nor another performer, would be able to engage in a manner suitable to realise my musical ideas. In a discussion of achieving immersion in music-making, Aden Evens describes the state that I was searching for as "an absorption, a total immersion in the music that blurs the distinctions between musician and instrument and appears to take over or occupy the musician's body" (Evens, 2005, 131).

A similar concert to the one described in Section 3.3.2 above took place at the same location at the University of Edinburgh, in which I was playing an augmented prepared upright piano. I had fixed a MIDI controller above the keys of the piano, in the hope of trying to more closely relate some of the performance gestures with the electronics sounds by placing the two control mechanisms in close proximity: both the actual piano keyboard, and the MIDI controller. Yet this only served to further separate the different elements and processes that I wished to present as a coherent whole, by providing an indication to the audience of when I was starting and stopping the DSP. Furthermore, I was also using a Keith MacMillan Softstep MIDI controller as a foot pedal, hoping to align some expressive qualities of the electronic processing with the already familiar pianistic gestures of using pedals. This particular controller can be used in various modes including offering toggle switches, or pressure sensitive pads. I was attempting to create an ergotic interaction, physically manipulating the resistive pedal in order to produce an energetically linked change in parts of the electronic sound.

However, while I continued to use this technique in performances for around two years, I eventually abandoned it after many awkward moments attempting to force one foot firmly onto the Softstep pads while attempting to balance on the other, reach inside a grand piano, keep a chord pressed on the keyboard, and so on. This point is emphatically made by contemporary pianist Sarah Nicolls (2009). These techniques were not offering any type of embodied or immersive experience for me as a performer. How then could I find ways to access the non-physical elements of the performance system in such a way that the "instrument does not mediate, does not stand between the musician and the music. Neither does the instrument disappear, for it remains integral to the music, offering itself to the musician" (Evens, 2005, 159).

3.3.3 Instrument as Controller and Sound Source

Some of the first appearances of the hybrid piano were in the context of compositions involving live electronics, which explored the notion of using the instrument both as the sound source, and as the controller. This idea is used extensively by Di Scipio, in his design philosophies that challenge the ubiquitous and perhaps over-used notion of *interactivity* (Di Scipio, 2003). In the context of the compositions, the use of MIDI foot pedals for triggering were avoided. Their employment is a commonly encountered performance practice within compositions involving acoustic instruments and live electronics, used either as a trigger for sound file playback, or to advance preset sections within the software. As detailed above, however, I found the addition of extra pedals problematic and distracting, despite what might appear to be a simple extension of an already learned instrumental technique.

I wished to find more organic means of moving through the pieces and to avoid reliance on a system where, for example, the performer is required to press the pedal several times per second, or a large number of times within a section, inevitably leading to anxiety about whether the trigger has been successful or not. And certainly repeated moments of unease, precisely forty-five for one such piece by Enno Poppe (Michailidis & Berweck, 2011), cannot be helpful to any performer. Of course difficult passages within any piece of music may make a player anxious, but here I am referring to the act of avoiding adding unnecessary non-sounding gestures where other methods could suffice. Instead, within those compositions that used a timeline, I employed a more fluid approach, which made use of time-windows combined with dynamic or pitch based triggering systems. Thus, realisations of compositions, which often featured improvisational elements, could be more easily moulded into a form more fitting of a particular performance, as determined by the particular environment. So, for example, if the performer feels that the present section needs more development then they may prolong it up to a point, within the given time frame. In this way, as well as giving the performer more of a sense of value to their movements, there is more chance that the audience will perceive the sonic and semiotic information as resulting from a particular instrumental gesture, which will contribute to the listeners' experience of the music.

This approach makes use of the enactive knowledge already accumulated within the motor skills of the pianist. These early works employed basic machine listening techniques, in which the acoustic material was continuously analysed by the computer for various information such as pitch, dynamic, phrase length, and perceived silence. Through intimate exploration with the system, there emerged a strong desire to adhere to what I only later learned could be classed as Cadoz's *instrumental gesture*, in the sense that the ergotic interaction and resultant sound should be energetically coupled, as described in Section 3.2.3. Using the piano as both the sound source and the interface to the digital sonic world would help to facilitate this type of union. This leaves the pianist free from having to operate additional controllers, and hence able to negotiate the instrument and focus on the playing, extended techniques, and general musicality within the performance. In a sense, this is not so far removed in ideology from the approach of Essl and O'Modhrain discussed earlier in Section 3.2.1: in both cases it is the sensorimotor skills already known to the user that are exploited in their relationship to the instrument.

The case of a musician using an augmented instrument is simply a subset of the more general case. Similarly, the coupling of gesture to sound in the hybrid piano made use of the idea of making tangible the type of real-world forces at work. Hence, just as granular synthesis was physically represented through colliding pebbles, the hybrid piano uses, for example, the attack of the hammer on the string to bring forth an impulse through a resonant filter. Another example of this type of interaction was the use of very short decaying feedback delays coupled to the scratching of the strings with the side of a piezo contact microphone. Here, the delays were triggered only using the sound picked up by the piezo microphone. More importantly, the energy of the gesture of sweeping one's hand over the strings was preserved in the decay of the delayed sampled sound, almost as if the trace of the hand's gesture could be heard.

3.3.4 Augmented Amplification

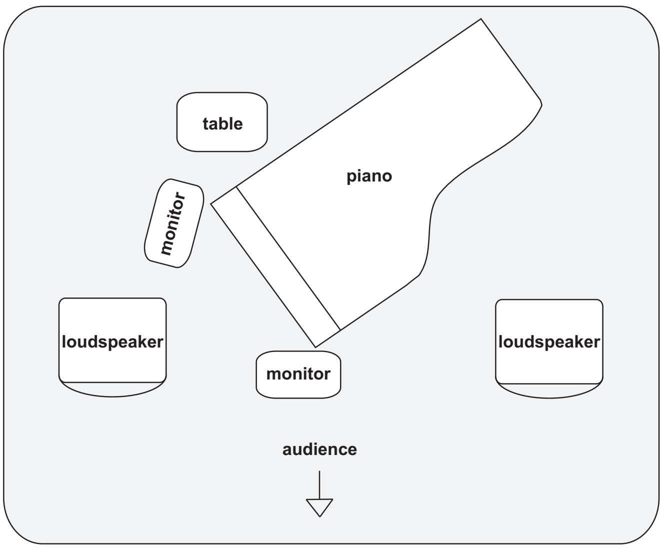


Figure 3.3: Ideal stage layout for the hybrid piano.

In performances involving the hybrid piano, the acoustic sound of the piano is usually amplified through loudspeaker in order to complement the dynamic range of the electronic sound, and to help blend with it. This is not always necessary, however, and depends on the size and layout of the particular performance space. Speakers are placed proximally on either side of the piano, to give the illusion of the electronic sounds being emitted from the body of the piano itself. Various configurations are possible to achieve this, with the electronics often being pushed out to additional speakers placed at a slightly wider angle in a larger hall, for example. The most undesirable arrangement has been performances where the piano sits centre stage in a large space, and the electronic sound is projected via loudspeakers positioned high above the stage on either side, which destroys the cohesive sonic unity of the instrument as a whole. Arguably, if we do not think of the presentation as one of an instrument, but of a piece of music consisting of a piano and additional electronic sounds, this may not matter to the performer or composer, but nevertheless cannot help but to separate further the gestural energy of the performer from the resultant sound. As Emmerson states:

> The virtual imaging of two (even high quality) loudspeakers at the periphery of an auditorium is insufficient. Any off-centre listener will lose the image (if there was one to start with) and thus any real sense of a performer as source. We usually 'get away with it' because of the visual cues additionally available and sometimes a small amount of direct sound from the instrument. (Emmerson, 2007, 95)

One of Emmerson's proposed solutions to this common problem is to give more *power* to the performer in how the electronic material is projected, with attention given to both the 'local' sounds coming from the position of the performer on stage, as well as the 'field' encompassing the audience. This is an important issue, since I consider the loudspeakers to be part of the instrument, or performance environment that comprises the hybrid piano, it would follow that the performer should be able to affect the projected electronic sound, just as they naturally affect the acoustic sound. But as well as having a say in how loudspeakers are positioned, this should also be manifest in the dynamic relationship between performer and instrument.

3.3.5 Work and Effort

Tied into the themes of tangibility and interaction, is the idea of the work, or effort, contained within a musical exchange. Joel Ryan's suggestion that "physical effort is a characteristic of the playing of all musical instruments" (Ryan, 1991, 7) is a view that is universally accepted for acoustic instruments, but often neglected when building digital ones. Acoustic instruments resist the will of the performer, and it is within these precarious negotiations that expression is formed. Evens states that "music does not result from the triumph of the musician over the resistance of the instrument, but from their struggle, accord and discord, push and pull" (Evens, 2005, 160). The body of the acoustic instrument already resists the performer: pressing a key takes a small amount of effort; playing rapid staccato scales smoothly demands a different type of work; on plucking a string inside the frame, another set of resistances and forces is felt. The piano, then, could be thought of as a force feedback, or haptic interface to the computer. The obvious difference in the case of the hybrid piano is that instead of data read directly from physical parameters, such as the distance that a key is depressed, parametric data is derived from the acoustic properties of the instrument. However, this can certainly still be a useful measure of performance energy. Comparatively, when working with the Novint Falcon, an inexpensive three-dimensional games controller with force feedback that I discuss in Chapter 5, aside from the programmable forces offered to the user, the output data sent to the computer is simply x, y and z position information. There is no obvious reason why this is a better choice of representing the physical energy put into a system than an analysis of the produced auditory information. This discussion of instrumental resistance, and how it is embraced within the portfolio pieces will also be addressed further in Chapter 5.

3.3.6 Figurine-Operated String

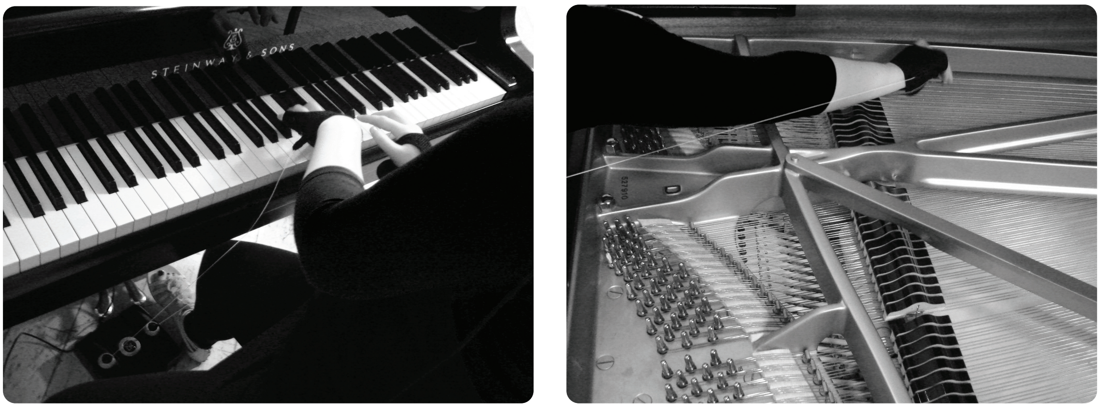


Figure 3.4: Resistive and restrictive Gametrak controller.

The portfolio piece ***Figurine-Operated String*** (2012) for piano and live electronics embraces all these ideas in an attempt to create an immersive performance environment, with a mutable and dynamic relationship between performer and instrument. Most of the engagement is based around the grand piano as both the sound source and controller, and additional data is received through a simple game controller, the Gametrak, which collects 3-dimensional position data from the hands of the pianist (see Appendix E for details). The pianist must wear fingerless gloves, which are connected to the base unit of the controller—which sits on the ground—via two thin tethering cables (see Figure 3.4). This creates a further resistance that the performer must engage with in order to *feel* their way around the electronic parts of the music that they produce (see also Section 5.2.1). The commentary below is a reflection from a performance at the Reid Hall, Edinburgh, 29th May, 2013.

With a forceful attack, I start the piece, and also the electronics as they are intrinsically linked. I move from agressive jerky syncopated chords and runs on the bass notes, up to contrasting delicate high, sparse notes. The electronics are triggered by attacks and the density of my playing, but the combination of directly discernable cause and effect, and more durational processes still feels *meaningful*, and allows me to improvise without worrying about how I might be affecting the digital processes. Moving my hands up to the highest octave on the keyboard, I suddenly freeze both the position of my hands and, concurrently, the electronic sound world (see Media Example 3.2) c. 30”). I know that as I cross back and forth between the high and low ranges that the music is wholly *in my hands* (and body). When I choose to pause, the dense clusters of electronics will either instantly cease, or they will start to decay to a frozen phase-vocoded, spectral-gated sound. As time passes, more digital signal processes are activated, but I feel immersed in the physicality of the performance environment. I am not *in control*: I cannot diverge from the piece, and must continuously negotiate my way through it. Yet, I feel very connected to the instrument and performance space, not just because I am physically bound to it via the controllers on my hands. I know that as I move around the different parts of the keyboard, I am accumulating data which will eventually trigger additional DSP modules and increase the amount of live sampling both of the piano, and of the electronics themselves. There are forces uniting me with the instrument, both as physical bonds, and through the energy that I am instilling in the system itself: this feels as if I am in a musical *playground*. The resistances that the hybrid piano is confronting me with are productive in offering ongoing moments of potential expression, as well as engendering my creative ideas. At the chosen moment, I reach inside the piano, using a paint roller to mute the strings, in order to produce natural harmonics (see Media Example 3.2 c. 2’30”). As I do this, the processing ceases, and I activate a new sound world which compliments the delicate nuances that I am creating inside the piano.

3.4 Haptic Augmentation: Perceptually Guided Action

Over an extended period of research, which included numerous and regular performances with the hybrid piano, it became apparent that developing palpable sense of the physicality of the electronic sound was just as important as the analysis techniques, DSP, and the transducing of physical gesture into corresponding changes within the software. That is to say that the *feel* of the instrument, as a whole, including the acoustic piano, laptop, hardware, software, and loudspeakers, became an important consideration. Of course I am not suggesting that I needed to be in direct contact, and physically touch each of these elements, but it became clear over time that something was missing, in my experience as a performer. While I was receiving the usual physical vibrations from the acoustic part of the instrument, through the acoustic resonance naturally felt in my hands, along with the more subconscious vibrations felt through my feet in connection with the pedals or floor, for the digital audio there was no analogous tactile feedback mechanism. I had to rely purely on my ears, and sometimes eyes via the laptop screen, to receive information about the sonic digital counterpart. The electronic sound would emerge from loudspeakers placed proximally to the piano, when the concert setup would permit this, or on either side of the stage, when this was not feasible, as is an unfortunate reality of many concert scenarios. Even with stage monitors, however, I felt a strong sense of disconnect, a feeling of being literally *out of touch* with what I was playing, despite being able to hear it, to some extent. Furthermore, as I will describe in Chapter 4, reliance on the screen is problematic when using augmented instruments, as it can be distracting and interrupt the sense of absorption in the task at hand. When this occurs for the performer, the audience are likely to perceive it too.

3.4.1 Performer-Embedded Feedback

As discussed in Chapter 2, attempts have been made to address the issue of the lack of tangible feedback in DMIs by embedding the vibrotactile feedback in the instrument itself (see O'Modhrain, 2001; Berdahl et al., 2008; Marshall & Wanderley, 2011), often to make the DMI feel like an acoustic instrument. My motivation for the further augmentation of the hybrid piano with vibrotactile feedback was to maintain perceptually guided action through play, by being physically *in touch* with both the acoustic and digital sound worlds. From a practical perspective, embedded vibrotactile feedback would not be appropriate for a piano. Firstly, the pianist is accustomed to the most palpable vibrations being felt through the hands, and thus would have to be in continual contact with the instrument in order to perceive the embedded feedback. This would work for the direct, instrumental gestures, but would be problematic for auditory responses that were not directly linked to the performed gesture. For example, a sound with delayed onset, or long duration, would no longer be perceived once the hands had been lifted from the piano. Secondly, it is worth mentioning that the hybrid piano has no real-world unique identity, in that it is designed to be constructed around any piano model. I have performed hybrid piano pieces on both Bösendorfer Imperials and Steinway Model Ds, as well as abandoned uprights, which are prepared in a Cagean fashion, with screws, thumb tacks, tape, and so on (see Figure 3.5). The solution to this was to embed the vibrotactile feedback directly onto the skin of the performer, instead of the instrument. This was done by placing small vibration motors on the hands of the performer using a thin, light weight glove. Other work in the field has explored using vibrotactile rings (Rovan & Hayward, 2000), but it was decided that a fingerless glove would be less invasive for a pianist. By driving the motors with pulse width modulation, a large dynamic range of sensations can be felt, from a barely perceptible tingle, to an almost overbearing full vibration. The vibrotactile device will be discussed in more depth in Chapter 4.

Figure 3.5: Clockwise from top left: a prepared upright in Malmö; Yamaha DC7A Pro Disklavier at SARC, Belfast; battered upright in Edinburgh; keyless New York O at King's Place, London.

3.4.2 Perceiving Variable Extracted Features

As mentioned in Section 3.4.1 above, the hybrid piano can be constructed around diverse acoustic pianos. By developing the technology around the *musician* rather than the instrument itself, it becomes much easier to cater to every possible performance situation. By correlating the haptic feedback with the produced digital sound through a simple amplitude mapping, the performer of the hybrid piano receives immediate, private feedback about both the acoustic (through the piano itself) and the electronic sound worlds (through the haptic device). The potential for performance as perceptually guided action is fully enabled through the mutually affecting relationship between performer and instrument. Again, Cadoz in support of the enactive view, suggests that "the (ergotic) gestural interaction (which may concern the whole body)... is inseparable from a specific perception, the tactilo-proprio-kinesthetic perception

(TPK), and this perception is needed for the action just as the action is needed for this perception" (Cadoz, 2009, 217). The possibility to play, and to perceive the effect on the skin, from outside the body, now exists, felt on "specific points of contact where the hard surfaces of the instrument meet the soft flesh of the musician" (Evens, 2005, 159). Just as the various structural materials of acoustic instruments, not to mention changes in environment and temperature, will give different sensations to the performer, it is worth exploring the range of perceptual possibilities that the vibrotactile feedback paradigm offers. Firstly, alternative mediations between the digital sonic output and the haptic vibration can be introduced. For example, by feeling the *density* of the sound on the skin, or the amplitude of a single process within the electronic part, the performance can differ drastically, especially in the case of improvisation, as the sensory perception will be completely changed. Of course, multiple sensations can be experienced simultaneously, but this can quickly result in a sensory overload. Since the practice of using sensors to extract information about the gestures and movements of the performer is almost ubiquitous in the world of live electronic music, it seems worthwhile to explore different filtering or analysis methods to extract information from the digital auditory signal to send back to the performer.

3.5 Summary

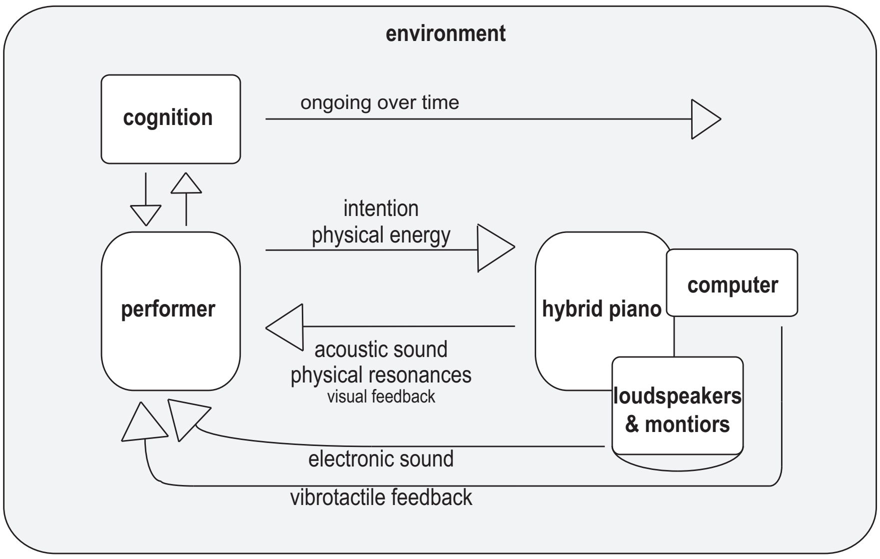


Figure 3.6: Multimodal engagement of the haptically-augmented hybrid piano, acknowledging the influence of the environment.

Within the area of digital and electronic instrument design, the focus is overwhelmingly directed towards methods for yielding input data, with minimal attention given to the feel of the instrument for the performer, and the instrument-performer relationship. In this chapter I have attempted to delineate some of the historical thought that has informed current research into the use of haptic technology within this field. By examining various enactive approaches to DMI design, we can see that common threads emerge:

- the interaction between performer and instrument is multimodal, dynamic and mutable (see Figure 3.6);
- structural coupling between sound and interface can result in energetically linked, ergotic interactions;
- the notion of action as guided by perception can be explored through haptic, vibrotactile feedback;
- it is useful to consider the notion of performance environments, acknowledging the influence of the performance space—in addition to the performer/instrument relationship—on a piece of work.

The haptic augmentation of the hybrid piano was demonstrated to have evolved out of these ideas, despite already offering what appeared to be a largely embodied mode of interaction for the performer. This feedback system allows the performer and instrument to be more closely intertwined, which in turn significantly influences the musical outcomes, not only in the live performance situation, but also within the compositional process. As a composer, I found that I was able to access my work in a perceptual manner that I could not have done otherwise, gaining insight into how the music actually *felt* throughout the process of creation. As well as providing an enhanced mode of reflection—in addition to listening back to test recordings of what I was creating—at various points during the compositional process, I was able to consider the work from the perspective of its live performance, and the challenges and requirements that would be presented.

Chapter 4

Feedback and Communication

4.1 Introduction

In the previous chapter I discussed my initial approaches to creating a hybrid instrument, specifically a digitally-augmented piano. In order to develop an immersive, intuitive instrument which offered the potential for embodied interaction, I considered the complex relationships between performer and instrument. In this chapter I build on these ideas by examining two themes: feedback and communication. The feedback that I address is not the type of sonic feedback that is created by the existence of a loop between input and output devices, but rather that of haptic sensation, in the form of *vibrotactile* feedback. I look at how employing this feedback through technology that I develop can help to enhance modes of perception—and consequently, action—for performers of electronic music in various different ways. I approach this by examining the performance requirements of both digital compositions, as well as improvisation-based works. I explore various implementations of sensory feedback through a series of case studies. These musical works involve myself both as solo performer, as well as in conjunction with other musicians who play both traditional acoustic instruments, as well as hybrid electronic systems. Importantly, this allows me to evaluate the body of practices and methodologies that I develop in different contexts. While the technologies that I am working with have arisen out of a long, personal practice, collaborating with other musicians has helped to inform my own research about issues that simply would not have arisen otherwise, such as the placing of the vibrotactile feedback on the body. The collaboration discussed in Section 4.3.6 below began in 2008, and therefore has given me a platform from which to evaluate how my progressing research has shaped my own role in this musical partnership.

4.2 Feeding Back the Composition

In Section 3.4, I described the ways in which vibrotactile feedback was used to replace some of the lost tactile connection that a performer might feel when working with a purely electronic or augmented instrument. This approach focussed on mimicking the natural vibrations experienced from the sonic resonances of acoustic instruments. Moving away from this notion of *substituting* lost vibrational feedback, I will develop a further possible confluence between human and computer, by proposing that the artificial feedback that I am embedding may be used to convey not only a physical representation of the audio, but other dimensions within the performance environment that we might wish to embody.

Some of the types of feedback that a musician may make use of during a performance could be:

1. feedback from the instrument or environment;
2. feedback about any prescribed music, for example from a score or timeline;
3. feedback signals from a conductor;
4. feedback from other performers.

Note that I am not assigning these types of feedback to a particular sensory modality. Merleau-Ponty stresses that we cannot separate the sensory organs into separate systems of perception, claiming that each sense "brings with it a structure of being which can never be exactly transposed" (Merleau-Ponty, 1962, 262). I wish to highlight that the sensory information that a performer will use will be *multimodal*; musicking in any form is a multimodal affair. For example, in the first scenario—which was addressed in Chapter 3—the performer may make use of the tangible physicality of the instrument, audible reverberation of the concert space, and so on. Analogously, Ingold refers to the "multimodal feeling-hearing of the blind" as "neither touch, echo, nor motion but a blending of all of these" (Ingold, 2000, 274). Ingold suggests that it is a consequence of the fact that through vision we can perceive the boundaries between an object and its surrounding environment that such distinctions between touching and hearing are commonly made.

In this section I will explore the second situation listed above, where instructions about *what*, *when*, and perhaps even *how* the performer is required to play are communicated through vibrotactile feedback. In this scenario, the action (the performing) is still very much perceptually guided both aurally and tangibly, and to a lesser extent visually, through engagement with the instrument. Following Ingold, I am not trying to isolate these sensory modalities, but rather find ways in which I can bring out their mutually supportive roles. Where the direct amplitude-correlated haptic feedback discussed in Section 3.4.2 affects action-perception processes on the near-instantaneous micro level, this secondary type of sensory information will influence playing on the conscious macro level of musical structure, influencing aspects of timing, phrasing, and expression.

4.2.1 Problems with Visual Feedback

In most cases, a good performer does not need to look at their instrument the whole time that they are playing, if at all. David Sudnow gives a phenomenological account of how one can acquire the skills for (specifically bebop) piano performance through an embodied approach. He sums up the importance of touch over vision, with regards to instrumental performance:

> Reaching the point where, with eyes closed, I may now sit down at the piano, gain an initial orientation with the merest touch anywhere on the field, if at all, and then reach out to bring my finger precisely into a spot two feet off to the left, where a half-inch off is a very big mistake, come back up seventeen inches and hit another one, go down twenty-three and a quarter inches and get there at a fast clip—a skill a great many competent players have—this takes a lengthy course of gradual incorporation. (Sudnow, 1978, 16)

Visual engagement would rarely have been placed above auditory and haptic feedback in order of sensory importance within a musical environment, with perhaps the exception of cues from a conductor, or between performers in a group setting—for example, where a first violin gives gestures to indicate timing. Merleau-Ponty extends this notion to apply to the listening experience itself:

> Music is not in visible space, but it besieges, undermines and displaces that space, so that soon these overdressed listeners who take on a judicial air and exchange remarks or smiles, unaware that the floor is trembling beneath their feet, are like a ship's crew buffeted about on the surface of a tempestuous sea. (Merleau-Ponty, 1962, 262)

When performing with a hybrid or augmented instrument, the problem often arises as to where to position the laptop. In the case of an augmented piano, there are really only three options:

1. placing the laptop inside (in the case of a grand piano), or on top of the piano itself;
2. positioning the laptop to the side of the piano;
3. positioning the laptop either out of the way, or with the lid half-closed, as it does not need to be seen by the performer.

The first solution is not ideal for two reasons: firstly, this may interfere with the performance of any pieces that make use of extended techniques inside the piano. Secondly, the noise of the laptop's cooling fan may be picked up by microphones that have been positioned inside the piano. Indeed, the second solution was the one that I employed in the earlier stages of my practice (see Media Example 4.1 and Media Example 4.2) but I found that it was incredibly distracting to not only *look* for visual feedback, but also to *anticipate* it. As a result, the flow of the performance felt interrupted, even though this may not have always been apparent to the audience. The following passage describes the first performance of ***kontroll*** (2010) at the Roxy Arthouse, Edinburgh, 16th May, 2010, from my perspective as the composer/performer.

I begin the piece, back to the audience, scraping the strings inside the battered upright piano that I have brought over from its home in my rehearsal space at the university. I am building up rhythmic patterns, alternating between the harsh sounding steel guitar slide scrapes and the bass string harmonics. Some of the attacks are triggering the snare drum to produce drum rolls. I know that by playing an attack of a certain level within the specific time frame that I have composed, I will have direct influence on when the electronic processing will proceed to the next stage. On one hand I feel pleased that I have designed a system to let me advance the progression of the piece intuitively in this way. On the other hand I have no idea how long I have been playing for in this way, and whether I am close to the start of this time-window. I have to glance over to peer at the laptop screen (see Media Example 4.1, particularly c. 58" and c. 2'). But it is tricky: I do not want to interrupt the forward momentum that I am creating, and it will be hard to turn my head while maintaining my outstretched position with my arms on the lowest bass strings of the piano. As I try to sneak a look at the laptop screen, I am immediately aware of how this might look to the audience, especially to those used to watching performances involving laptops: that moment when, as an audience member, you wonder whether something has gone wrong, and become distracted trying to workout what kind of information the performer is searching for. I need to reestablish myself within the flow and structure of the piece, without revealing that I am wavering... It is towards the end of the piece, and I start to feel as if I want to reach a conclusion, but I am aware that I can't finish until I reach a certain point within the timeline. While I can hear quite clearly through the monitors, it is difficult to identify exactly which stage in the piece I am at due to subtleties in DSP between two adjacent sections. I can expand or reduce the total length of the piece by drawing out the final section: I have created the piece in this way. However, I can only stop *during* the final section, as this is when a particular oscillating pattern begins on both the snare drum and the DSP. Again, I will need to glance at the screen to find out whether or not I am close to reaching this section yet; and *then* consider what I am going to play. I try to wind down the piece, yet I do not know if I have preempted the end (see Media Example 4.2, particularly c. 35"). The music will have to continue if I am too early, and I will, all too consciously, have to continue to weave between the high arpeggios and the low bass harmonics.

After several performances like the one described above, I finally decided that the third solution of removing the need for visual feedback seemed the most ideal, both in terms of logistics and performance. Certainly, for a performance involving a clarinet, for example, where the performer can maintain a relatively static stage position, a laptop could easily replace the traditional score as a visual focal point. For a pianist, however, the kinaesthetic energy required by certain performances, along with the larger amount of space that they may have to traverse during play, means that this is highly impractical. Almost common-place extended techniques—which may require reaching inside, underneath, and playing from the back of the piano—only add to the problem.

4.2.2 Case Study: *kontroll*

4.2.2.1 Motivations

As discussed in Section 3.3.3, many of my early works for the hybrid piano used a flexible, but linear timeline, along which the various sections of the piece could be triggered within certain time-windows. As these windows were only around 20 seconds in length, it was necessary to watch the laptop screen during the performance for the clock and score position, cues and time-windows, and confirmation that a trigger had been successful. This structuring mechanism was also used in the portfolio composition ***kontroll*** (2010) for prepared piano, self-playing snare drum, and live electronics. As I started to perform ***kontroll*** in various concert scenarios, the need to completely get rid of the visual feedback from the laptop became apparent: this would allow me to focus more on the actual musical expression and structure, rather than having to check for various parameters on a screen, which I found would interrupt the flow of performance. This was achieved by creating a new vibrotactile glove, discussed in Section 4.2.2.5 below. This device would be able to send haptic information to the hands of the performer. Within this feedback would be encoded all the necessary information that I, as the *hybrid pianist*, would need to successfully perform the piece. Rather than just providing sensory information about the properties of the sound being created, the extra layer of information in this *compositional* context could be thought of in the same way as a traditionally notated score: as aiding the performance of the composition.

4.2.2.2 *kontroll*, ICMC, Huddersfield, 2011

Performance of ***kontroll*** at ICMC 2011, Huddersfield, 4th August 2011. Vibrotactile feedback was used and the laptop screen was dimmed (see Media Example 4.3).

I can feel my hands shaking nervously as I take my seat in the middle of the university bar in Huddersfield. I am performing ***kontroll*** as part of the International Computer Music Conference, 2011. Programmed as part of the late night concert, beginning at around 11pm, I have been told that there is no room for my piano on the stage, so I have been positioned in the centre of the bar seating area, with the audience sat at tables all around me. I am grateful to the announcement that the conference director has made regarding keeping noise to a minimum during the concert, as the entire piece is based around machine listening, and attack-based triggering. In a noisy environment I would have no control over the piece, as clunking glasses could very well trigger a new part of the piece, and the delicate sounds of rubbing the edge of a steel guitar slide on the strings would be practically inaudible. Before I begin, I call to the sound engineer to confirm that he is receiving the microphone signal. I do a quick check over everything before starting the piece via a clock on the screen. A concerned audience member suggests “Have you got your DAC on, love?”. I ignore him and finally dim the screen on my laptop. I am ready to begin. As I start I am aware that I am *flying blind* in that I cannot see or touch anything directly on the laptop, which I have discreetly placed to one side of the piano. My confidence rests in the system that I have built and my connection to the instrument that I have spent the day assembling. I am at the centre of a precarious situation involving each member of the audience, and my trust in them to remain silent throughout, along with my hope that the remainder of cliental at the bar aren’t going to make too much noise. Despite the fragility of the situation, through the signals that I am receiving on my arm, I am able to proceed, completely absorbed in what I am doing. My sense of the passing of time is gently guided by the vibrations, but in a manner that allows me to respond to these signals as if they are a natural part of the instrument-environment that I am negotiating.

4.2.2.3 Artistic Goals

kontroll was composed on an abandoned upright piano that I had being using since 2008 as part of my master’s degree. This was a piano that was freely donated to me from an Edinburgh household, that had not been well-maintained or regularly tuned. Previous works—including my master’s piece *transient* (2009) for prepared piano and live electronics— examined the percussive properties of the instrument through a sound world consisting of the bell and gong-like preparations of the piano, an idea that was first explored in John Cage’s *Bacchanale* (1940). With ***kontroll***, I wanted to work again with the prepared piano and extended techniques, but to focus instead on bringing out the more harmonic qualities from the initial percussive sounds of the acoustic instrument. The harmonicities would be derived from pitches tracked through analysis of the sonic material. On the other hand, to compliment the drum-like patterns created by the prepared piano, I extended the performance environment to include a self-playing snare drum, which would be triggered in relation to rhythmic parts within the piece. This was simply a small loudspeaker which was placed on top of a drum skin, inside a snare drum, sending out impulses via the software (see Figure 4.1). I had first seen this technique used by saxophonist Marcus Weiss, performing Wolfgang Heiniger's *Desafinado*, in the Reid Hall, Edinburgh[1]. However, rather than providing a complementary counterpoint, weaving in and out of the solo instrumental music, the snare drum in my piece directly provided a rhythmic extension of the music, through both reactive and preprogrammed patterns, as impulses and noise were fed through the internal loudspeaker.

Figure 4.1: Loudspeaker placed face down inside snare drum to excite membrane.

4.2.2.4 Fluidity of Structure

The structure of the composition involves improvisatory blocks, each with a predefined musical theme or idea as an initial seed. These blocks are grouped within sections along a timeline, with each new section invoking a different set of presets within the Max/MSP patch. This enables or deactivates different DSP modules and pathways as specified, as well as potentially changing

[1] This concert took place on 25th November, 2009

how the control data that is derived from the analysis of the piano's acoustic signal is used[2]. The piece advances by triggering a new section, based around attack detection at a specific dynamic, often in combination with silence detection, pitch tracking, and approximation of phrase length. The piece was composed for a single performer, rather than the common situation where a live electronics performer (often the composer) sits at the mixing desk with access to a laptop running the software, ready to correct any missed cues or mis-triggering that might occur. But not only was my machine listening solution, described in Section 3.3.3, a failsafe method for advancing the piece; it also allowed me to exploit the improvisatory nature of the work.

The pieces that I have presented in this portfolio of work all make use of improvisation, to differing degrees. Although I allude to the existence of a continuum from composition to improvisation in Chapter 1, I do not believe that it is particularly useful to talk in such terms in any more than a loose metaphorical sense. There would simply be no way of measuring how one piece might be more *improvised* than another. While many scholars and musicians have attempted to define one activity in terms of the other, such references to improvisation as *instant*, or *real-time* composition, are perhaps—as Fred Frith argues—just unhelpful clichés (Bowers, 2003). As Bowers points out, we do not talk about composition as "slow improvisation" and, furthermore, comparing the practices of composition and improvisation would simply not make sense in many non-Western art music contexts. So why do I continue to refer to my works that feature largely improvised material as compositions? The answer lies in the fact that despite the improvisatory nature of the playing in these works, the structures, material, and musical ideas are all considered, and in some cases determined, well in advance of the performance. Herein lies the compositional element: the actual *composing* of the performance environment in which I will be able to adequately improvise around these prescribed scenarios within the piece. As the description in Section 4.2.1 above illustrates, while I had created a fluid, organic manner of traversing through the piece, the improvisation needed some *guidance* to fit within the loosely prescribed structure. The solution, involving performer-embedded vibrotactile feedback, would allow me to adjust my playing accordingly, and inform me about the surrounding structure involving change points, triggering, and live sampling.

4.2.2.5 Technical

The vibrotactile device that I developed was initially built using an Arduino microcontroller, and three small vibration motors, similar to the type found inside mobile phones. The motors were attached to a simple glove, worn on the left hand, and vibrations were sent to the performer

[2]See Appendix C for the performance, software, and hardware requirements of this piece.

indicating:

- a five second warning for an approaching change in score position, represented by a steady increase in vibration intensity;
- a strong, short vibration when a new section of the piece had been triggered;
- the guide tempo of a particular section.

The glove was made of a light thin elasticised material (see Figure 4.2). Two of the motors were positioned on either side of the back of the hand, and the third was positioned directly underneath, on the wrist, so as to achieve some distinction between the three locations of the vibrations. In this way, even whilst playing the piano, I could accurately perceive three discreet channels of information. The pager motors used were Samsung disk coin-type vibration motors[3]. By selecting extremely light motors (0.99 grams each and measuring 1 cm in diameter), no additional noticeable weight would be added to the hands of the pianist, and so the embodied knowledge of the performer would not be impeded by the device. The motors were connected to the Arduino's digital/pulse-width modulation pins, which would allow a smooth gradation in the intensity of vibration felt through the motors, from a negligible tingling, to a deliberate buzz. Long length wires were run from the motors to the Arduino, which was connected to a laptop using a USB cable. Information was sent to the three motors using the Maxuino[4] helper patch for Max/MSP, allowing all computation to be contained inside a single programming environment. This allowed the system to be easily integrated with the pre-existing performance patches. Although the cables were not particularly restrictive since I usually remained seated at the piano and did not have to move about the concert space, I worked with engineer Marije Baalman during a residency at STEIM in 2012 to develop the system further. We created a wireless system, which would allow up to four different devices to be controlled at the same time, each with three vibration motors. More technical details can be found in Appendix C. This development meant that performers would not be restricted by needing to be in close proximity to a laptop.

4.2.2.6 Outcomes and Observations

As I describe in section 4.2.2.2 above, the result was extremely beneficial to the execution of the performance: the ease with which I could ignore the screen and concentrate on the performance was immediately apparent. The vibration signals were non-invasive and did not

[3]Available from http://www.pagermotors.com/index_files/Products/DiskL/DiskL.htm [accessed 24th August 2013].

[4]http://www.maxuino.org/ [accessed 23rd August 2013]

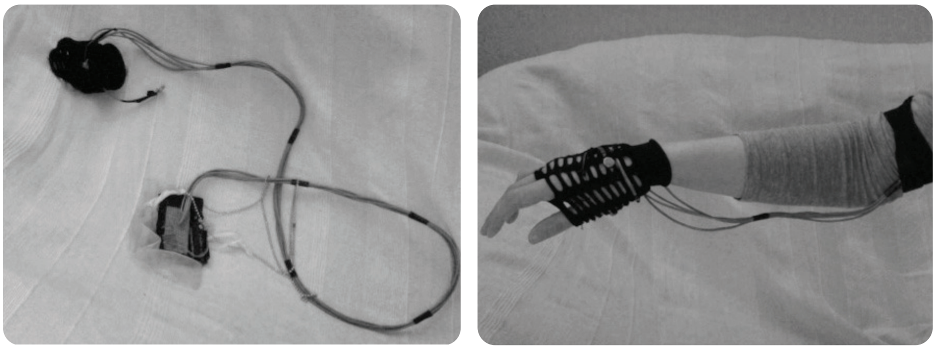


Figure 4.2: First version of vibrotactile feedback glove: motors connected to Arduino, which is worn as a necklace.

distract from the actual playing. There was a strong sense of being fully coupled to the system as a whole, as the structure of the piece was being *applied* directly to the body, offering more security in the often unpredictable world of live electronics, and allowing for a more focused performance. While the piece has been received favourably in both academic and non-academic contexts (Groth, 2011), more importantly, it has not been received as something shrouded in technological prowess, but rather as a focused and expressive piece of electro-instrumental music. In an article discussing my work in relation to the historical development of the piano, musicologist Rasmus Holmboe writes:

> At first glance, all of this seems as technical detail, involving only the musician or composer. But when you see and hear [Lauren] Hayes, however, it is clear that this also concerns us, the listeners, in the form of better and more focused performances, with greater degree of control over the interaction between technology and performer. In other words, Hayes' development of a modern instrument can help to refine very basic musical ideas in a very elegant and historic informed way. (Holmboe, 2012)

Furthermore, I had the opportunity to perform with this system when problems that were out with my control occurred during a performance, and I believe that by situating myself within the instrument-environment, through direct physical feedback, I was able to maintain composure, adjust my playing, and get through the piece. ***kontroll*** requires an engineer to balance the acoustic and electronic sounds from a position in the audience, or at the back of the hall, as this is simply something that I am unable to do while performing on stage. With adequate sound-checking time, this should not require much intervention from the engineer during the performance as levels will be balanced in advance, and they may simply need to account for minimal, but nevertheless often significant audience noise, or presence. During the performance of ***kontroll*** at the Electroacoustic Music Studies Network conference, New York, 2011, the engineer had misunderstood that the signal from the microphones to the sound card that run via the desk must remain at a fixed level for the duration of the performance. However, shortly after I started playing, my input level increased by around 6 decibels, as the engineer had turned up the microphones to compensate for the audience presence. As a result, despite being ultimately successful, the performance was difficult and a definite struggle as the system now felt much more aggressive and responsive than usual, due to increased triggering from the dynamic increase. Nevertheless, the added sense of embodiment and connectedness with my instrument meant that while I was struggling with the performance I did not have any added anxiety about keeping within time-windows, or losing track of where I was in the piece. Despite the extra difficulties presented by the situation, I still felt bound to the piece, and moreover the instrument itself. I now avoid this problem by using two DPA 4061 miniature microphones, which I send directly into my sound card for all live processing and triggering, while the sound engineer will amplify the piano separately, and balance the acoustic signal with the (usually stereo) electronic signal that I send out from my sound card.

4.2.3 Injecting Energy: *subspace*

While ***kontroll*** allowed me to investigate how various pieces of structural information could be perceived tactually throughout a piece, I also wanted to examine how this would be received by other performers. Crucially, I wanted to investigate whether the haptic feedback could affect the actual character and energy of a particular performance, merely by its very presence on the skin of the performer. This approach turns around Hunt and Wanderley's (2002) notion of injecting energy into a system, by instead directing this energy initially at the performers, rather than the instrument. In early 2013, I was selected to take part in the annual *Electronics* project[5], run by one of Scotland's most prominent ensembles, Mr McFall's Chamber. This would comprise a day residency with the chamber ensemble, in the form of a string quartet, at a studio just outside of Edinburgh. Without the added pressure of having to complete the piece of work for immediate performance, the workshop format enabled me to explore three main research themes:

- how an open structure score would work with the ensemble;
- how plausible it would be to incorporate improvisation into the ensemble piece;
- how the vibrotactile feedback might influence the performance.

This was explored through the piece ***subspace*** (2013) for string quartet and live electronics (see Appendix F for score and technical details). During the workshop session, I both processed the string instruments, and also performed analogue (Korg MS20) and digital (laptop

[5]http://www.mcfalls.co.uk/News/Electronics [accessed 24/8/13]

Figure 4.3: Rehearsing with McFall's Chamber, each performer wearing second version of vibrotactile feedback device on left arm.

and controllers) electronics. If, as Waters suggests (see Section 3.3), the boundaries between performer, instrument and environment do become increasingly muddied once we engage with computers (Waters, 2007), then by interfering with these complex, dynamic relationships by using technology, we may be able to influence the musical outcomes in ways that would be otherwise unconsidered. Just as performers excite their instruments, causing them to vibrate the air and produce sound, we may imagine the vibrotactile technology as somehow affecting the performance of the players. In the first section of the piece (see Media Example 4.4), the vibrotactile feedback was used in a similar, symbolic manner as it had been with ***kontroll***: single buzzes instructed the players to advance to a new cell, and triple buzzes indicated that they should return to the centre cell. Different guide tempos were also sent to each player. In the final section of the piece, the performers' only instruction was to play loud, harsh, accented attacks. Vibrations were sent to each performer's arm, in a type of phasing pattern, with the players starting synchronously, and gradually moving out of time (see Figure 4.4). Obviously this could have been notated, or a click track could have been provided. With the vibrations, however, I was curious to see how the direct sensation of this sort of *nudging* on the arm of the player could influence the sound that they were making, and the overall mood of that particular section of the piece.

4.2.3.1 Outcomes and Observations

We rehearsed the piece both with and without vibration, and the results were quite noticeably different, most significantly in the final section of the piece (see Media Example 4.5). The energy of the attacks was much more concentrated, there was a heightened tension, and the character of the music was brought alive. Both the anticipation of waiting for the sensation, as well as the actual intrusiveness of the buzzing had a marked effect on the sonic outcome. The performers made several observations about the vibrotactile feedback:

- the longer the vibrations were used, they more started to feel desensitised to the feedback;
- on hearing a sound from another player simultaneously with a short buzz, the auditory information was much more prominently perceived than the haptic;
- when the nudge vibrations started to occur in a temporally regular succession, they started to anticipate the buzzing, and would often accidentally play where there was actually no buzz present;
- the players noticed that while they all had a certain latency from when they received the nudge to when they made their sounds, this seemed to be the same with each player, and didn't cause any noticeable difficulties;
- vibration motors had to be repositioned higher up the arm, away from the wrist, due to interference with the already established sensory mechanisms of bowing hand.

Figure 4.4: Wireless vibrotactile devices with battery pack on upper arm.

The performers noted that the vibration was at times intrusive, using phrases such as "wired" and "on edge", and commented on the sense of tension that it evoked. One performer suggested that the actual shape (envelope) of the vibration itself was influencing her playing. Despite only working with the technology for a relatively short amount of time, the comments of the quartet, along with the marked differences between takes, suggest that as the perception of a musician is influenced by this type of embedded haptic technology, their musical responses will also be changed. Deliberately situating the performers in a physical relationship with the computer, despite perhaps not necessarily being a *comfortable* coupling, had considerable effects on the character of the music. Robert McFall summarised the performers' experience of the vibrotactile devices in a blog post, which also points to the humorous reaction that most often accompanies any discussion of the vibration, which is of course a rather intimate sensation:

> the purpose of the day was to see if these could effectively be used to deliver precise signals of timing for us to play slightly out-of-phase with each other. We eventually gave them the thumbs up, but not before they had sparked a lot of rather feeble innuendo from me (I think largely ignored by the others) and, at times, a slightly emotional reaction from some of us to having such a very intimate electronic nudge mechanism strapped to our arms. Where best to wear it? Which arm? Maybe a leg would be better? Mid-arm or wrist? (McFall, 2013)

4.3 Agency and Communication

4.3.1 Introduction

This section describes the development of a networked vibrotactile improvisation system, or *NeVIS*, for providing both communication between performers, as well as improvisation suggestions from an external agent within the software. This is explored through two case studies involving improvisation. The work surrounding the portfolio piece ***Socks and Ammo*** (2011) was undertaken in collaboration with Christos Michalakos.

4.3.2 Communication

The motivation behind much of the current laptop-centred *networked* performance seems to be the construction of enhanced musical relationships within a system comprised of performers and instruments. Often, due to the logistics of performing with laptops, where information is displayed on a sizeable screen, and the laptop is usually placed on a table along with peripherals, such as sound cards and controllers, the scope to facilitate gestural anticipation, recognisable visual cues, or meaningful physical movements is much more reduced than with performances using traditional instruments. If a performer has to negotiate several different controllers, or focus on a laptop screen, then they may be more deeply consumed with their own playing, and less aware of other performers than someone playing a traditional instrument. As Frederick Seddon observes, "when jazz musicians play together they have at their disposal verbal communication, non-verbal communication (e.g. eye contact, aural cues and body language) and musical communication" (Seddon, 2005, 47). When a percussionist hits a drum, the other performers and the audience have a clear idea of the causal agency between the action and the resultant sound. However, in the field of electronic music, and laptop performance, it becomes more difficult to rely on physical gesture to convey, for example, the onset of one's sound to an audience, or to communicate with other performers. This may be due either to the nature of the interface being used, in the case of mice, keyboards or other devices involving micro-movements of the hand; or to the complexity of the sonic outcome, where it may be unclear how a sound has been produced, or indeed who has made it. Moreover, as Emmerson notes, these instrumental gesture mappings are often of the "crudest type of simultaneity" (Emmerson, 1994, 98).

4.3.3 Networked Music Performance

Along with recent technological possibilities, the issue of communication within live electronic performance practice has driven musicians and sound artists increasingly to explore various types of networked music performance (NMP). Many ventures, such as the *SoundWIRE* project, at CCRMA, Stanford, examine methods of creating networks over the Internet as a means of extending the realm of computer music performance. In fact, one particular concert spanned a geographical distance of over 6000 miles (Cáceres, Hamilton, Iyer, Chafe & Wang, 2008). Such NMPs were emulated in the *Apart Project*, undertaken at the Sonic Arts Research Centre, Belfast, in order to "better understand conditions for performance that are created, facilitated and suggested by geographically displaced network performance environments" (Schroeder, Renaud, Rebelo & Gualda, 2007, 114). Various scenarios were constructed in which performers in dislocated situations received audio and video feeds of each other, both with and without latency, so as to help better understand the complex effects of musical cues. Whilst thoroughly technically descriptive, this project clearly alludes to the power of networks in relation to social concepts, such as community. Moreover, it concludes that rather than trying to recreate that which occurs on the stage, one should "rather take advantage of the network itself as a medium for performance" (Schroeder et al., 2007). It was this idea of using the network or system itself to guide a musical performance that was most of interest to me when constructing *NeVIS*, through an enhanced *network* of communication between players.

4.3.4 Networks as Agents

This idea of using the network as an agent for performance has been realised with the emergence of numerous laptop orchestras, such as *PLOrk*, based at Princeton University, one of the first to be established. Using local wireless networks and focusing on data transmission of parameter and timing control, rather than audio-streaming (although not precluding wired audio networks), this group has developed strategies for performing with laptops and localised speakers by applying techniques for real-time synchronisation, cueing, scheduling and non-bodily visual communication (Trueman, Cook, Smallwood & Wang, 2006). Here, the notion of connectivity within the digital realm is furthered by the introduction of a *conductor machine*. This can guide the piece by, for example, sending simple text instructions to the performers, or by directly affecting specific parameters such as tempo (Trueman et al., 2006). As our improvisation duo Můstek, Michalakos and I took part in a performance that was part of the Birmingham Network Music Festival[6]: a four-city wide performance hosted by the Concordia Laptop Orchestra (CLOrk). Ensembles were located at the University of Edinburgh, the University of California (San Diego and Irvine), and Concordia University (Montreal); the performance was streamed live on internet radio (audio only), and into the concert space in Birmingham (audio and video). The composer, Eldad Tsabary, took on the role of the conductor, sending each ensemble textual cues received as IRC chat messages. The piece was made up of numerous sections, in which each performer was instructed to improvise in a certain manner. With around thirty musicians performing over five different cities (including the live stream in the festival venue), the network both facilitated this scale of engagement, bringing together these different communities. Perhaps more interesting, was the manner in which our playing had to adjust due to the large number of audio streams and cues that we were listening out for. Media Example 4.6 shows Můstek performing Eldad Tsabary's *Small World Network* (2013) with CLOrk as part of the Network Music Festival, 23rd February, 2013. The video is shot from the point of view of the ensemble at the University of California, Irvine; we appear in the bottom middle window of the projection screen. The extract shows our solo where we have been directed to "accelerate to medium intensity".

Two further projects that draw on this idea of a virtual conductor, yet remain within the realm of improvisation, should be mentioned. Anne La Berge and Robert van Heumen's duo *Shackle* consists of a local network between two laptops, over which a series of cueing commands are sent. These directions include "aspects of restriction, either in sound material, timing, dynamics or other musical parameters" (La Berge & van Heumen, 2012), and are sometimes also presented in a somewhat abstracted form to the audience on a projection screen. Additionally, the players may skip past a particular state, if so desired. The ensuing performance presents the two musicians indeed *shackled*, but clearly toying with and struggling against the imposed restrictions. Similarly, external direction is given to a group of four performers in Eric Lyon's *Selected Noise Quartets*, where instructions are generated in real time and sent to each

[6]http://networkmusicfestival.org/programme-2/performances/clork/ [accessed 24th August 2013]

performer via a laptop screen (Lyon, 2011). Here, it is noise itself that guides and creates the structures behind the improvisations; the performers must be able to react quickly to the often highly unpredictable changes. The noise that Lyon refers to is simply the noise of randomness, created through a random number generator on the laptop. Again, a struggle may arise as the instructions are frequently unfamiliar, and may in fact be technically impossible to carry out. Yet, through all the exertion, “the voice of each musician is heard; and behind it, the voice of noise” (Lyon, 2011). Thus, the main threads that emerge from these various aforementioned scenarios include:

- strategies for structuring improvisations;
- strategies for communication between performers;
- novel interaction between performers.

4.3.5 Improvising as Conversation?

One of the most exciting yet possibly troublesome aspects of group improvisation is that, rather than a single-person led evolvement, ideas may be put forward by any agent present (Edwards, 2010). Moreover, new material may be emergent, appearing only as a result of everything that has previously been put forward by the present assemblage of players. But how might we begin to consider new methods that challenge these characteristics of improvisation, which appear to be rather ubiquitous? After performing together for a significant amount of time, performers begin to predict or expect what their well-known partners might contribute in any given situation. On the one hand, this is of course an advantage in long-term collaborations, as players become familiar with the sonic worlds of their peers; but, in some cases, it can also lead to a lack of spontaneity, or at least spark a desire for a freshness of sorts. Seddon suggests the need for “risk taking and self-challenge” (Seddon, 2005, 49) to avoid predictability. In the case of our collaboration as Můstek, introducing a third unpredictable agent into the system was certainly something that was appealing as a way to continuously challenge our performance, not only for the sake of newness, but moreover because we would be able to consider its role in the construction of the sound and musical form. Of course, inviting third party collaborators to join us always brought about new methods of musicking, both in terms of the way we used our instruments and the social engagement between the players, as well as the music created. The collaboration with John Pope, a double bassist and improviser, can be heard on the portfolio CD ***Signal Powder*** (2011).

Analogies have been drawn between improvisation and vocalising, either as monologue, emulating the flowing nature of singing (Sudnow, 1978), or as conversational dialogue (Healey, Leach & Bryan-Kinns, 2005). The dialogical comparisons suggest that a certain pattern of interaction occurs within group free improvisation, whereby one person provides a new idea and the others listen and respond to it, just as may happen with a new choice of topic in conversation. Analysis of group improvisational sessions seems to confirm this (Healey et al., 2005). However, this phenomenon suggests a certain structure and development to the music: it does not readily facilitate synchronisation points or cues between players. Just as would not typically happen in conversation, a group of performers would not usually move synchronously to a set of new ideas, unless a clear cueing command was given. This was one of the main motivations for creating the imposed framework: these cue points would be suggestions to simultaneously move to new material, synchronously. Bowers points out that while much discourse tries to maintain the connection between jazz improvisation and conversational organisation, where phenomena such as call and response or mimicry spill over into electroacoustic free improvisation, Derek Bailey's (1993) *non-idiomatic* descriptive forms such as symmetry, uniformity, equality and so on, may be more useful when talking about the structures and events of free electroacoustic improvisation (Bowers, 2003). Furthermore, as Janet Bavelas and Nicole Chovil give extensive evidence that certain "nonverbal acts are an intrinsic part of language use in face-to-face dialogue" (Bavelas & Chovil, 2006, 110), I would suggest that within musical improvisation, nonverbal communication is fundamental and worth exploiting beyond merely the gestural domain.

While traditional visual cues continue to exist between performers of electroacoustic and electro-instrumental music, there is a need to find other solutions to some of the problems that arise when working with new technologies. Dislocation of the sound source and the loudspeakers means that stage layouts become complex and often confused. Naturally, the origins of the acoustic sounds of augmented instruments are situated within the body of the instrument. Ideally, any approach to positioning loudspeakers around augmented instruments should involve a conscious effort to integrate the sound worlds. However, due to the nature of a particular space or the availability of equipment, often loudspeakers are *not* placed proximally to the acoustic component of the hybrid system, and so discerning what each player is actually doing can become a difficult task. Similarly, it can be difficult to always situate instrument stations so as to maintain an adequate line of sight between performers (see Section 3.3.2). As well as engaging with the acoustic instrument, performers will often be manipulating other devices, such as foot pedals or MIDI controllers; this may expend the amount of time available to watch out for cues from other players.

4.3.6 NeVIS

The Networked Vibrotactile Improvisation System (NeVIS) arose out of my continuing collaboration with composer and percussionist, Christos Michalakos. Since 2008, we have worked together exploring combinations of the augmented drum kit, Michalakos' percussion and live electronic performance instrument (Michalakos, 2012), and my own work with the hybrid piano, along with analogue synthesisers, drum machines, and live electronics. The individual systems that we use for improvisation are designed to enable as much freedom as possible from the constraints of looking at laptop screens or focusing on interfaces other than the original acoustic instruments, which were employed both as sound sources *and* as controllers, as discussed in Section 3.3.3. Nevertheless, especially in the early stages of playing together, we often felt consumed by the operation of our hybrid instruments. Both being practitioners of digital augmentation and hybridisation of our chosen acoustic instruments, we inevitably began to develop strategies that attempted to tackle some of the issues related to improvising with augmented acoustic instruments in a collaborative environment. We both also engage in a variety of extended techniques. This collaboration has led to three albums which have been included as part of the portfolio, demonstrating different performance environments that I have developed over the course of this research (see Section 1.6.1 for details):

- ***Signal Powder*** with John Pope (2011);
- ***Node/Antinode*** (2012);
- ***Socks and Ammo*** (2013).

The third album is a collection of versions of the piece ***Socks and Ammo***, performed in three different concerts, through which we explored NeVIS.

4.3.6.1 Structure by Suggested Cues

A cue-based framework, the core of which is timed event-points, drives the system. Before a performance, we would decide on the number of sections that the piece should consist of, and the duration of each section. This information would then be entered into the Max/MSP patch[7]; alternatively, there is an option to allocate an arbitrary number of sections, or to have these sections assigned random durations of thirty seconds minimum. Enforcing a minimum

[7] See `/portfolio/SocksAndAmmo/code/` on the accompanying DVD for the Max/MSP patch used for NeVIS's vibrotactile feedback and cueing management.

Figure 4.5: Můstek performing *Socks and Ammo* at Sonorities Festival, SARC, Belfast, 9th April, 2011.

section length was an aesthetic choice, used to allow for a moderate amount of time for propagation of musical ideas. The total duration of the piece is also displayed within the graphical user interface, mainly as a guide for concert situations where a predetermined piece length is required. The section changes are simply predetermined cues, and the timeline can be paused, expanding a certain section if desired.

One of two laptops acts as a conductor, sending the timing cues and other information, which will be outlined below in Section 4.3.6.2, as OSC messages over a local network connection to the second laptop. These cues are mere indicators to suggest when musical cuts and changes may occur during the improvisation. These changes can be textural or rhythmical, and either in the acoustic or electronic sound worlds. Although the specific moment when these events occur within timeline is predetermined by the cue list—unless, of course, one of the performers freezes the state of play—it is left up to the players to decide whether to acknowledge and respond to these suggested prompts. To summarise: *how* changes are made and *what* is changed in the musical progression is entirely up to the performers. We will merely receive a signal telling us *to* change. This cue list is perceived cutaneously, as vibrotactile feedback, through the surface of the skin of the performers.

The only other quasi-predetermined parameter is tempo. This is sent in the form of a pulse, and is included not so as to enforce strict time keeping, but rather to serve as a foundation around which possible interlocking between parts can be created. The pulse can change between different sections. Of course, this phenomenon can occur naturally during play, but again this is an additional suggestion to be integrated, or not, as desired by the individuals present. The performers must predetermine the tempos of each section within the patch (no pulse given, if this parameter is left undefined), but they do have the option to stop receiving the pulse if it becomes either too distracting, or unfitting to the current state of play. Of course, a situation may arise where one performer is playing along with the pulse, and the other may have turned it off; this is just one scenario where the *voice* of the system itself may become noticeable. Another advantage of the suggested pulse is that we often slipped into a few standard tempi during previous improvisations, and so the conducting provided a gentle prod towards fresh ideas. Moreover, transitioning synchronously to a new tempo is virtually impossible without some form of direction, and conduction gestures were not something that either of us were comfortable with.

4.3.6.2 Communication Between Performers

During performances, we found that we would often drift into a state of semi-isolation, focusing on, gauging and reacting to the specifics of the individual augmented instruments. Thus it was often difficult to attract the attention of the other player for visual cues. In order to remedy this, a *nudge* function was build into the system, which served as a tool to enable visual communication. This is initiated by pressing a button on a MIDI controller, sending a burst of three short pulses to the arm of the other musician, over a duration of 1800 milliseconds. This would simply alert us to make eye contact; the meaning or intent of the actual visual cue given after contact was made would depend, on the ensuing gestures, glances or signals. As an artistic choice, we have always performed in close proximity to each other. However, this function could certainly be used across greater distances and locations providing that a low-latency network could be established. Perhaps this could be thought of as an extended notion of Schafer's "touching at a distance" (Schafer, 1977, 11). Martin Parker (2006) describes a networked performance across three different cities where not only audio, but also control data was exchanged, with a latency low enough to enable real-time performance. This is an example of what Gil Weinberg terms as "the Bridge approach" (Weinberg, 2005, 27), whereby performers in distant locations attempt to play as if they were spatially together. Certainly NeVIS could be tested in more extreme situations, but our aims were to investigate the effects of the system on the structural outcome of the music, and to enhance our already established communication practices.

4.3.6.3 Choice of Modalities

In duplicating the vibrotactile device for this duo performance, we found that using a glove was not suitable for a percussionist: when positioning the motors on the hand, perceivable changes in vibration were ambiguous due to the natural feedback felt from hitting the drums. Instead, motors were placed on an armband worn on the forearm or upper arm. The advantages concerning issues of privacy, feedback and creating intimacy with the instrument were the main reasons that I decided to use vibrotactile feedback as the method for communicating the signals and cues, rather than visually or through a click track, for reasons already mentioned. Within electro-instrumental music, in the absence of a conductor, the use of click-tracks for performers is sometimes deployed, whereby a metronome pulse is heard through headphones. Karlheinz Stockhausen's *Helikopter-Streichquartett* (1999) is an extreme, although perhaps apt example: four performers play from inside four helicopters, spatially distanced from each other, and directed only through click-tracks on headphones. We felt, however, that the use of headphones reduces the ability to listen clearly to the overall sonic results: indeed simply discerning distinct electronic parts in a group setting can be difficult enough, and one arguably has to listen more to other performers in an improvisational setting. Short continuous pulses (lasting 75 milliseconds) were transmitted to the hands and arms of the performers, allowing the tempo of each section to be adequately perceived, and a signal of three short bursts of vibration was transmitted as a nudge. Similarly, the section cues were indicated by a vibrotactile sensation that was persuasive enough to trigger an impulsive reaction from performers, but that would also give just enough time to prepare any electronic changes that might be necessary. A ten-second approach signal was used, which increased in intensity over the duration. This length was chosen as it gave adequate time for any musical changes to be made, yet preserved enough of the spontaneity that we wished to arise from the appearance of the synchronisation points.

4.3.7 Results

The work that resulted from the initial development of NeVIS, *Socks and Ammo*, was performed at various festivals and conferences, including Sound Thought (Glasgow), Sonorities Festival of Contemporary Music (Belfast), Soundings Festival of Sonic Art (Edinburgh), Sound Festival (Aberdeen) and NIME (Oslo). With the exception of Soundings, where the guest double-bass player participated in the improvisation in addition to NeVIS, the system was used in the same format. Not only its usefulness, but also the musical character of the project became apparent the more that it was adopted in performances. The nudge function was immediately utilised as a simple communication tool, and enhanced our on-stage communication, as well as forcing us to discuss potential ambiguity in our visual cues and glances. Moreover, as this is a private method of interaction, it arguably helped to give the audience the illusion of a more integrated and polished performance, as there were less visually obvious coordinating gestures. We also

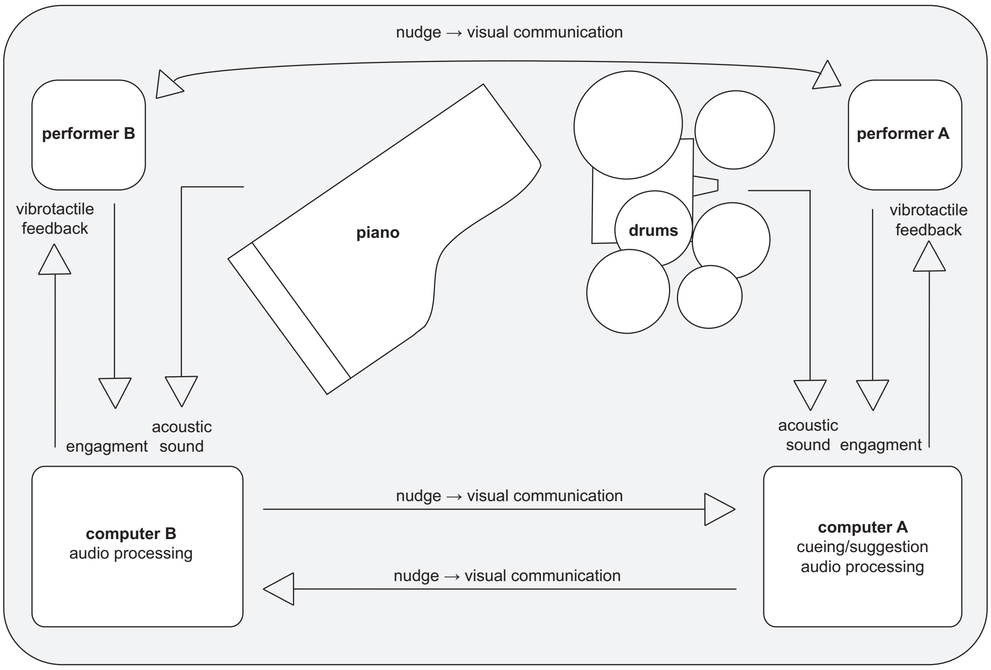


Figure 4.6: Signal flow of NeVIS.

found that it helped to quickly rouse us from the states of absorbed isolation that sometimes occurred, and re-establish any required visual contact. Indeed, after the concert at Sound Festival in Aberdeen, one reviewer described the strong sense of integration and coherence between both the acoustic and electronic sound worlds, as well as the advanced communication between players that was evident in the music:

> What was truly impressive in this performance was firstly the way in which every element of the performance whether acoustic or electronic was so completely integrated together to form a true unity of sound. Secondly, only from the programme did we realise that much of this music was improvised but like the best of jazz musicians who seem in a positively supernatural way to be able to read one another's minds, this duo thought and performed as one entity. (Cooper, 2011)

The section changes raised several points worthy of discussion. The knowledge that there was an imminent change at first very often resulted in a state of self-awareness and anticipation, rather than an engaged performance or progression with musical ideas. This was particularly noted when testing the system with other performers at third Laboratory for Laptop and Electronic Audio Performance Practice[8] (LLEAPP), 2011, at the University of East Anglia. LLEAPP is a yearly roving researcher-led project, which I co-founded at the University of Edinburgh in 2009. The venture aims to highlight and tackle many of the issues related to the live performance of electronic music through self-organising collaborative workshops. Here, participants initially found the system restrictive and counterintuitive to their former improvisation prac-

[8]http://www.lleapp.org/ [accessed 23rd August 2013]

tice, but after some time they began to comment on the potential usefulness of it. Indeed, after performing with the system many times over a period of several weeks, the anticipatory nature of our own responses receded. At this point, NeVIS became more clearly useful as a tool to shape the improvisations. This can be attributed to the fact that having performed extensively with the vibrotactile feedback, it became an integral part of the performance; and after a certain degree of familiarity was achieved, the musical output became the main focus once again. The perceived instructions and suggestions would be taken into account *only* if they served the already established musical material and direction, and whilst they were very often acknowledged, they could be and *were* ignored too.

Of course, due to the autonomy of the performers within the framework, all cues could potentially be ignored and therefore be rendered meaningless. However, this never happened in performances as we wished to understand how the voice of the system might be heard amidst our own playing. Certainly, it was mentioned in the audience feedback at NIME (2011) that the system could clearly be perceived to be influencing the direction of musical progression in ways that would not otherwise have arisen naturally: this was illustrated mainly by the synchronised and often abrupt changes in direction (see Media Example 4.7, particularly at c. 25" and c. 2'30"). By introducing an element of unpredictability and surprise, the performances, conversely, appeared to take on a stronger sense of direction. Moreover, a comparison of the three portfolio albums, which were all recorded in collaboration with Christos Michalakos, illustrates the diversity of our collaborative output; yet the character of NeVIS can clearly be heard on listening to the three different live performances of ***Socks and Ammo*** included on the album. The frenetic character of this music is contrasted with the more durational approach taken on ***Node/Antinode***, and the jazz-tingled lyrical material of ***Signal Powder***.

4.3.8 Case Study: *multifingeredbodyparts*

The final piece that I wish to mention in this chapter is a short, solo laptop performance, using a generic game controller, entitled ***multifingeredbodyparts*** (2010). The piece is an improvisation in which the vibrotactile feedback is used to direct the performer by way of tempo and rhythmic information. While many game or rumble pads do offer haptic force-feedback, this was not present in the one that was used. As Bowers suggests, by using technology, we can inject abstract or *imminent* forms into live and even improvised electroacoustic music by "delegating that activity to a machine for real-time calculation" (Bowers, 2003, 50). He gives the example of using Fibonacci or prime numbers as part of an algorithmic process that is carried out by the computer during play, thus imbuing the music with a certain syntax, while the performer is free to improvise without having to mentally calculate in such factors live. The study ***multifingeredbodyparts*** makes use of a simple algorithmic process in this way, but not to calculate background DSP processes, but rather to give rhythmic suggestions to the performer. This echoes the idea of a structuring element or voice, that was present in ***Socks and Ammo***. I sought to achieve a high level of expression using only micro-movements of the hands and fingers. Thumbs pressed on the two joysticks could freeze and loop the electronic sounds, but the slightest movement could throw this off.

The device alone without haptics worked fairly well as a solo improvisational tool, triggering samples within Max/MSP which were sliced into segments of several milliseconds, and then processed in various ways. However, to create a more interesting and varied engagement of the very gestural and rhythmic character of the improvisations that I was producing, short pulses of 300 milliseconds were sent to the performer indicating that a short sound should be played that should attempt to match the duration of the vibration. The interval between these bursts was determined by an algorithm that would select values from a list, these lists themselves being altered over time (see Appendix B for technical details). This evoked the illusion of having different paces, along with unpredictable intervals between musical gestures. Similarly, longer vibrotactile signals, which would increase with intensity, were sent to indicate that a section of continuous sound should be repeated for the duration of the physical sensation. A variable timeline was established along which either of these two situations could occur, but this would not be known to the performer prior to the start of the piece. As with ***Socks and Ammo***, the vibrational signals were used to feed me extra sensory information with which to engage, almost as if there were a silent partner joining in with the improvisation, yet known only to me.

4.4 Summary

This chapter has examined various perspectives on using haptic vibrotactile feedback directly placed on the skin of the performer by exploring some of the requirements of works involving different degrees of improvisation. On the one hand, this work has been quite pragmatic, in that I have found solutions to many of the issues surrounding visual feedback, cues, triggering, tempo, and communication within live electronic performance practice. I have found a reliable approach to removing the need to watch the laptop screen for information, which can be particularly problematic when performing with augmented instruments. Furthermore, the vibrotactile feedback allows for a more immersive performance, in that the performer may feel more secure with the added private feedback, leading to more focus during performance. Perhaps more interesting are the subtle, yet important changes that these techniques have brought not only to my performance practice—by increasing my sense of intimacy and embodiment with my instrument—but also through the development of musical character. Used almost invasively, affecting the physiology of the players, the added sensory feedback has caused performers to respond with a more energetic musicality. Used as a signalling tool within improvisation, the feedback has allowed the voice of algorithmic processes to be manifested in the musical structures and outcomes. While there has been much research carried out with regards to modelling haptic feedback around acoustic instrument paradigms, as discussed in Chapter 2, it is clear that there are potential creative uses for this technology that go beyond improving the feel of an instrument.

Chapter 5

Effort and Struggle: Resisting Paths of Least Resistance

5.1 Introduction

> A violin, played at professional standard, can be likened more to a localised instrument of torture (with its complimentary disciplinary rewards), than a harmonious continuation with human agency. Why is there no impetus to develop a violin that blends ergonomically with the player? (Rebelo & Coyne, 2003, 288)

We have seen that when playing musical instruments, the haptic perception involving both tactile sensors in our skin (especially in the fingertips, hands, or lips), as well as our kinaesthetic perception of the position and movement of our muscles and joints, is pivotal within the complex relationships between performer, instrument, and the resultant sounds produced. It is precisely these ongoing negotiations and reassessments through multimodal feedback loops that lead to the diversity of achievable musical expression. In Chapter 4, I explored ways to enhance the audio-tactile link through added vibrotactile feedback, which has been largely missing in systems of digital music, where these instruments can no longer be said to describe only those resonating bodies of physical constructs. The sound sources of DMIs cannot usually be linked to real-world vibrating objects. Even through the evolution from analogue electronics to digital technology, numerical information portrayed on LCD displays has replaced physically manipulable knobs and dials. Emmerson writes that as performers we "sense this loss of 'tactile location' " (Emmerson, 2011, 370).

In this chapter I will explore the other type of audio-haptic relationship that is often neglected in DMI design. For not only do we sense this loss of feedback in the form of acoustic vibration, but we may have lost some of the fundamental qualities of instruments: their *resistance*. For example, MIDI controllers that are often modelled on the studio paradigm, consisting of buttons and faders, tend not to offer the types of interaction that make use of physical forces such as pressure, friction, collision, and so on. As discussed in Section 2.3.2, even instrument-based controllers, such as MIDI keyboards, not only fail to communicate the whole picture in terms of the gestural information of the performer, but do not go far enough in allowing the vitally *unharmonious* types of engagement to manifest between performer and instrument, as described in the quotation above by Rebelo and Richard Coyne.

5.2 Seams and Seamlessness

Rebelo and Coyne argue that while there are dominating trends within HCI to provide smooth and seamless ergonomic blending between the user and the computer, the apparatuses used within the worlds of art and music in particular, remain *necessarily* fractured (Rebelo & Coyne, 2003). A painter constantly works *with* the roughness of the canvas, the friction of different brush textures, and the fluidities of various paint blends. The surface of the painting, where the *painting* takes place, is continuously negotiated by the artist with brushes, rags, fingers, and so on. To perform piano glissandi, the pianist must encounter and overcome the meeting of the finger with every single note. It is a learned skill, which if mastered, can produce rapid yet delicate rippling sonorities. Could running a finger along the visual representation of a piano keyboard on a tablet computer, activating a series of synthesised or sampled piano sounds ever produce something as fragile and expressive?

In a related paper, Coyne, Rebelo and Parker suggest various strategies for challenging these prevailing types of smooth HCI, including various methodologies for practicing digital media artists (Coyne, Rebelo & Parker, 2004). It is within digital computing, they suggest, that the smooth and the seam, their differences, and the transition between them can be demonstrated and amplified, and that we might try to "render the operations of digital processing conspicuous, rather than trying to meld it away" (Coyne et al., 2004, 440). Here they are advocating that we work with and around the seams and discontinuities of digital interaction. Twenty years ago Mark Weiser advocated the—often misappropriated—notion of the invisibility of technology and ubiquitous computing (Weiser, 1993; Chalmers, MacColl & Bell, 2003). He suggested that computers should become invisible, embedded in networks of sensors and circuits in everyday objects, from light switches to name badges, "away from attention on the machine and back on the person and his or her life in the world of work, play, and home" (Weiser, 1993, 77). Matthew Chalmers, Ian MacColl and Marek Bell (2003) clarify Weiser's position, advocating that, indeed, the seams within systems can be used positively, as a resource that can be taken advantage of, rather than trying to hide away. In pointing out that musical instruments do not function through the abstracted control of symbols and icons, Aden Evens warns that certainly "A well-designed symbolic interface will disappear, cease to get in the way, but this ease is purchased at the price of creativity" (Evens, 2005, 168). An electric guitarist might play with the point where the sound starts to feedback: the feedback is not transparent to the audience, but accepted as part of the expression of the performance, offering the player a tipping point between tone and uncontrollable noise.

5.2.1 Work, Effort and Restraint

If we consider the physical threshold between the musician and instrument to be the point of contact between flesh and the surface it touches, here we encounter a friction, or resistance: the instrument "pushes back" (Evens, 2005, 160). The tight violin string, the taught drum skin, and the weighted piano key all serve to resist the musician, and transfer energy back into the body of the performer, the point made by Simon Waters, previously discussed in Section 3.2.1. The reed of the clarinet channels breath, and vibrates the air to produce sound. Performers will require different reed resistances to suit their own embouchure, the mouthpiece, and the particular clarinet that they are using. But as the embouchure develops, the performer may derive more musical sensitivity from a harder, more resistant reed. Evens suggests that continued development of technique does not mean that the musician will eventually triumph over the resistance of the instrument, but rather that by learning the various dynamics of the instrument itself, by embodying them, the musician will more readily engage with the detailed nuances and subtleties of the instrument.

But by making musical interfaces easy to play, the sought-after seamlessness in much HCI seems to negate the very resistances that make musical instruments expressive. Bennett Hogg and Sally Jane Norman suggest that it was the "Techno-euphoric ideals of effortless musicking that accompanied much early hardware and software development [that] led to monotonous performances with instruments requiring minimal exertion and manifesting little scope for individualised expression" (Hogg & Norman, 2013, 116-7). But of course the resistances that a musician must deal with may be manifest in both in the physicality of the instrument itself, but also in its complex and unpredictable behaviours. For example, Bowers implements discontinuous, non-linear, and dynamic mappings within his performance systems (Waters, 2007) which demand continual on-the-spot assessment and a high level of agility from the performer. Especially within the realm of improvised music, this provides something for the musician to struggle against as they try to deal with continuously finding themselves in unchartered territory. This was one of the aims of the suggested cues of NeVIS, described in Section 4.3.6, which could confront the performers with a change point every thirty seconds. By designing these instabilities into the software itself, or exploiting thresholds where they already may exist, we can avoid the stiffness of deterministic processes, where the computer is 'unable to surprise its user' (Evens, 2005, 167). The enactive approach taken by Armstrong, discussed earlier in Section 3.2.2, makes use of self-organising mapping systems, which respond to human action, and the physical forces engendered within the instrument's hardware. Armstrong notes that it is "The 'push-and-pull' of dynamical forces that is key to the instrument's resistance" (Armstrong, 2006, 124). Armstrong's work clearly demonstrates this duality of effort: it makes scope for a physical struggle, in addition to the dynamic and unpredictable behaviours of the software.

5.2.1.1 Resistance in Figurine-Operated String

My own work follows a similar theme. In ***Figurine-Operated String***, which I discussed in relation to the hybrid piano in Section 3.3.6, the pianist (the figurine) plays both with the strings of the piano, as well as struggling against the wires connected to the hands, which resist the pianist's movements (see Figure 5.2.1.1).

Figure 5.1: Playing piano strings with resistance provided by red wires attached to gloves.

The other wires involved in the piece are the patch chords of the Buchla 200 on which the electronic part was conceived, at the Elektronmusikstudion, in Stockholm, in late 2011. The piece is inspired by Matthew Barney's early *Drawing Restraint* (1987-) series, in which the artist attempts to create drawings around a studio, whilst physically restrained by self-imposed mechanical barriers. Barney's works draw upon the idea that an athlete must use resistance in order to strengthen muscles, owing to the prominence of athletics in Barney's early life (Latimer, 2010). The series also suggests the potential for creativity through restraint and limitation. In ***Figurine-Operated String***, counter weight is added to the hands of the pianist by way of retracting plastic strings that are attached to a glove worn on each hand, and anchored to the ground.

While this is not a drastically constraining force, it is just noticeable enough to add an extra layer of physical resistance, this encumbrance actually benefitting the musician. The slightest change in height of the wrist can direct the electronics to move between silence and a frozen, spectral-gated, phase-vocoded stasis—quiet, yet penetrating (see Media Example 3.2, c. 2'). I found that being able to feel my way around this sonic territory with the opposing force constantly pulling at my wrists, helped to allow me to focus my movements and hone in the particular articulations that I desired. But the idea of restraint, not only in physical terms, is an important one in the field of live electroacoustic music in general, where the potential endless possibilities of the computer can actually cripple creativity, or moreover, yield the types of monotonous performances that Hogg refers to above. Restraint, or limitation, can come in many forms: as the restraint of the body of performer (as in ***Figurine-Operated String***); as limitations within the DSP choices; or by restricting the potential for interaction through interfaces such as Bowers and Phil Archers' *infra-instruments* (2005).

Figure 5.2: Objects for extended techniques: paint roller, hair brush, small contact microphone, shot glasses.

While the remainder of this chapter focuses around performance environments that consist of purely electronic or digital instruments, it is important to note that the idea of cultivating material in this way, through the resistances discovered, plays through much of my creative practice. As Ingold (2010) suggests, it is when we follow the nuances of the particular materials that we employ that works of art, structures, and other worldly things take form. In ***Figurine-Operated String***, I use an array of objects inside the piano, including a paint roller, shot glasses, a hair brush, and so on (see Figure 5.2). Each of these materials offers a different type of engagement with the piano, and different sonic results. Through regular exploration of these objects I start to discover ways to elicit new sounds and music from them. For example, the smoothness of the shot glasses quickly became used to slide along the strings inside the piano. It was only after using them for several months that I discovered that the circular contact point on the strings would allow for bitonal glissandi when used with pressure. As Ingold suggests, "To improvise is to follow the ways of the world, as they open up, rather than to recover a chain of connections, from an end-point to a starting-point, on a route already travelled" (Ingold, 2010, 97).

5.2.2 Sound Sculpting

Emmerson recently suggested that the idea of sculpting sound was now "a metaphor that could be made 'real' through suitable haptic interfaces and three dimensional representation" (Emmerson, 2011, 371). In his discussion of the musical realisation of what a performer or composer develops within their imagination, he suggests that as we have moved to digital technology, the location of the sounds that we create has been lost, both in terms of their sonic origin, as well as the position of knobs or faders (in terms of analogue sound). By bringing back this sense of tactility, directly to the hands, Emmerson is suggesting that we are now able to both manipulate sounds themselves, as well as place them within (a) space. This idea of sculpting sound has resonated throughout my work, not only as a possible metaphor for the real-time manipulation of sonic material through "imagination as tactile activity" (Emmerson, 2011, 371), but also as a compositional method. Rather than a linear or algorithmic approach where musical ideas are explicated and iterated, I have instead tended to assemble *ad hoc* instruments, often recycling parts of code from previous works, and creating signal paths between various components of both hardware and software to create an initial substance. From this material—which is an exposition of the unformed idea, and may utilise a particular set of sonic characteristics, acoustic instruments, or hardware—I start to chisel away to discover interesting resistances within the system. In finding these limits and thresholds through experimentation and play, I continue to sculpt the piece of music out of these bounds.

At the end of Chapter 3, I touched on the notion of being able to *feel* a compositional process, revealed through the vibrotactile feedback that I was employing. But this is sensation in the passive sense, in that I am able to perceive the result of some process or action that I have performed. The idea of sound sculpting suggests an active process where we might deliberately shape sonic material through tangible interactions. The discussion of my own musical developments below in Section 5.3 will offer a modest step towards a realisation of this idea, where digital audio can indeed be moulded and articulated through a three-dimensional multimodal process. As a performer, not only do I want to be able to manipulate the material that I create, but I want to be able to feel this sense of the malleability of sound through my audio-tactile interactions, and to be able to sense that I am approaching the thresholds of my electronic processes both with my hands, as well as my ears.

In Chapter 1, I described the awkwardness and detachment from the sound that I was producing, which I felt when first performing electronic music using only the standard interface of the laptop itself: the keyboard and trackpad. While a large part of my practice has been based around the various incarnations of the hybrid piano, which I have discussed in detail in the previous two chapters, I have also performed extensively using a variety of hybrid (analogue and digital) electronic systems. These are assemblages of various components, including analogue synthesisers, hardware drum machines, various MIDI and game controllers, foot pedals, and bespoke software built using Max/MSP. These combinations are often thrown together to fit a particular concert space, as well as in consideration of any collaborators involved.

I often interact with all elements of the instrument through a single controller, the game controller mentioned in Section 4.3.8. This allows me to simultaneously *touch* and engage with different parts of the instrument, bringing a sense of immediacy into my hands. For example, in one configuration, the game controller may trigger very short segments of sounds, which in turn are analysed by the software, sending both MIDI information out via the sound card to trigger drum machine synthesis, as well as sending multiple control voltages out to the analogue synth; these two external devices are at the same time sent back into the laptop, and sampled and processed in Max/MSP, where several parameters are affected by my interaction with the game controller (see Figure 5.3). In this way I am able to access several parts of my performance system at once, bypassing some of the given control interfaces that are hard wired, such as the knobs of my Korg MS20 analogue synthesiser, or the buttons of the Elektron MachineDrum. A demonstrative example of this type of performance ecology was in a collaborative concert with John Bowers himself, at the University of Edinburgh in 2012 (see Media Example 5.1) where we both employed hybrid analogue/digital systems comprising various component parts.

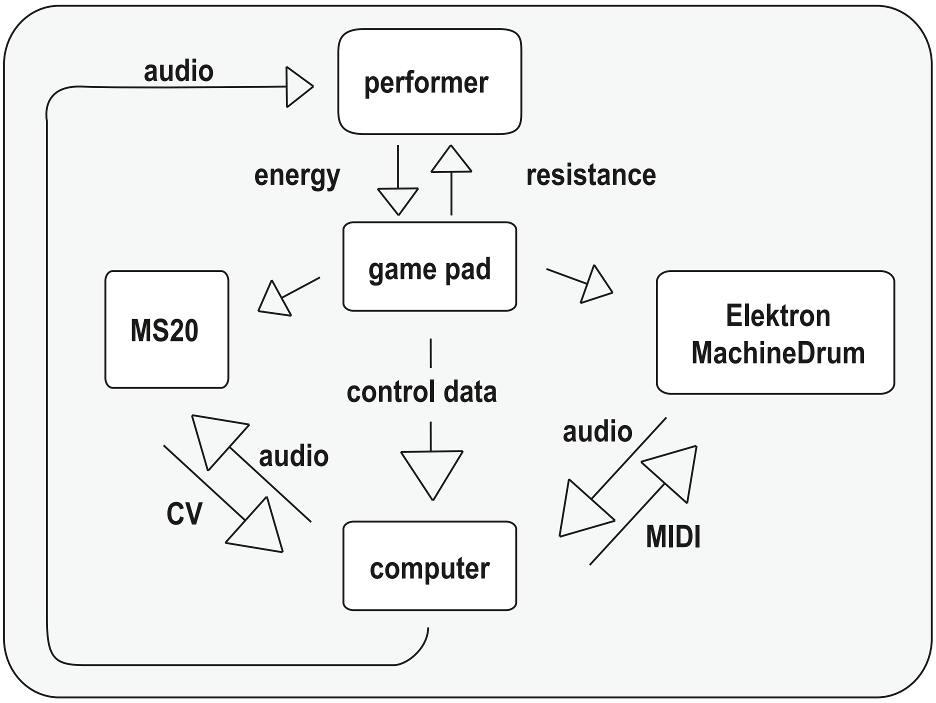


Figure 5.3: Network of signal paths within performance environment.

But while my approach involves initial *one-to-many* mapping choices, the overall result is a network of interdependent processes which feed into each other. Parker points out that due to their real-world origins in aviation control, "joysticks are easy to 'play'... Therefore, grafting the joystick's physical extremes to the limits of software parameters can result in an unrewarding musical experience." (Parker, 2007, 1). In response to this, Parker has constructed performance systems based around using the joystick to navigate through sonic territories. In contrast, the resistances in my performance environments often lie within the extreme potential for activity through interconnections within the audio signal path, which must be tamed by the performer, often through holding a static position for extended periods of time. The game controller, for example, *is* so easy to move, that the musicality comes from resisting this by holding both thumbs fixed on the joysticks, which requires a great deal of pressure from the hands, and creates a tension in the body: a movement of even one millimetre can drastically alter the sound. This can be seen in a performance by Můstek, at the Centre for Contemporary Arts, Glasgow, 21st November, 2012 (see in particular the start of Media Example 5.2).

5.3 Articulation and Expression through Haptic Interfaces

This section describes the implementation of two different types of haptic technology, which attempt to offer possible sites of resistance between performer and instrument. By introducing physical forces such as viscosity and elasticity we may increase the potential for articulation and expression within live electronic performance as gestures and movements become guided perceptually not just by audio and kinaesthetic sensory feedback, but also by extra haptic information. I explore the richness that the seams and boundaries of a performance system can offer through two works for small ensemble and live electronics, ***Running Backwards, Uphill*** and ***Sungazing***.

5.3.1 Background

The hybrid electronic system that I describe in Section 5.2.2 above offered physical resistance in that I would have to maintain pressure and hold my position for extended periods of time, which would often result in painful thumbs by the end of a long performance. It also offered resistance through a sort of *imagined agency* (Ferguson, 2013) that I projected onto the network of interactions: at points the system would behave aggressively, spewing out large amounts of MIDI data, which would repeatedly trigger the drum machine; at other times, I would move my hands frantically and almost nothing would sound. However, I also wanted to explore ways in which I could feel the boundary points within my electronics, just as I was able to negotiate some of these within the works for the hybrid piano, where the already rich dynamics of an acoustic instrument were available to me. As such, I started to incorporate an explicitly haptic game controller into my hybrid electronics system. By aligning physically felt boundaries—created in the programmed forces of the haptic controller—with the boundaries of the transformations within the DSP, I wanted to explore whether I would be able to elicit a stronger sense of articulation. Would it be possible to achieve something that offered more meaningful engagement than the types of seamful interfaces that Hogg and Norman criticise: "In the current creative industries context in particular, seamful, individualisable affordances of digital interfaces are often tokenistically shoe-horned features of what are in fact highly standardised and essentially market driven products" (Hogg & Norman, 2013, 117).

I decided to work with a haptic controller, the Novint Falcon. This is an affordable[1] commercial 3D game controller, which provides up to 9 newtons of resistant force-feedback to the user (Berdahl, Niemeyer & O. Smith III, 2009). While this is of a much lower bandwidth than, for example, Claude Cadoz's *Modular Feedback Keyboard* (Cadoz et al., 1990), one of the first haptic musical instruments, or "*gestural force-feedback transducers*", discussed earlier in Section 2.4.1, it is nonetheless receiving attention as a low-cost solution to designing haptic DMIs. Indeed CCRMA, at Stanford University, run a *Haptics Lab*[2], which offers an audio interaction workshop

[1] Costing around $250 at time of writing, January 2013.
[2] https://ccrma.stanford.edu/wiki/250a_Haptics_Lab [accessed 21st August 2013]

specifically based around the Falcon.

5.3.2 Technical Possibilities

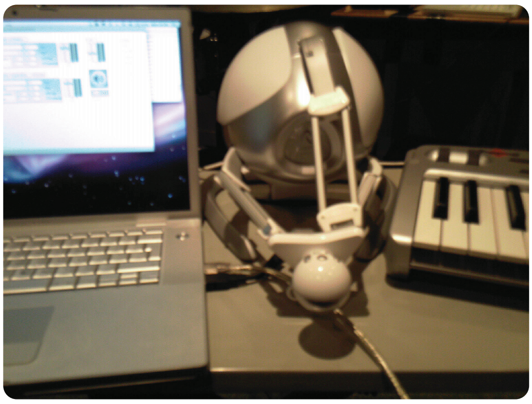


Figure 5.4: Falcon with ball grip.

Open source software is available from Non-polynomial Labs[3], enabling the Falcon to operate within musical programming environments such as Max/MSP and Pure Data[4]. Edgar Berdahl, at CCRMA, developed *HSP*, "a simple platform for implementing haptic musical instruments" (Berdahl et al., 2009, 262), aimed at making the incorporation of haptics into DMIs both inexpensive (by way of this affordable game controller), and easy to programme. The toolkit offers a series of basic force-feedback profiles for the Falcon, including virtual walls and springs. Used and adapted in combination with various DSP techniques, new instrumental prototypes quickly start to emerge. The Falcon ball grip can be moved within a 3D space of around 11 cubic centimetres. However, depending on design choices, a virtual space of *infinite* size could be traversed. Furthermore, the haptic technology can provide the experience of palpable (but virtual) objects, surfaces, and indeed textures. Thus possibilities for designing interactions based on a whole host of different gestures arise, where we can imagine not only *bumping* into different virtual surfaces, but also being able to move through different *atmospheres*, at different speeds, depending on the viscosity employed[5]. Furthermore, interactions that defy real-world physical relationships can be created through the HSP's interface. For example, a simple wall model could *disintegrate* after being hit with a particular velocity, and *reform* once the user has passed through to the other side. Of course, meaningful relationships between such interactions and the sonic outcomes must be considered.

5.3.3 Negotiating Surfaces and Boundaries

Emmerson's (2011) notion of sound sculpting suggests not only 3D movements of the interface apparatus, but also the ability to mould and manipulate multiple aspects of the sound

[3]http://sourceforge.net/projects/libnifalcon/ [accessed 21st August 2013]

[4]As well as providing cross-platform functionality to include OS X, which is, at time of writing, unsupported by Novint.

[5]Viscous damping is implemented in the HSP toolkit through a series of biquad filters.

simultaneously. The very nature of the Falcon affords this type of interaction, given that even a simple single movement will produce a vector of at least three data streams. On the most primitive level, x, y and z position data can be extracted, before even considering more complex variables, such as deriving the acceleration of a particular gesture. The potential for complex multi-mapping is rich. As mentioned in Section 2.3.2, the expressive qualities of acoustic instruments can, in part, be attributed to the dynamic structural couplings that are inherent. Nevertheless, as I demonstrated in Section 5.2.2 above, building just a few simple relationships into a performance ecology can dramatically increase the potential for unpredictability, imagined agency, and an arguably more complex, and therefore more interesting musical language. Thus, simply by nature of its design, the Falcon already goes some way in offering the qualities necessary to make a convincing instrument.

The addition of the force-feedback would allow me to create haptic physical models of both real and imaginary scenarios, and more importantly, align the boundaries that I would encounter physically with the bounds and extremities within the DSP. As I began to experiment with the various material physical models offered by the HSP examples, I found that I was drawn to the simple virtual wall model. This was used most extensively as a starting point, as the action of striking a surface with different objects and forces could be considered to be one of the most primitive sound-producing gestures. One of the most interesting aspects of the instrument was that depending on the different force profiles used, it could rapidly change between allowing wild gestures, to a very resistant, even *secure*, environment where traversing through the detailed nuances of a sound could be explored. The four buttons on the small ball grip of the Falcon allow rapid switching between different forces profiles and parameter mappings, within a single performance.

After initial experimentation within this environment, the possibilities for prototyping new haptic-based musical instruments become obvious. Compared to interfaces such as standard MIDI controllers, where the performance space is shared only between knobs, faders, and micro-movements of the hand, on a fixed tabletop surface, the three degrees of freedom allow for much more unrestricted movement of the arm within space. Thus much larger gestural movements can be *transduced* into parametric information, while still allowing for finely focused articulations.

The first public performance using the Falcon was at the second LLEAPP (Laboratory for Laptop and Electronic Audio Performance Practice), at Newcastle University/Culture Lab, 19th May, 2010. At Newcastle, I performed in a trio alongside Cavan Fyans and Nicholas Williams, where we attempted to integrate acoustic instruments with an array of live electronics, from

Figure 5.5: Live electronics trio, *LLEAPP*, University of Newcastle, 2010.

laptops to tape recorders and hardware hacking (see Figure 5.5). For this performance the Falcon was used as a gestural interface, allowing specific sounds to be *placed* or *dropped* into the improvisation. The performance highlighted the fact that the instrument did not provide a smooth and easily controllable mode of interaction, but rather had to be constantly struggled with. Media Example 5.3 illustrates some of the issues that occurred when using the basic impulse on a virtual surface model: sometimes I would feel that I had hit the surface but no sound would be produced (c. 30") which resulted in an odd reversal of the usual perceived disconnect between sound and gesture in laptop performance; at other times the recoil of the device would be so forceful that it was difficult to keep it from jumping around the table (c. 1' 40"). While the performance as a whole was not particularly coherent, the ergotic interaction within the Falcon is clear: energy is conserved within the action of playing the instrument in that as I inject energy into the system, it in turns exerts a force back onto me. Moreover, during the points where the instrument functioned as I had intended, this gives a believable visual impression for the audience (particularly the gesture at c. 2' 5").

5.3.4 *Running Backwards, Uphill*

This section describes the implementation of the Falcon as a performance instrument within a compositional framework. When the opportunity arose to work with the Artisan Trio, an

Edinburgh-based piano trio, I reflected on the types of both musical and cultural expectations that this would bring. On one hand, the composition would encompass live processing of the acoustic instruments, but on the other I wanted to present the electronics as an instrument that could sit equally among the others in terms of the amount of potential expression that it could convey. The resulting piece, ***Running Backwards, Uphill*** (2011) for violin, cello, piano

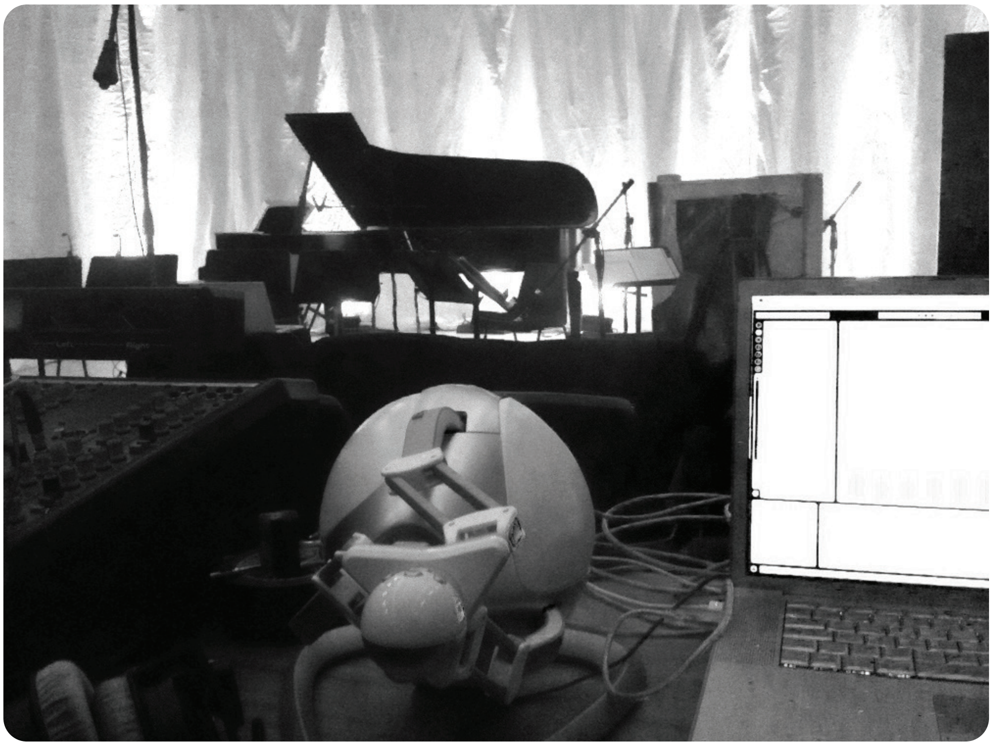


Figure 5.6: Performance of *Running Backwards, Uphill*, Reid Hall, Edinburgh, 2011.

and live electronics, attempts to explore the relationships between touch, gesture, and timbre by examining the sonic qualities of the acoustic instruments, and furthering these through the use of electronics. The performers are directed to lurch and fall off the keys; or, to create the most delicate airy bowed sounds. Extended techniques are combined with sound analysis and machine listening methods, resulting in a network of integrations between the two sonic worlds. One of the challenges with this composition was to develop a way of articulating the electronic part that could evoke the same expressive qualities within the music as would be expected of the professional ensemble. The musical language of the piece itself is very gestural (see Appendix C for the full score), and it was important that the electronic part should also be performed in such a way as to reflect this.

5.3.4.1 Articulation and Expression

In the first part of the score (see Figure 5.7), the Falcon is used to play short segments of samples of a prepared piano. With the added resistance of the controller, I was able to make micro-movements along the domains of both the start and end points of the sample, as well as the speed of playback of the samples themselves. Without the force to play off, the re-

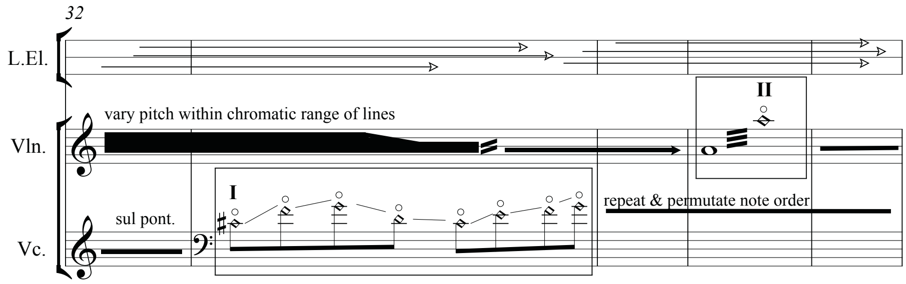


Figure 5.7: Score with black lines illustrating gradual transitioning of sound.

sult would have sounded jerky and ill crafted, whereas pushing through the resistance allowed smooth transitions between the various parameters, producing a *legato* effect (see Media Example 5.4 c. 17"). In this section, the string instruments play long tremolo lines in which both the speed of the tremolo, and pitch transition continuously. The dynamics also ebb and flow gradually until the entrance of the piano. I wanted the electronic part to reflect these characteristics by gradually morphing in timbre, dynamic, and pitch. While it could conceivably be possible to use a non-haptic 3D controller, such as a joystick, to perform this section, the *feeling* of moving through the sound for the *performer* could not be experienced in the same way. Most importantly, the difference in using a haptic controller such as the Falcon is the potential topology of sensation that it affords. While non-linearity can be employed within software algorithms for audio DSP to give the impression of moving through a terrain (Parker, 2007), or unpredictability within a system (Bowers, 2003), by changing the degrees of feedback within the haptic force profiles, this non-linear resistance could be experienced differently in different parts of the virtual performance space.

In the middle section of the piece (see Figure 5.8), the Falcon was used to transduce fast gestural sweeping movements to process various effects (including bit-crushing, feedback, and filtering), which were applied to a second set of samples. Here, the piano part leaps through descending cluster chords, in a syncopated manner. The pianist is instructed to play "clumsily, with hands almost falling off keys". A different, non-uniform force profile was used in this

Figure 5.8: Score illustrating manic, gestural section.

section, facilitating the jerky movements required, but also providing more resistance at the boundaries of the DSP (see Media Example 5.4, c. 2'10"). In this way I was less likely to, for example, hit the more piercing parts of the audible feedback, as the resistance would not easily allow access to that part of the instrument's range.

The following account gives a description of performing the electronic part of the piece in the Reid Hall, Edinburgh, 23rd April, 2011.

We've only had, in total, forty-five minutes to rehearse this piece, and just one single proper run-through. I realise that once again I have possibly taken on too many roles, having to simultaneously be the composer—trying to focus and listen to what the instrumentalists are playing—while also processing the ensemble in real-time, as well as trying to sort out my own contribution with my more immediate instrument, the system built around the Novint Falcon. In a rather schizophrenic role, I have allocated the system on my righthand side to take care of the live processing, most of which needs no interjection other than monitoring levels. With my left hand I perform a quite separate series of electronics, which are not reliant on input sound from the ensemble. I have a lot to manage, but the force feedback of the Falcon gives me so much perceptual guidance that it is just about possible to keep all the plates spinning. As the piece begins with a long section of transitioning tremolo in the strings, I feel able to react to the delicate ebbing and flowing of sound as I weave lines of fast repeated samples, mirroring the repetition of the tremolo. But while I know that my sound is being generated from just one sample, I feel as if I can work within the nuances of the sound itself, despite the very simple processing that I am applying (altering the speed and direction of playback). I have found that when I pull the ball grip towards me, the sounds will speed up, thus rising in perceived pitch, but this will also trigger much more live processing of my own material as the more frequent attacks will be picked up by the analysis part of my patch. Similarly, if I move to the leftmost part of my available gestural space, the sample will slow down and reverse. But the physical resistance in this area allows me to play right on the boundary of this change, so that I can really elicit these articulations between an almost completely stopped sound, and a slow growling that appears as the sample plays in reverse. Later in the piece, the music becomes fast paced, syncopated, and highly gestural. I want the electronics to reflect the pizzicato, slaps, and digging bow movements, as well as the jerky clumsy lurches that I have demanded from the pianist, not of course just in movement, but also in character. I change the Falcon to move through a different force profile, with less viscosity in general. I can swing my arm, punch at the sound, and I create fittingly aggressive white noise and rapid filter sweeps. I know that there are points where the filter could explode, but the resistance is stronger in these areas on the physical map, so that if I do hit these areas, which I fully intend to do just for brief moments, my hand will be thrown back on impact, as protection.

5.3.5 *Sungazing*

This section describes a second case study in which a different type haptic technology was employed. In 2011, I developed the idea of the Inventor Composer Coaction (ICC)[6] with Tom Mudd. This became a long-term project facilitating collaboration between composers (many of whom had not previously had the opportunity to work with any form of electronics) and designers of new DMIs. The instruments were selected from an international call, and each composer spent several months exploring their chosen instrument, before creating a piece for the new instrument and the Red Note Ensemble, one of Scotland's prominent contemporary music ensembles. The project was funded by the Roberts' Fund for Researcher-Led Initiatives and also received an Innovation Initiative Grant from the Edinburgh Fund. My own instrument choice was the AlphaSphere (see Figure 5.9), a new musical instrument consisting of forty-eight pressure-sensitive pads, arranged in a spherical configuration. The instrument appealed to me in that not only was the sole method of interaction through the tactile pads, but that these pads seemed to offer a physical elasticity that I had not previously encountered on any other type of pad-based device. The AlphaSphere's pads are built using an elastic membrane

[6]http://inventorcomposer.net/ [accessed 22nd August 2013]

which allows them to be highly malleable, giving several millimetres of leeway, much more in the case of the larger pads. This is quite a dramatic contrast to the hard surface of standardly used pressure pads on, for example, the Korg NanoPad. Being the first composer to write for the AlphaSphere, I was given the loan of a prototype instrument that was 3D printed by University of Exeter's new Centre for Additive Layer Manufacturing (CALM), who recently manufactured the first 3D printed violins. Through the piece ***Sungazing*** (2012) for bass clarinet, trombone, and live electronics, I was able to explore the potential to shape the digital processing through this resistant tangible interface (see Appendix D for details and the score).

Figure 5.9: Performing *Sungazing* with the AlphaSphere.

5.3.5.1 Mapping

While the AlphaSphere is presented for its capacity to facilitate circular arrangements of diatonic and chromatic scales, with a strong focus on mapping harmonic patterns across the forty-eight pads (Place, Lacey & Mitchell, 2013), I was more interested in its potential abilities to sculpt and transform sonic material itself. While the Falcon had allowed me to devise physical thresholds of my own choosing, the AlphaSphere dictated its boundaries at the limits of the elasticity of each pressure pad. Smaller pads would travel a maximum distance of much less than the larger pads. But of course elasticity is non-linear: there is much less free movement on approaching the limit of the fabric's stretch. As a result non-linear scalings were applied to all parameter mappings within the software. While many of the pads were mapped in a *one-to-many* configuration, the majority used a rather obvious strategy of mapping amplitude of sample to intensity of pressure. In this way, the amplitudes of multiple samples could be individually controlled simultaneously, which allowed me to weave the sounds in and out of the piece simply by varying the pressure from different fingers. While being active on a particular pad also toggled sounds on and off, this created a secondary threshold to play with, where I attempted to find the point between an extremely quiet dynamic, and complete silence. Similarly, a low-pass filter was mapped to intensity of pressure on different pads, and this was logarithmically scaled. This proved to be a very intuitive way of playing with fast filter sweeps within the piece. A further technique that I used to control various other processing modules, such as phase vocoders and pitch transposition, was to combine the amplitude of these modules with a secondary parameter that could be manipulated on a different scale. For example, in a ring modulation module, the pressure would control both the amplitude of the effect, as well as the multiplier frequency of the ring modulation.

5.3.5.2 Outcomes

The AlphaSphere's documentation emphasises the modular layout of the instrument, and the ability to map individual sounds or processes onto each individual pad. This seems to make it more difficult to overcome these potential one-to-one mappings. While it was difficult to actually reach the pads that were on the far side of the sphere while performing, I found that the most expressive moments tended to occur when I was only playing with two of the pads, one with each hand, almost in the same way that one might sculpt wet clay (see Media Example 5.5). This suggested to me that removing the divisions between areas of the sphere might be a more fruitful approach in that it would allow for an almost messier, sculpting-like interaction. Nevertheless, the expressive capacities of the elastic membrane of the AlphaSphere are quite apparent: there are multiple potential sites of resistance which can be explored very readily.

5.3.6 Summary

Rebelo describes his notion of *participatory* space shared between musician and instrument as somewhere where the performer employs "negotiation of subtlety and the recognition of threshold conditions." Rebelo (2006). By introducing force-feedback haptic devices into our performance systems we can increase the potential for this type of multimodal engagement. Working with the Falcon in different contexts raised questions about the construction of a haptic feedback based DMI. Certainly, it would be useful to explore scenarios where the performer may traverse a virtual space, encountering various objects and forces which could also emerge or disintegrate in real-time. However, the purpose of this research was not to detail the technical capabilities of the Novint Falcon, as this is thoroughly described elsewhere (Berdahl et al., 2009), but rather to describe how employing a haptic device can manifest imagined musical ideas and *expressive* nuances. Implementations of different force profiles, combined with viscous damping, allow the performer to *feel* their way through different aspects of digital audio, and sculpt the sound accordingly. In the work described, using resistant forces with *simple* physical manifestations allowed vastly different types of engagement at different stages of the piece.

One of the most noticeable drawbacks of both of these systems is that they both conform to the desktop model that Weiser objects to. He is particularly wary of approaches that attempt to create a virtual reality, inside the 'virtual computer world' (Weiser, 1993). The Falcon, in particular, falls into this category, as an infinite number of virtual topological instruments could be constructed. The AlphaSphere, on the other hand, has a fixed physicality. Nevertheless, both must be placed *on* a desktop which presents problems in itself. More forceful gestures would cause both controllers to move on the tabletop, particularly noticeable in the LLEAPP performance. Nevertheless, through the use of haptics, as a performer, I could more easily position myself within the shared participatory performance space. Moreover, both these ensemble pieces demonstrate that this strategy allows the laptop to exist as an instrument alongside the traditional ones, without necessarily having to take on the role of processing the live acoustic sound.

Chapter 6

Conclusion

6.1 Audio-Haptic Relationships

This dissertation has explored, from various angles, ways in which embracing the relationships between sound and touch has informed and shaped the musical practice that has been undertaken over the course of this research. This enquiry has led to the production of both tangible technological developments, as well as an extensive musical portfolio. The practical outcomes have been grounded in a theoretical discourse that has provided a framework from within which to understand *why* particular decisions were made along the way.

This research has taken an approach that is evidently reflexive. The elements of the practice have been presented in an order which is not necessarily chronological, but which instead illustrates how the multifaceted nature of the work has touched on the various aspects of the audio-haptic link by looking at the particular themes of feedback, resistance, communication, and materiality. But in addition to the non-linear tracing of events, it has emerged that these themes overspill into the territories of one and other. Where I have begun to explore a particular element of research through a piece of musical work, I have found that one area proves to be intertwined with another. Thus, through the portfolio works, in addition to the examples of the numerous performances that I refer to throughout, I am drawing focus to certain aspects of a much wider field of embodied electronic music performance practice, examined through my own phenomenological experiences. For example, **Figurine-Operated String** is discussed in Chapter 3, in terms of dealing with the materials presented by a digitally augmented piano, and how I have cultivated a musical practice out of this. Later the piece is reintroduced in Chapter 5 in relation to looking for resistances within material/software systems. Similarly, the piece **Socks and Ammo** is discussed in Chapter 4 as a case study for NeVIS, which encompasses both the themes of feedback *and* communication.

Many elements of this research have come about by attempting to find pragmatic solutions to the problems presented by performing live electronic music through embracing the connections between the modalities of hearing and touching. In Chapter 2, I questioned the role of touch within musical performance practice. My investigation showed that physicality has always been a crucial element of instrumental performance, and that tactile sensation is part of the vital closed feedback loops that musicians continue to make use of when playing instruments. Accordingly, much research has been done in attempting to use acoustic instrument paradigms to model haptic technologies. While this is a positive step, in that many DMIs fail to address the issues of multimodal interaction—in which I would include both the activities of listening and performing—this research generally does not go far enough in moving beyond skill acquisition experiments. Yet there are various low-cost and DIY methods that I have referred to, which would allow a wider community to embrace simple haptic technologies.

This work has been grounded in Varela, Thompson and Roche's notion of enactivism (1991), which in turn was influenced by Merleau-Ponty's notion of the double embodiment (1962), as discussed in Chapter 3. I elaborated on the idea of performance as perceptually guided action, whereby as the performer plays an instrument, so too does the instrument push back with haptic and resistive forces upon the performer. This has been the key influence behind the artistic practice, giving both a context for the paths taken, as well as suggesting the quite literal notions of active and passive touching which have shaped the two sides of the technical elements. I demonstrated the development of the hybrid piano which illustrated that by considering such enactive approaches, we can maintain the sense of immersion, intimacy and embodiment with digitally augmented hybrid instruments.

In Chapter 4, vibrotactile feedback was employed in several distinct ways:

1. as a means to enhance the feel of a digital or hybrid instrument;
2. as a means to convey information to the performer(s) in lieu of visual means;
3. to provide a means of communication between performers;
4. as a means to introduce an unpredictable element into improvisation.

But while the initial development and use of new technologies arose out of predominantly functional requirements (specifically in 1 & 2 above), this gave way to musical possibilities that went beyond logistical problem solving. Of particular note were both the structural characteristics of the improvisations that arose out of the NeVIS project (see Section 4.3.1), as well as the marked change in the character of playing from the string quartet (see Section 4.2.3). This led me to conclude that vibrotactile technology can be used not only to solve logistical performance issues, but also as a creative means to influence both the structures, as well as the energy of a performance.

Haptic and physically resistive technologies were explored in Chapter 5 in the ensemble pieces **Sungazing** and **Running Backwards, Uphill**. Through these works, I sought to play out in practice the ideas of sound sculpting as a tactile activity (Emmerson, 2011) and aligning resistances within the physicality of an instrument with resistances in the digital signal processing (Evens, 2005). I have demonstrated the expressive potentials of these methodologies, which have allowed sophisticated articulation of electronics and digital processes in situations not involving augmented instruments. Indeed, working with low-cost haptic technology allows the creation of highly expressive performance environments. By facilitating ergotic gestures, energy is conserved in a system which ties together the sonic output with the physicality of the performer.

The autoethnographical reflections that have been interwoven throughout this text have served to provide further insight into the problems encountered throughout the various stages of my practice, as well as the benefits and progress made. Much in the manner of Sudnow (1978), these passages provide a phenomenological account of significant fragmented moments of my creative practice. Not only supporting the more scholarly technical, theoretical, and analytical text, I would suggest that these elements, along with the numerous supplementary media examples help to build up a sense of the scope of the practice in which this research has been grounded. As Suzanne Little points out, approaches that aim to make meaning of the world should "take into account the presence and role of the researcher in the research process" (Little, 2011, 22).

I also note that in the background, throughout this whole period of study, I have engaged with the ideas put forward in this thesis through numerous outreach projects (for example, BBC Learning[1] and Big Ears[2], SARC), as well as through continued music workshops with community groups involving adults with learning difficulties and disabilities. I have chosen not to include this extensive practice as part of this body of work since the goals were not to assess the therapeutic benefits of exploring the tactile properties of sound. I would argue, however, that the performance work that I understake in such situations has no less significance than in the concert hall and festivals (see (DeNora, 2003, 157)). Just as it acknowledges the benefits of collaborative work (Smith & Dean, 2009), the role of creative practice research should take into account the richness that work undertaken outwith the academy cannot help but feed into the research proper. All the vibrotactile technology that I have developed has been used in other scenarios, which has only cemented my belief in the importance of how sound relates to

[1] http://www.bbc.co.uk/learningzone/clips/composing-music-to-accompany-action/13988.html [accessed 21st August 2013]

[2] http://www.somasa.qub.ac.uk/~BigEars/ [accessed 20th August 2013]

touch, and has helped to feed ideas back into my own established performance practice.

6.2 Future Developments

6.2.1 Dramaturgy of Process

In this body of work I have employed haptics as a tool for the practitioner, with little focus on how the actual *presence* of the technology has impacted the performative element of the work. As a reviewer from the Můstek performance at Sound Festival (see 4.3.7) noted about the vibrotactile technology: "As one person suggested, she thought to begin with that the drummer was ill and had a drip fitted to his arm" (Cooper, 2011). A NIME peer review comment of the same piece similarly stated: "I couldn't help saying to myself 'Now that we just got over the laptop musician looking like checking e-mails, here we get acoustic musicians looking like laboratory rats!' "[3]. This suggests that while this body of research has been concerned with the uniquely private tactile sensory mechanisms of performers, there may be scope for examining how revealing elements of the process can affect the audience's reception of the work. Furthermore, while the work done with the string quartet (see Section 4.2.3.1) unearthed the potential invasiveness of the embedded vibrotactile feedback, the technology used so far has generally been tolerable. Future investigation might look towards pushing the tangible feedback to more extreme cases, such as mild electric shocks via commercially available muscle-toning pads, or muscle actuators which would produce involuntary movements of the limbs. Such methods would allow both the symbolic information exchange (see Section 4.2) as well as elements of unpredictability (see Section 4.3.1), while potentially adding a performative element by manifesting aspects of the process in the visually perceivable gestures of the performers.

6.2.2 Auditory-Tactile Synchronisation

This research has focused on the physicality and tangible perception of the performer of live electronic music. But of course tangible information used by a performer cannot be experienced by the audience. Towards the end of this period research, I began to make some developments using vibrotactile interfaces which allow listeners to also experience sound as physical sensation directly applied to the body. Based around ideas of being able to feel characteristics of the music on the skin, this "potential new art form" (Gunther & O'Modhrain, 2003, 380) aims to expand the listening experience, by coupling it with various physical sensations. Drawing inspiration also from Kaffe Matthews' *Sonic Bed* (Matthews, 2006) project, I created the piece *Skin Music* (2012), which was an initial testing ground for this concept. The listener receives a piece

[3]In personal email correspondence from the anonymous peer review process for NIME 2011

of music, through a sensually augmented set up consisting of a chaise longue in a darkened room, with loudspeakers on either side of the chair. The work draws on the ideas proposed by Angela Chang and Conor O'Sullivan (2008), who suggest looking toward audio-visual theories, such as those proposed by Michel Chion, in order to develop ways of linking both the tactile and auditory sensations. *Skin Music* ran for five weeks at Summerhall art gallery, Edinburgh, and employed techniques such as temporal linearisation[4] and synchronisation[5], by way of both vibrotactile feedback and low frequency tactile transducers embedded on the chair. This area of composition and music perception is largely unexplored and deserves a dedicated investigation, particularly in light of recent developments in the field of music perception, as mentioned in Section 2.6.2.

6.2.3 Live Electronic Performance Practice

It is clear that the technical outcomes of this work could be greatly expanded through future developments. As Berweck (2012) demonstrates, there are many instrumental performers who could benefit from the use of the vibrotactile technology. The interdisciplinary potentials are also evident: at the European Commission funded conference on Human Computer Coaction at IRCAM, 2013, I engaged with researchers from not only the field of music, but also neuroscience, interaction design, cognitive psychology, and so on. The haptic technology that I have developed has already been implemented in the AHRC Digital Transformations funded project ChoreoHaptics[6] at the Edinburgh College of Art, which aims to explore whether blind dance audience members can experience effects of kinaesthetic empathy despite their lack of vision. This project will also incorporate added sonic feedback at a future date.

While the technical aspects of this work all pave the way for these future developments, I would suggest that more work needs to be done in terms of understanding the performance of live electronic music from the embodied experience of the performer. As mentioned in Section 3.2.1, the importance of the physiology of the musician is significant in the relationship between performer, instrument, and environment. As noted, this has been one of the main motivations for my own presence as a performer (and composer) throughout my work, and my reluctance, as yet, to pass my portfolio onto other performers. In 2012, I directed the Inventor Composer Coaction[7], in an attempt to give composers an opportunity to work with electronics, many of whom had never done so previously. But not only did this long-term project allow the composers to write for a particular digital instrument, but also to spend several months *getting*

[4]Employing a physical sensation directly before a sonic impulse to create a sense of causality
[5]For example, synchronisation would involve the sound and the sensation occurring at the same time.
[6]http://hapticexperiments.wordpress.com/about/ [accessed 22nd August 2013].
[7]http://www.inventorcomposer.net [accessed 19th August 2013]

a feel for the nuances, limitations, and the bounds of these instruments. Interestingly, all the electronics were *performed* by the composers from the stage, many of whom would not class themselves as performers. This supports my belief that prolonged, embodied relationships with new musical instruments, which lead to highly personalised practices can only help in allowing us to fully engage with the materials involved in live electronic performance practice.

Appendix A

kontroll

This appendix describes the portfolio composition ***kontroll*** (2010) for prepared piano, live electronics and self-playing snare.

A.1 Portfolio Content

Files are located in `/portfolio/kontroll` on the accompanying DVD.

kontroll (2010) has received several international performances to date, including Norberg Festival (Sweden), Electroacoustic Music Studies Network (New York), and ICMC (Huddersfield) (see Section 1.6.1 for the full list of performances. The portfolio version `lsh_kontroll.mov` is a video recording from the second performance in the Reid Hall, Edinburgh, 15th July, 2010. An audio version of the same performance has also been included `lsh_kontroll.wav`. This was the first public performance using the vibrotactile feedback device which I discuss in Section 4.2.2.5. As I was still testing the technology, the laptop screen remained open during the performance, and I can be seen checking it to verify that the system was functioning correctly. As demonstrated in Section 4.2.2.2 future performances were able to take place successfully without any visual feedback from the computer.

The piece has been recreated in various venues, including the concert hall, a disused barn (Norberg), a student union bar (ICMC), and so on. Despite the particularities of the performance requirements (see Section A.2.2 below, which include the additional snare drum, amplifier, loudspeaker for inside the snare drum, as well as several hours to prepare the piano, the performance environment has successfully been recreated within these different space, and on the various different upright pianos.

A.2 Performance Requirements

A.2.1 Piano Preparations

The sections lists all the original preparations made on the piano, assuming note names A0 - C8. Tacks are standard brass thumbtacks or drawing pins, inserted directly into the hammer head. Screw lengths have been noted, although different lengths and widths may be used to achieve desired sound, as indicated. On notes with three strings, positioning of screws has been indicated: thus, '1&2' means that screw should be inserted between the first and second string. Height indicates the number of centimetres above dampening felt, as shown in Figure A.2.1. There is a total of thirty-eight preparations on thirty-four notes. Gaffer tape should be applied to all the strings, bar the bottom ten, and be placed above the hammer strike position from the left hand side, gradually descending so that all hammers above note E2 will strike the tape.

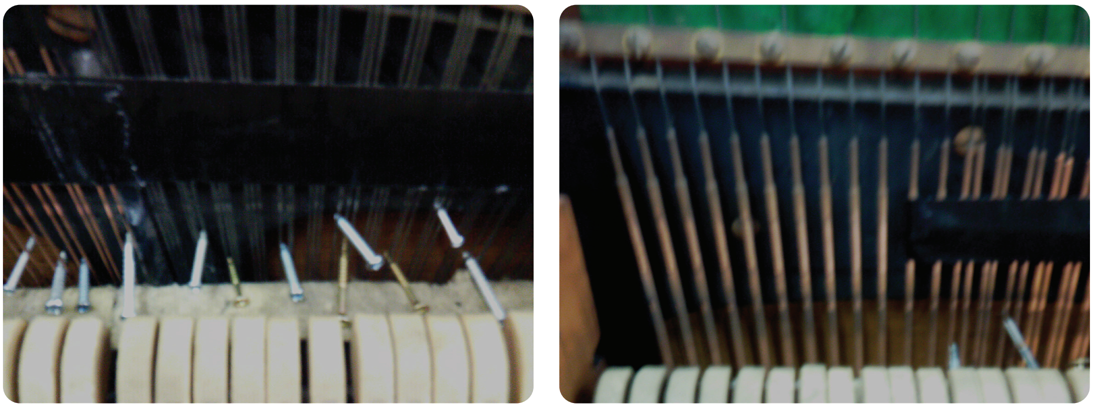


Figure A.1: Piano preparations.

Note	Type	Screw Length (cm)	Strings	Height (cm)	Notes	Sound Desired
E1	Tack					Tack
A1	Screw	3.75		0		Bell-like
B1	Screw	5		5		Bell-like
C2	Tack					Rattling
E2	Tack					Tack
F2	Screw	3.75		2		Rattling
A2	Tack Screw	 2		 2		Tack
Bb2	Screw	2.5		3		Bell
B2	Screw	3.75		0.5	Screw hits side of soundboard metal	Rattling/harsh
C3	Screw	2.5		0		Bell/harsh
D3	Screw	3.75		3	Screw head into soundboard	Muted chord
E3	Screw	2.5	2&3	3	(as above)	Inharmonic
F3	Screw	2.5	1&2	2	(as above)	Bell
G3	Screw	2.5	1&2	3		Inharmonic
A3	Screw	2.5 5	1&2 2&3	5 2		Inharmonic
B3	Screw	3.75	2&3	0		Inharmonic
C4	Screw	2	2&3	6	Hammer hits screw slightly	Muted Bell
D4	Screw	3.75	1&2	0	Screw head into soundboard	Bell
F4	Screw	2 2.5	2&3 1&2	4 3.5	Screws touching each other	Bell
Ab4	Screw	2.5	1&2	3		Muted bell
B4	Screw	2.5	1&2	4		Marimba
C5	Screw	2.5 3.75	2&3 1&2	4 0		Marimba
E5	Screw	2	2&3	3	Screw head into soundboard	Inharmonic
F5	Tack					Tack
Ab5	Screw	2.5	2&3	0		Inharmonic
B5	Screw	3.75	1&2	0		Marimba
C#6	Screw	2.5	1&2	2		Marimba
Eb6	Screw	2.5	2&3	1		Marimba
F6	Screw	5	2&3	4		Marimba
A6	Tack					Tack
C7	Screw	2.5	2&3	4		Marimba
E7	Screw	3.75	2&3	4		Chime
F7	Screw	2	2&3	5		Chime
G7	Screw	5	2&3	5		Chime

Figure A.2: List of piano preparations.

A.2.2 Technical Requirements

- upright piano prepared as in Figure A.2.1
- 2 microphones (condenser, e.g. Neumann KM 184)
- 2 (or more) channel sound-card
- 2 loudspeakers, plus adequate monitoring for performer
- 2 microphone pre-amps, e.g. API 3124
- 1 snare drum with loudspeaker facing downwards inside
- 1 amplifier for snare loudspeaker
- mixer
- laptop or computer running Max6
- objects for extended techniques: 2 bullet magnets, 1 steel guitar slide, 1 wooden percussion stick

Microphones should be placed 10cm above the hammers of the piano, and 20cm from the centre. Monitors should be placed on either side of the piano. The piano should be positioned centre stage with the keys facing the audience, thus the performer will have her back to the audience. The snare drum can be positioned at the end of the keyboard, on either side. Loudspeakers should be placed proximally to the piano, on either side, with additional loudspeakers used depending on the size of venue: the result should give the impression of all sound emanating from the piano. Level control for the acoustic piano and the electronics may be adjusted by a sound engineer during the performance on the mixing desk to balance the two components. Input levels of the microphones should be tested before the performance begins since these are crucial to the response of the Max/MSP patch (see SectionE.2.3).

A.2.3 Software Requirements

The Max/MSP patch has been tested on an Intel Macbook Pro 4GB internal RAM using Max6 Version 6.0.7 and can be found as a Max project in */portfolio/kontroll/code* on the accompanying DVD. The vibrotactile device (version 1) should be connected before the patch is opened (see Appendix G for details). To test for correct microphone level, the `ezdac` should be turned on and the patcher `analysis` should be opened. Setting the pink highlighted number

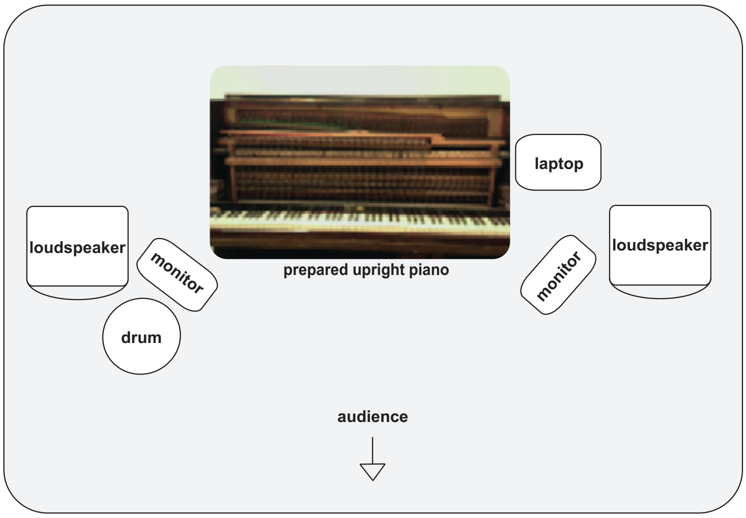


Figure A.3: Stage layout.

box to 20, middle C should be played on the piano *pianissimo* which should trigger a bang out of the *bonk˜* object. This should be repeated for velocity 128, where a note played *sforzando* should trigger an attack. Microphone levels should be adjusted accordingly. Additional compression on the piano input levels may be used if necessary. The piece also requires the Native Instruments Kontakt 3 sampler, East West/Quantum Leap Symphonic Orchestra Silver Edition samples, as well as samples from Soundiron Rust Vol 1. collection.

Any snare drum can be used and most types have a small hole in the side through which to pass the loudspeaker wire. The loudspeaker should be placed face down onto the drum skin and can be fixed with tape. The piece has been tested with a 40W loudspeaker and amplifier.

A.2.4 Common Music Code

Common Music[1] was used to generate the MIDI sequences that control the samples and drum sounds during the first section of the piece. The following code is an example of the Common Music programming used to these algorithms. This example analyses a prerecorded MIDI file of the opening theme, to produce variations on it.

```
;; make sequences from markov analysis
;; palm muted pitches on piano (markov analysis of opening theme)
(defun map-slot (seq slot)
  (loop for x in (subobjects seq)
        when (typep x 'midi) ;; ignores non-midi information
        collect (slot-value x slot)))

(defun palm (reps order tempo)
      (let* ((order 2) ; order of markov chains

     (odds1 1)
     (odds2 1)

     (midi-list (import-events "intro.mid"))

     (k-list (map-slot midi-list 'keynum))
     (d-list (map-slot midi-list 'duration))
     (a-list (map-slot midi-list 'amplitude))

      ;; make sequences from markov analysing
     (mark-key (markov-analyze k-list :order order :print? false))
     (mark-amp (markov-analyze a-list :order order :print? false))
     (mark-dur (markov-analyze d-list :order order :print? false))

     (gap (new markov
:of '((q -> (w 0.6) (q 0.1) (h 0.2))
      (w -> (w 0.1) (q 0.9) (h 0.2))
      (h -> (h 0.5) (q 0.5) (w 0.1))))))

(process repeat reps
 for k = (next mark-key)
 for a = (next mark-amp)
 for g = (rhythm (next gap) tempo)
 for i from 1

 set odds1 = (interp i 0 0 50 0.9 100 1)

 output (new midi :time (now)
     :duration (rhythm 'h tempo)
     :channel 1
     :keynum k)

 wait g)))

(events (palm 100 2 160) "palm.mid")
```

[1]http://commonmusic.sourceforge.net/ [accessed 25th August 2013]

A.3 Score

The score for ***kontroll*** is shown on the following pages. This is simply a graphic representation of the piece for documentation purposes and is not used for performance. Symbolic notation of the sampled instruments, the self-playing snare and the DSP processing have been included. Pitches indicated are only relevant to the piano as prepared in A.2.1, and rotated letters used within the staves indicate that the marked theme should be improvised upon. As shown in A.4, the theme announced in section E would be the basis for improvisation. Notes and rhythms indicated for all non-prepared piano parts are merely suggestive of sonic activity, as they will be different on each playing.

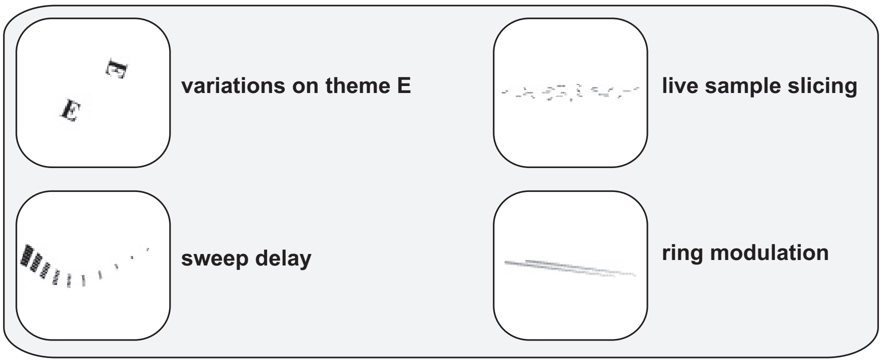
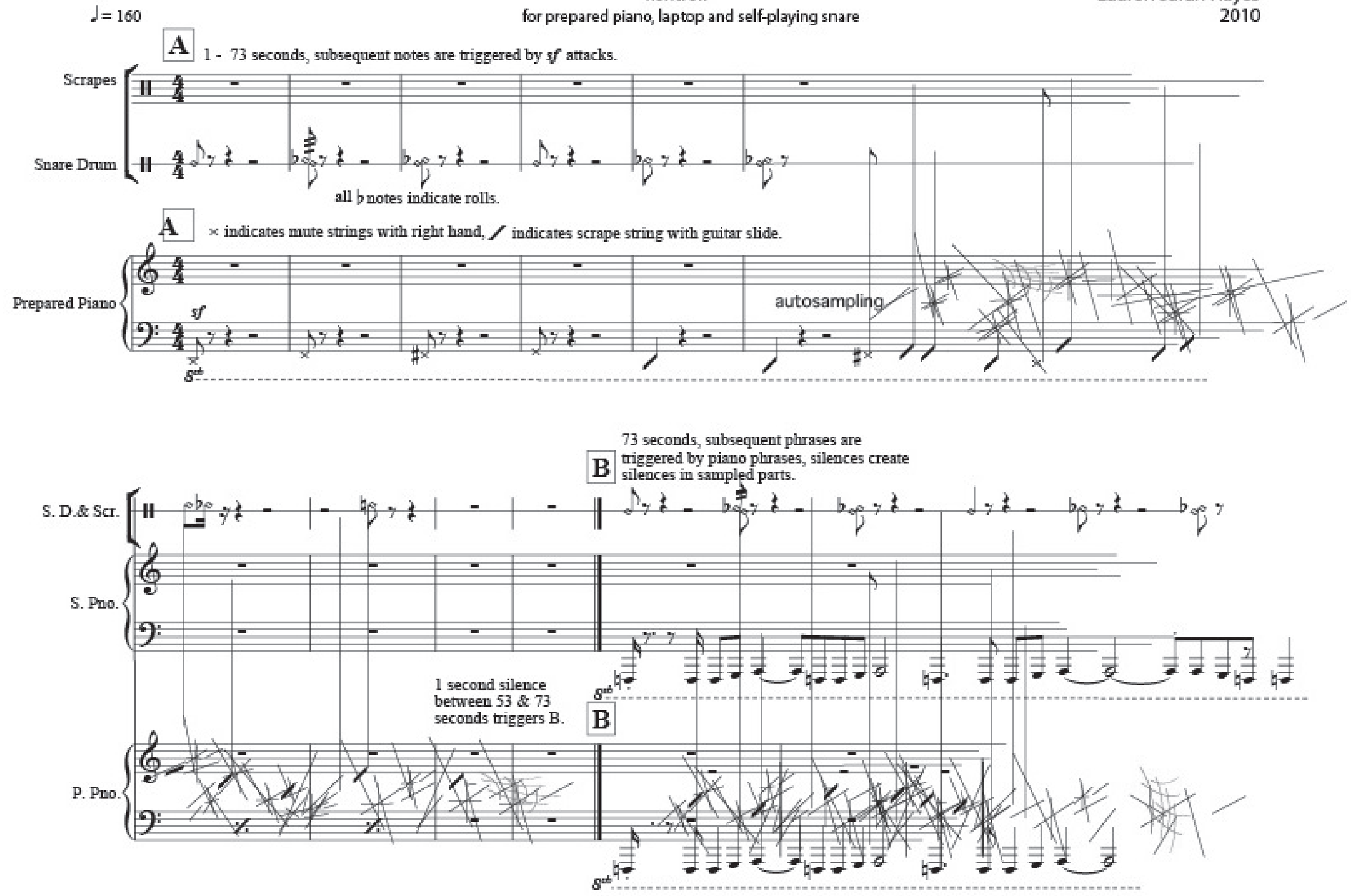


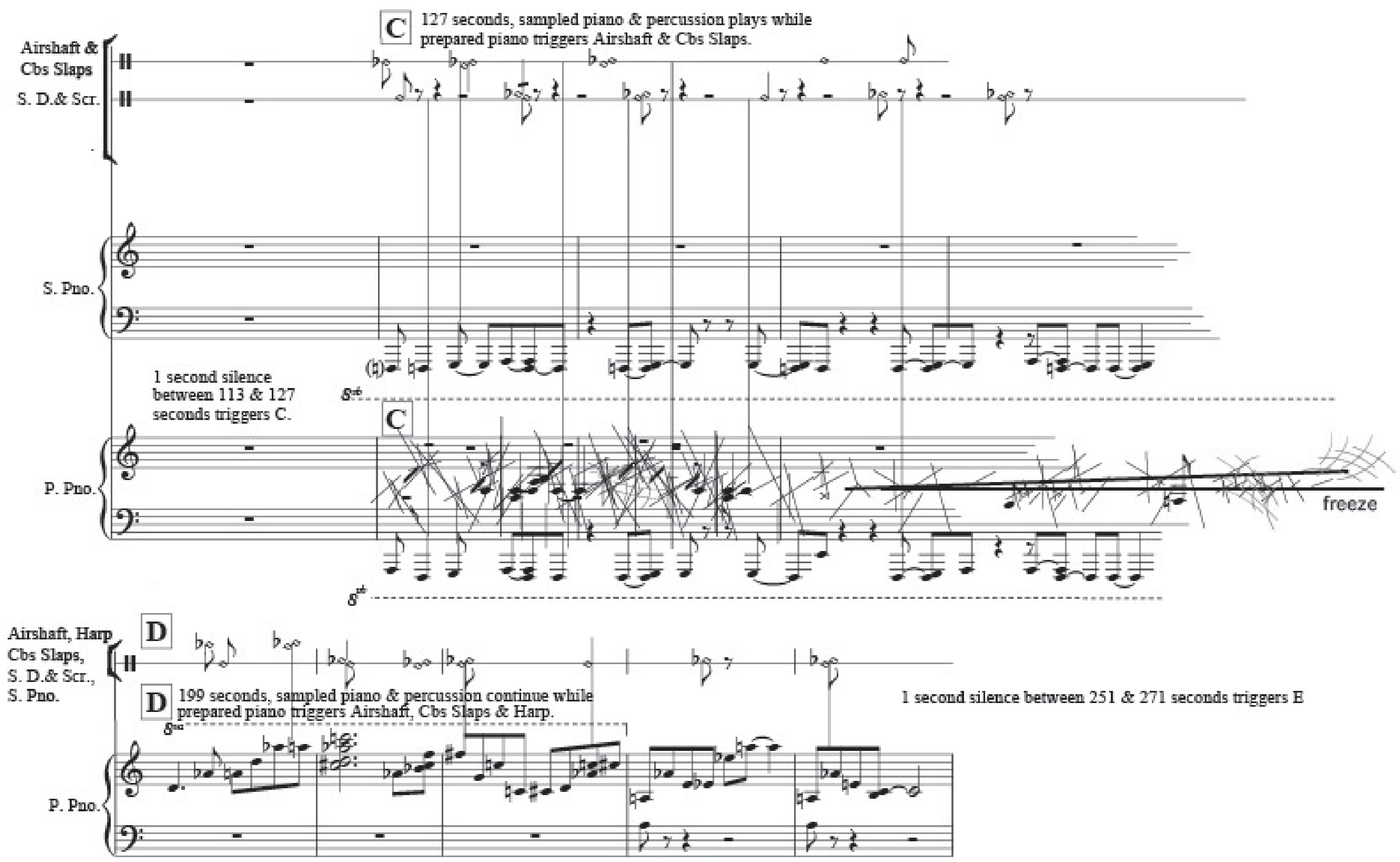
Figure A.4: Examples of notation symbols.

kontroll

for prepared piano, laptop and self-playing snare

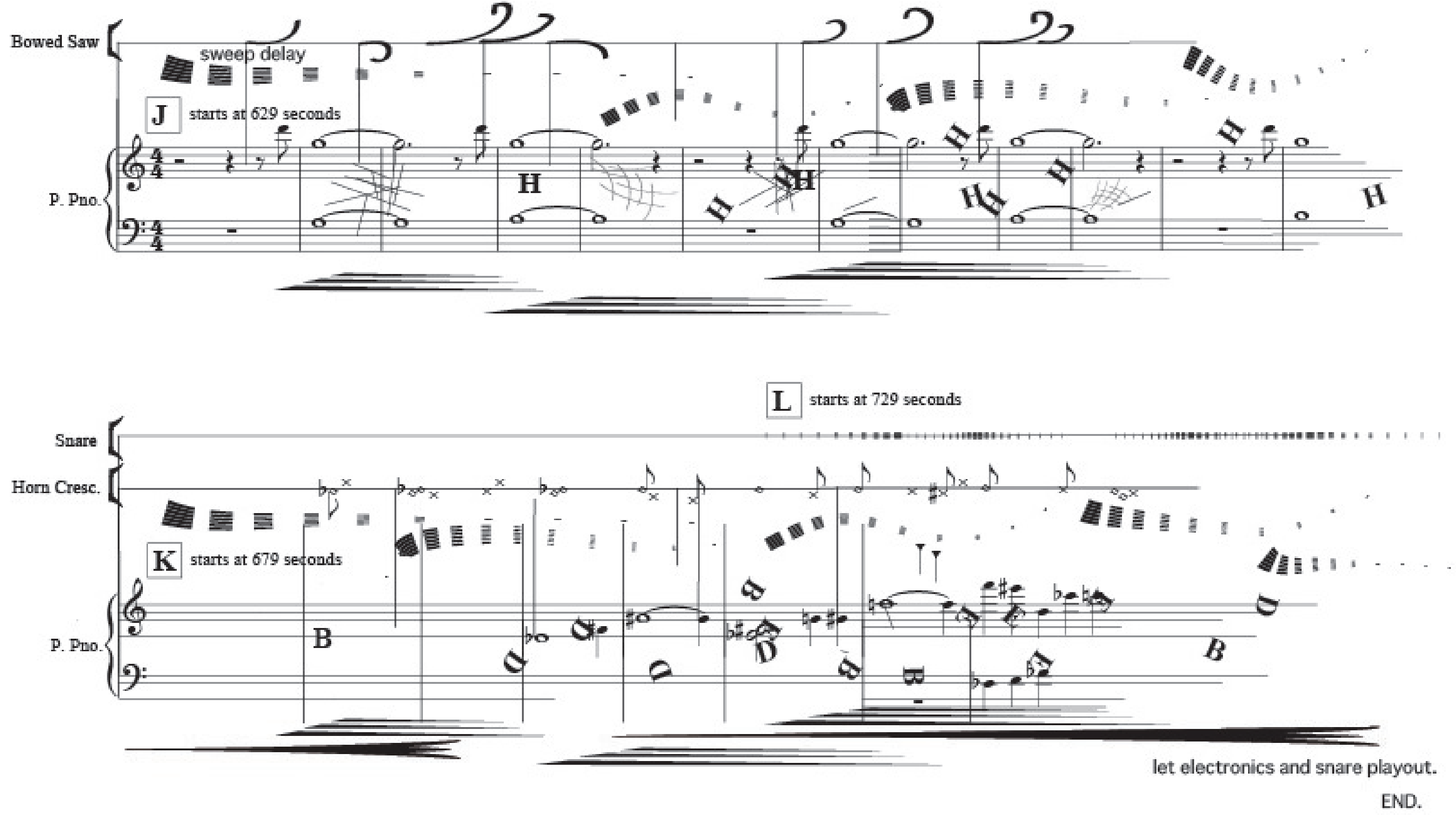
Lauren Sarah Hayes
2010




C
127 seconds, sampled piano & percussion plays while prepared piano triggers Airshaft & Cbs Slaps.
Airshaft & Cbs Slaps
S. D.& Scr.
S. Pno.
1 second silence between 113 & 127 seconds triggers C.
C
P. Pno.
freeze
Airshaft, Harp Cbs Slaps, S. D.& Scr., S. Pno.
D
D
199 seconds, sampled piano & percussion continue while prepared piano triggers Airshaft, Cbs Slaps & Harp.
1 second silence between 251 & 271 seconds triggers E
P. Pno.


Airshaft, Harp
Cbs Slaps,
S. D.& Scr.,
S. Pno.
P. Pno.
1.2.3.
3.
Harp &
Cbs Slaps
♩= 120
Piano strings plucked with right hand, stave lines represent 5 consecutive strings beginning at E7
rep. 4 times
Plucked Strings
E
1 second silence between 343 & 363 seconds triggers F
Harp, Cbs
Slaps & Pizz.
Sampled Plucks
F
♩=♪


G starts at 423 seconds: mf attack between 423 & 433 seconds triggers recording.
Harp & Pizz.
P. Pno.
slicing/sampling
Hit piano strings with guitar slide, pluck strings.
descending sine tones
Harp, Pizz. & Horn Cresc
H starts at 493 seconds
sin wave partials
P. Pno.
ring modulation of piano
I 1 second silence 561 & 581 seconds triggers I.
Bowed Saw
P. Pno.


Bowed Saw
sweep delay
J starts at 629 seconds
P. Pno.
H
Snare
Horn Cresc.
L starts at 729 seconds
K starts at 679 seconds
P. Pno.
B
D
E
let electronics and snare playout.
END.

Appendix B

multifingeredbodyparts

This appendix describes the portfolio piece ***multifingeredbodyparts*** (2010) for generic game controller, laptop and vibrotactile feedback device.

B.1 Portfolio Content

Files are located in */portfolio/multifingeredbodyparts* on the accompanying DVD.

multifingeredbodyparts (2010) was recorded in August, 2010, and has been the basis of numerous improvisations and collaborative performances that have followed since. The original recording has been included `lsh_multifingeredbodyparts.wav`. The piece is performed with a generic (unbranded) game controller and uses vibrotactile feedback to direct the improvisation (see Figure B.1).

Figure B.1: Generic game pad with vibrotactile feedback glove.

The algorithmic suggestion is generated by cycling through lists of durations in milliseconds. These are sent to the performer as two types of vibration. Firstly, short bursts are sent to indicate when fast, snappy gestural material should be played. Secondly, a vibration increasing in intensity is sent to indicate that current sonic material should be looped over this period.

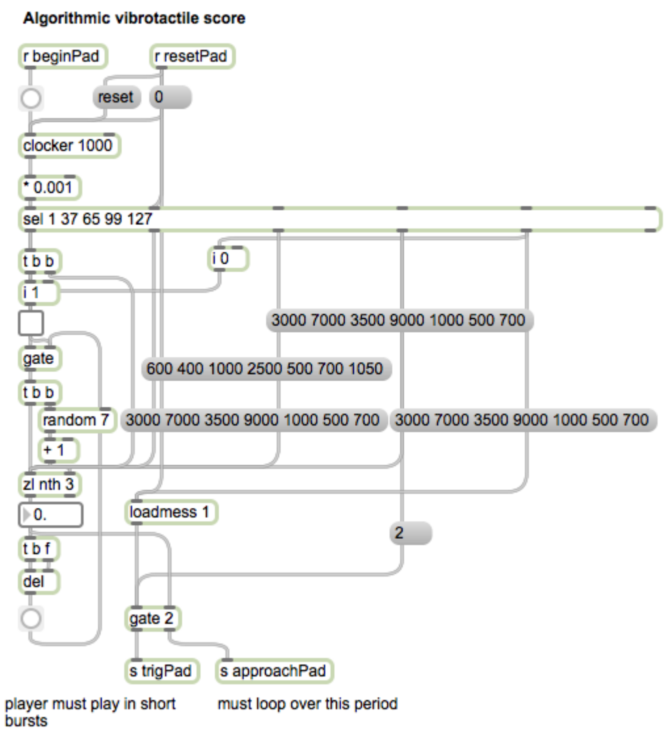


Figure B.2: Algorithmically generated vibrotactile suggestion.

B.2 Performance Requirements

B.2.1 Technical Requirements

- 2 (or more) channel sound-card
- 2 loudspeakers, plus adequate monitoring for performer
- mixer
- laptop or computer running Max6
- USB game controller

B.2.2 Software Requirements

The Max/MSP patch has been tested on an Intel Macbook Pro 4GB internal RAM using Max6 Version 6.0.7 and can be found as a Max project in `/portfolio/multifingeredbodyparts/code` on the accompanying DVD. The vibrotactile device (version 1) should be connected before the patch is opened (see Appendix G for details), as should the USB game controller. The piece makes use of several sample libraries that I have recorded over the years:

85 : a set of 85 samples recorded from my prepared piano, Edinburgh;

buchla : a set of Buchla 200 samples recorded at Elektronmusikstudion, Stockholm;

crackle : a collection of CrackleBox samples recorded at STEIM, Amsterdam;

metal : a collection of sample sets of percussion sounds recorded in Edinburgh;

vcs3 : a set of VCS3 samples, recorded at STEIM, Amsterdam.

The piece also requires the Native Instruments Kontakt 3 sampler and samples from East West/Quantum Leap Symphonic Orchestra Silver Edition.

Appendix C

Running Backwards, Uphill

This appendix describes the portfolio composition ***Running Backwards, Uphill*** (2011) for piano, violin, cello and live Electronics.

C.1 Portfolio Content

Files are located in */portfolio/RunningBackwardsUphill* on the accompanying DVD.

Running Backwards, Uphill (2010) has received two performances to date. The portfolio version `lsh_runningBackwardsUphill.mov` is a video recording from the first performance in the Reid Hall, Edinburgh, 23rd April, 2011. An audio version of the same performance has also been included `lsh_runningBackwardsUphill.wav`. This was the first proper performance of my work using the Novint Falcon (as discussed in Chapter 5. As there were restrictions on the use of the piano, the piece had to be performed using a piano soundboard for extended techniques, as well as the grand piano. This was not an issue in the second performance. After the first performance seen on the video here, it was noted by the ensemble that as a performer I should have joined them on the stage, as a fourth player. This was the case at the next performance, which was at the International Computer Music Conference, Ljubljana, 10th September, 2012

C.2 Performance Requirements

C.2.1 Software Requirements

The Max/MSP patch has been tested on an Intel Macbook Pro 4GB internal RAM using Max6 Version 6.0.7 and can be found as a Max project in */portfolio/runningbackwardsuphill/code* on the accompanying DVD. The piece requires the libnifalcon open source driver for the Novint Falcon[1].

[1]http://qdot.github.io/libnifalcon/index.html [accessed 22nd August 2013]

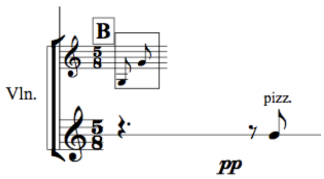
C.3 Score

Notes

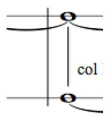
When dynamic point changes are not specified, this is left to the musician.

Unless otherwise stated, transitions in the opening section and **section A** should be smooth and musicality should prevail over notation.

Ideas in boxes such as are themes that should be repeated and improvised on gradually tending towards the next encountered idea: transitions in pitch and dynamic should be as smooth as possible. Arrowheads indicate to tend towards next box, interpolating dynamics, pitch and speed of tremolo, where possible. Lines alone mean repeat until next idea.



Boxes in **section B** are chromatic ranges from which to select pitches. Pitches selected will depend where performers hands fall whilst sliding down the neck with left hand, within ranges provided.



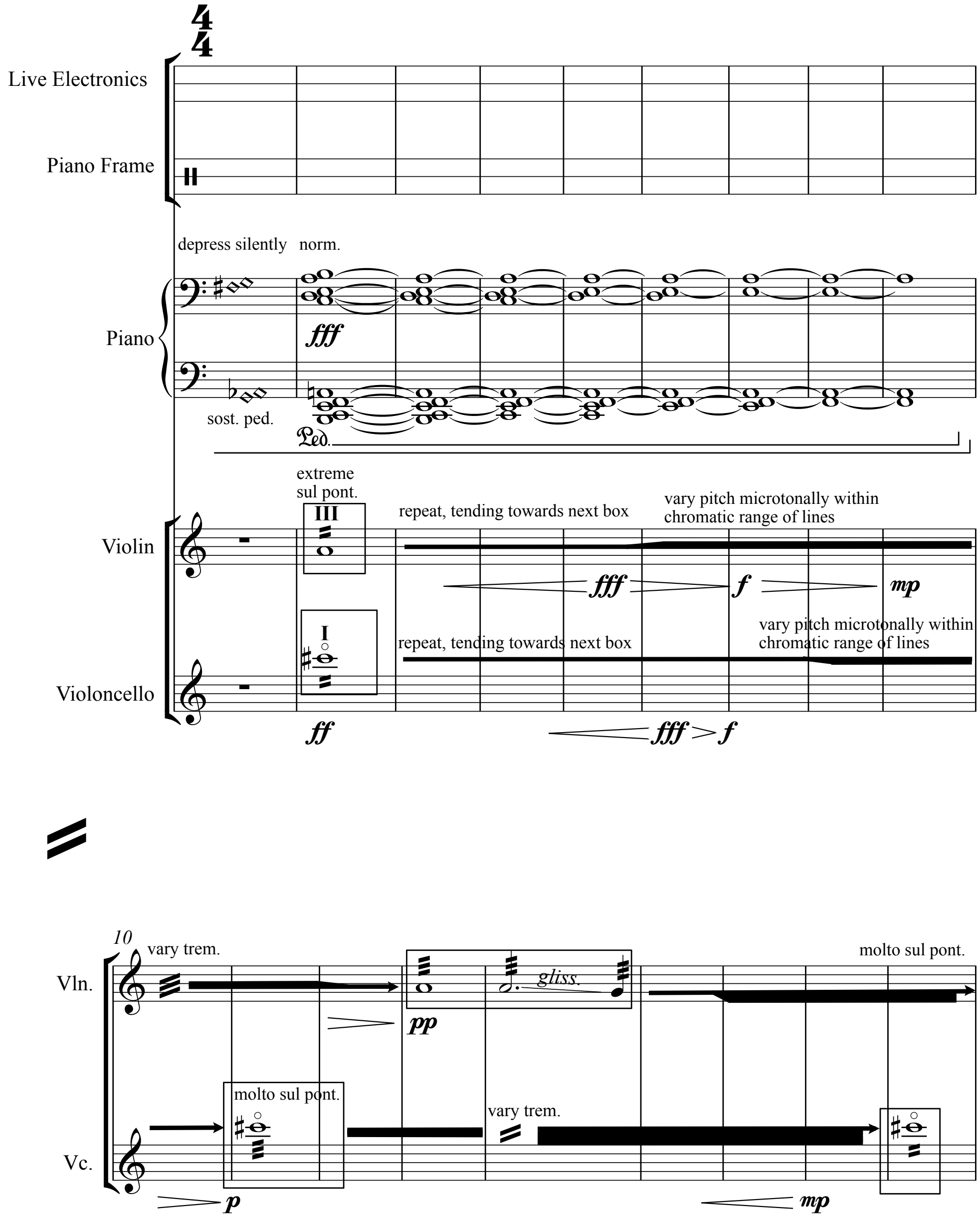
In **section D** vertical lines indicate that the performer should choose a pitch related to the instrument suggested. The idea is to create a sense of there being 'one' instrument or sound.

♩ = ca. 120
struggling & scurrying

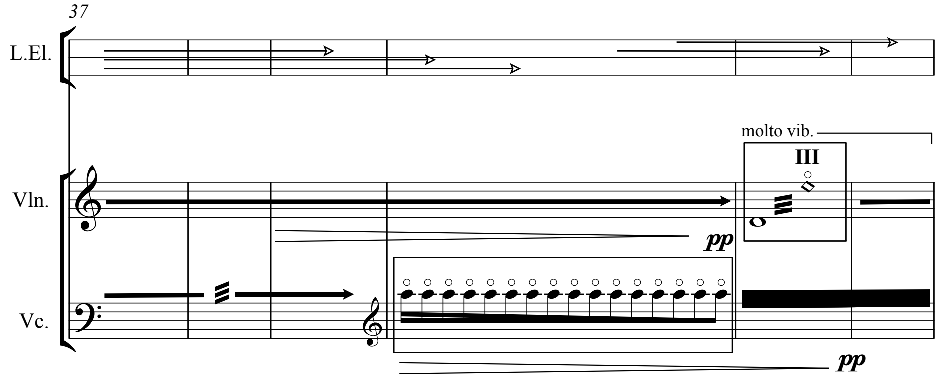
Running Backwards, Uphill

♩ = ca. 120
struggling & scurrying

Lauren Sarah Hayes



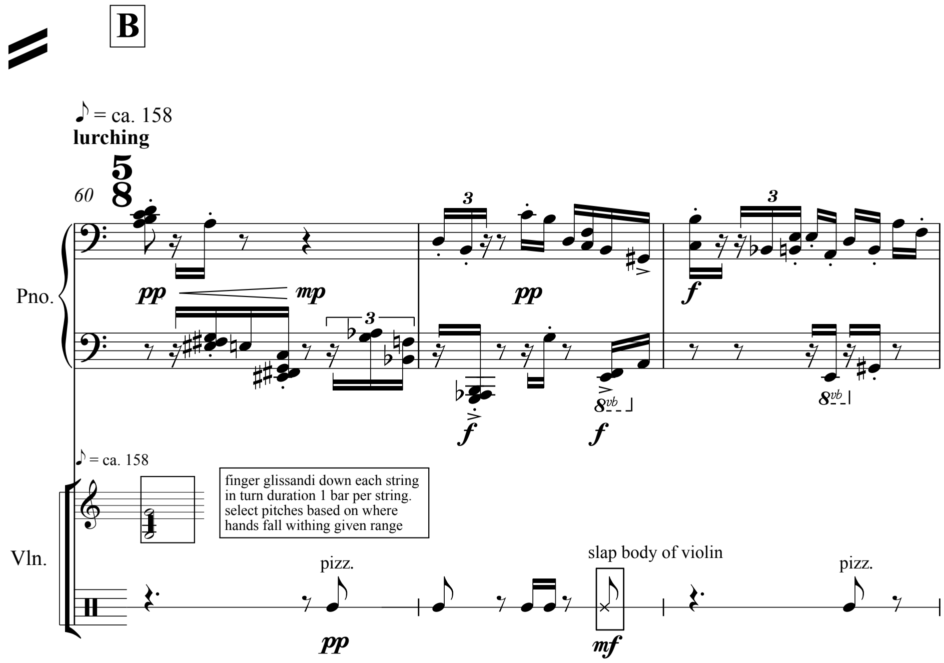

19
Vln.
Vc.
mp
sul pont.
I
p
25
molto sul pont.
III
mf
molto sul pont.
27
L.El.
ring mod.
repeat & permutate note order
sul pont.
f
32
vary pitch within chromatic range of lines
II
mp
sul pont.

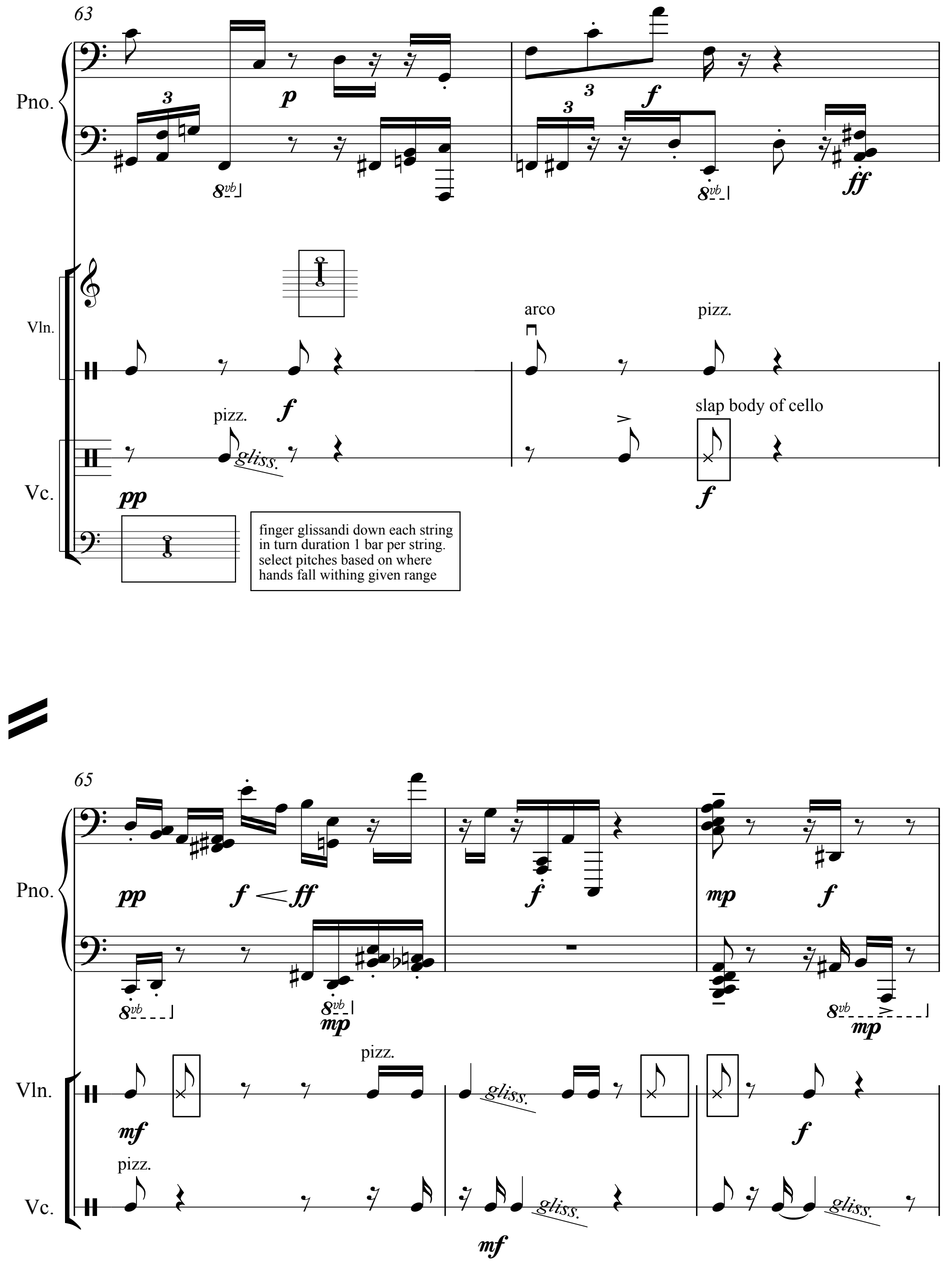

37
L.El.
Vln.
Vc.
molto vib.
III
pp
pp


43
L.El.
Pno.
Vln.
Vc.
A
live sampling
clumsily, with hands almost falling off keys
pp
3
A
mf
gliss.
II
pp


48
L.El.
Pno.
Vln.
Vc.
sul pont.
repeat & permutate note order
54
molto sul pont.
II
gliss.
molto sul pont.


57
L.El.
Pno.
8va
f
mp
8vb
repeat & permutate note order
Vln.
p
Vc.
p


B
♪ = ca. 158
lurching
60
Pno.
pp
mp
pp
f
f
f
8vb
♪ = ca. 158
finger glissandi down each string in turn duration 1 bar per string. select pitches based on where hands fall withing given range
Vln.
pizz.
pp
slap body of violin
mf
pizz.


63
Pno.
p
3
8vb
f
ff
Vln.
arco
pizz.
f
Vc.
pizz.
gliss.
pp
slap body of cello
f
finger glissandi down each string in turn duration 1 bar per string. select pitches based on where hands fall withing given range
65
Pno.
pp
f
ff
mp
8vb
Vln.
mf
pizz.
gliss.
Vc.
pizz.
gliss.
mf


68
sample triggering via pitch following.
L.El.
Pno.
chromatic
Vln.
arco
pizz.
arco
ric.
Vc.
71
chromatic
gliss.
arco
pizz.

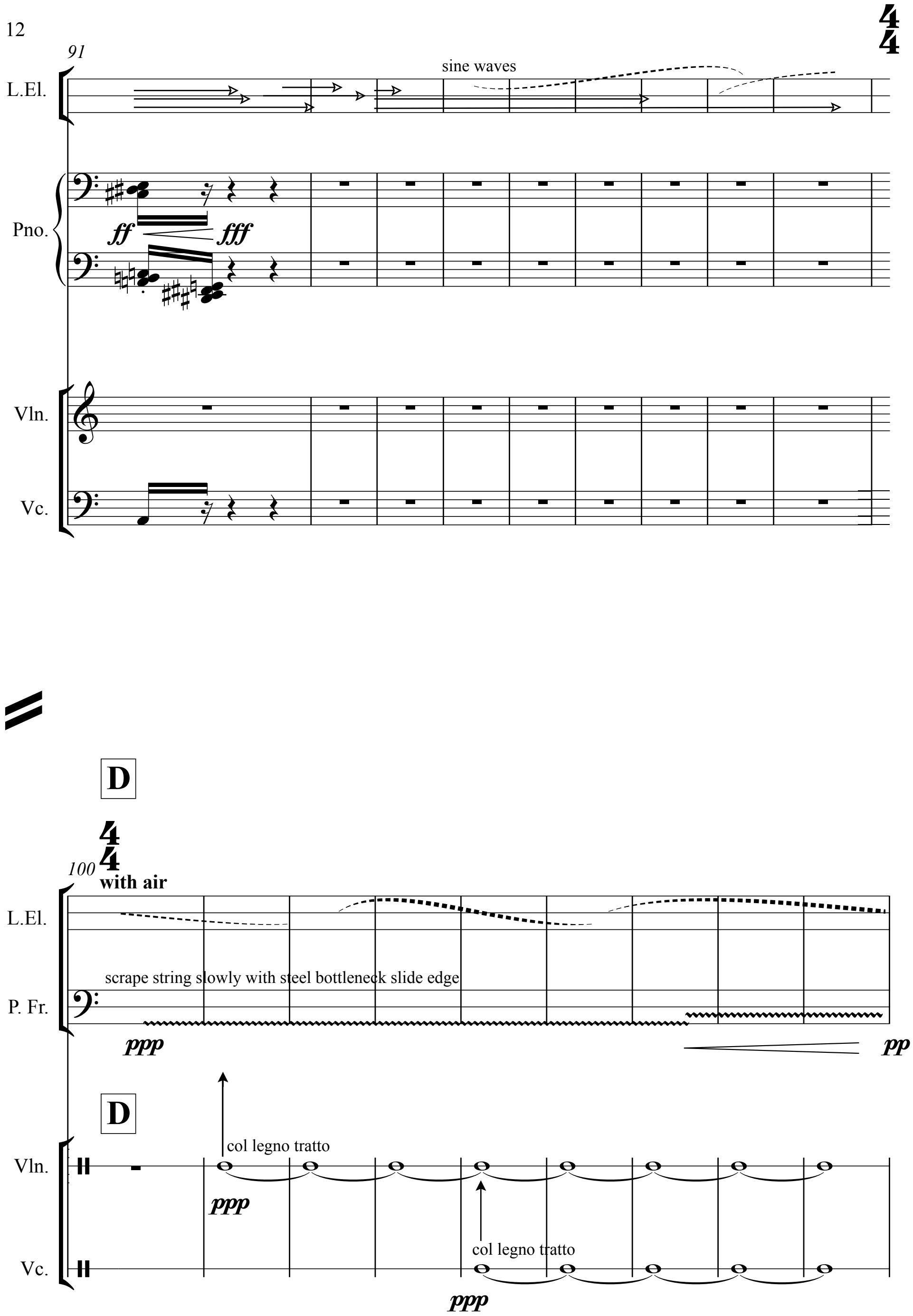

73
L.El.
Pno.
3
Vln.
arco
f
Vc.
arco
f
75
L.El.
Pno.
3
Vln.
gliss.
3
gliss.
gliss.
mf
Vc.
pizz.
gliss.
mf


77
L.El.
Pno.
Vln.
Vc.
gliss.
gliss.
gliss.
gliss.
3
p
pizz.
arco
79
L.El.
Pno.
Vln.
Vc.
mf
f
3
3
3
ff
8vb
8vb
spicc.
f
spicc.
f

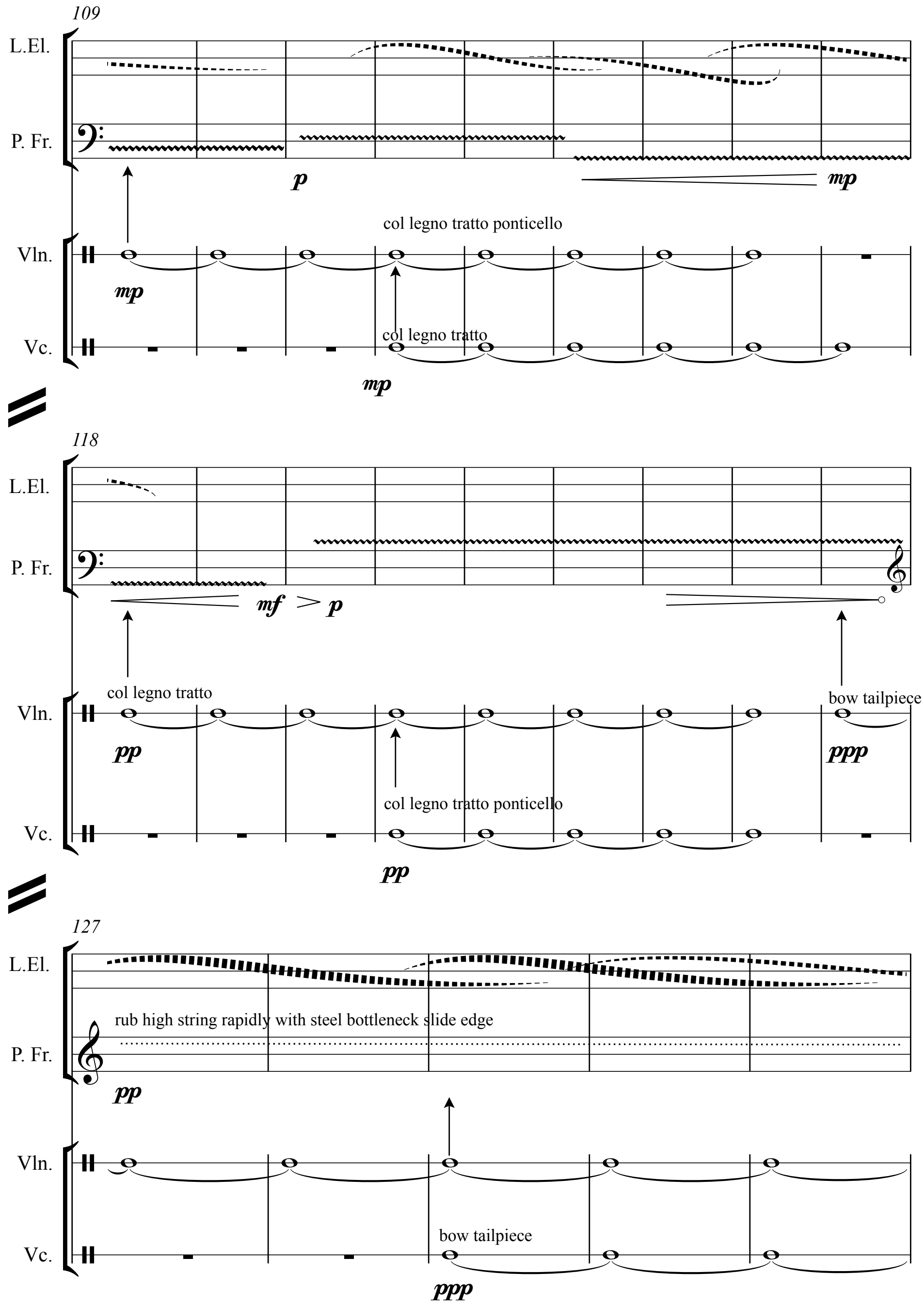

83
C
L.El.
Pno.
C
arco.
Vln.
arco.
Vc.
85
L.El.
Pno.
spicc.
Vln.
spicc.
Vc.

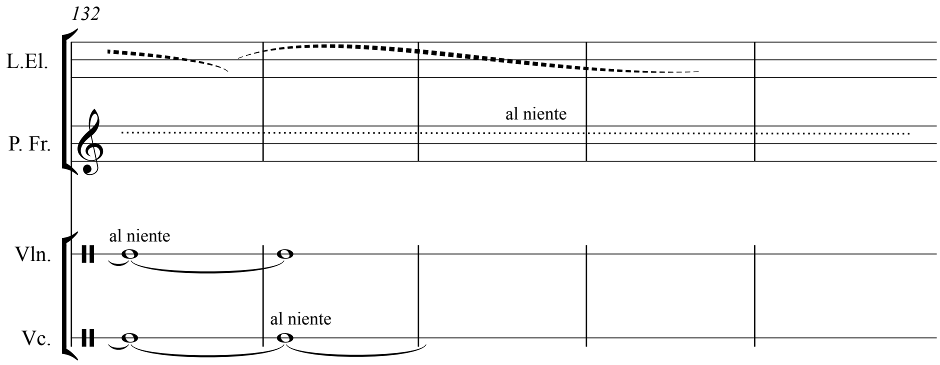

87
L.El.
Pno.
Vln.
Vc.
3
mp
ff


89
L.El.
Pno.
Vln.
Vc.
3
ff
pp
f
ff



91
sine waves
L.El.
Pno.
ff
fff
Vln.
Vc.
D
100
with air
L.El.
scrape string slowly with steel bottleneck slide edge
P. Fr.
ppp
pp
D
col legno tratto
Vln.
ppp
col legno tratto
Vc.
ppp


109
L.El.
P. Fr.
p
mp
col legno tratto ponticello
Vln.
mp
col legno tratto
Vc.
mp
118
L.El.
P. Fr.
mf > p
col legno tratto
bow tailpiece
Vln.
pp
ppp
col legno tratto ponticello
Vc.
pp
127
L.El.
rub high string rapidly with steel bottleneck slide edge
P. Fr.
pp
Vln.
bow tailpiece
Vc.
ppp


132
L.El.
P. Fr.
al niente
Vln.
al niente
Vc.
al niente

Appendix D

Sungazing

This appendix describes the portfolio composition ***Sungazing*** (2011) for bass clarinet, trombone and AlphaSphere.

D.1 Portfolio Content

Files are located in */portfolio/Sungazing* on the accompanying DVD.

Sungazing (2012) was performed by the Red Note ensemble as part of the Inventor Composer Coaction, at the Jam House, Edinburgh, 9th May, 2012. The Inventor Composer Coaction was a project that I directed with Tom Mudd and Christos Michalakos, developed to facilitate collaboration between composers and inventors of new digital instruments. It was funded by the Roberts Fund for Researcher-Led Initiatives and an Innovation Initiative Grant from the Edinburgh Fund.

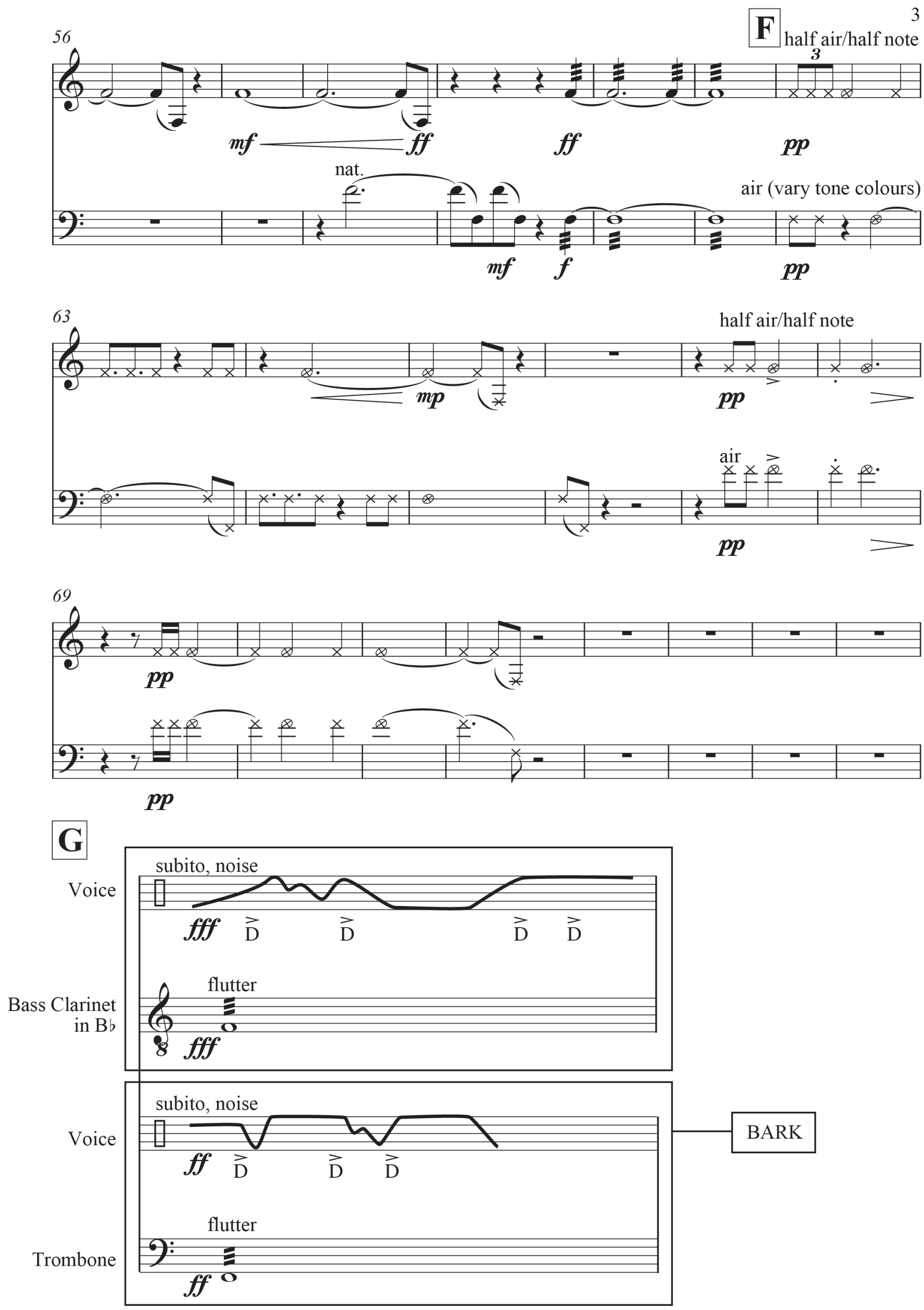
The portfolio version `lsh_Sungazing.mov` is a video recording from the live performance, with Pete Furniss (bass clarinet) and John Kenny (trombone). An audio version of the same performance has also been included `lsh_Sungazing.wav`. This was the first public performance using the AlphaSphere, which I discuss in Chapter 5. The AlphaSphere comes with its own software, called AlphaLive which has not been included as it was only in the prototype testing phase when I used it.

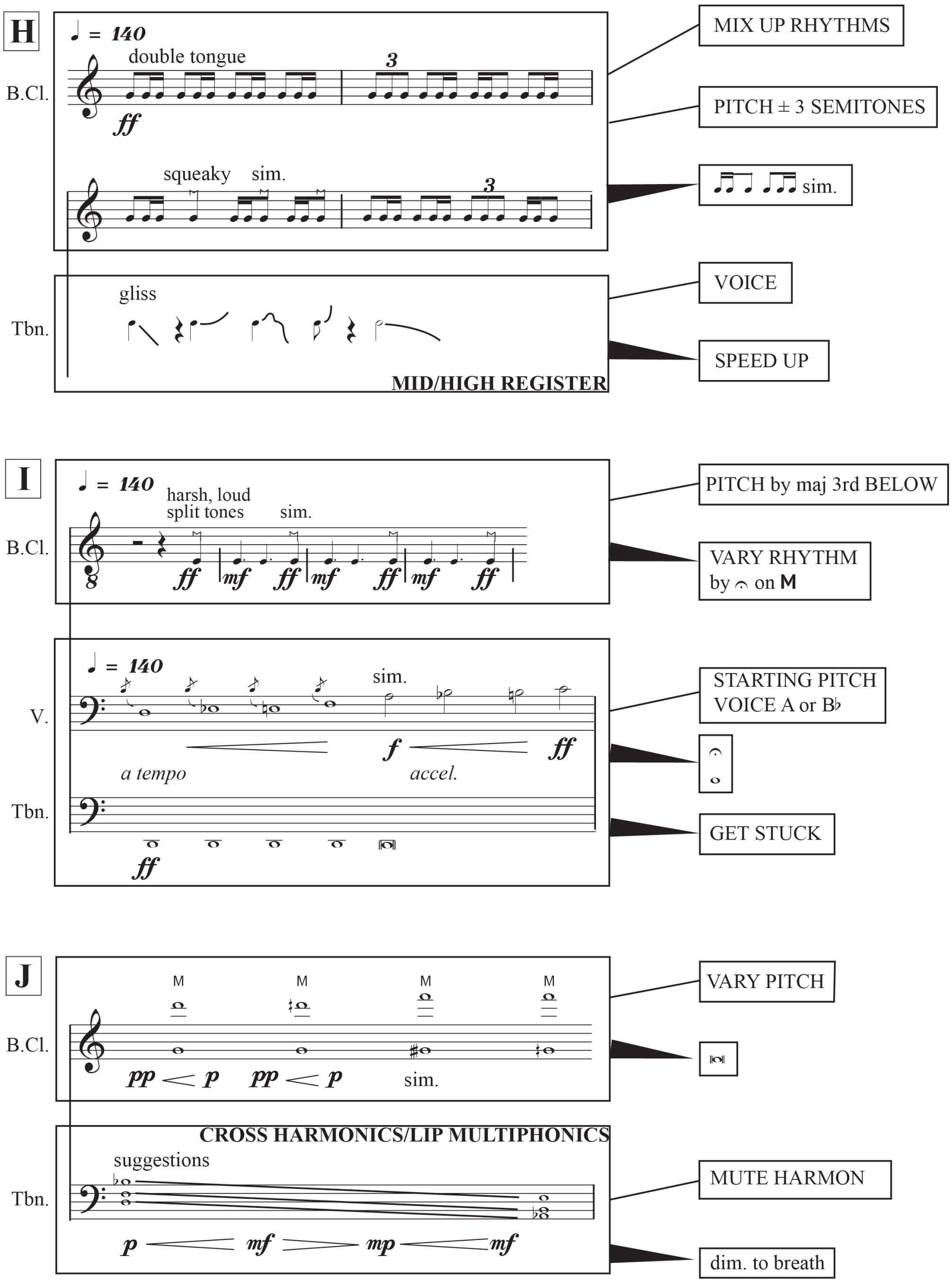
D.2 Score

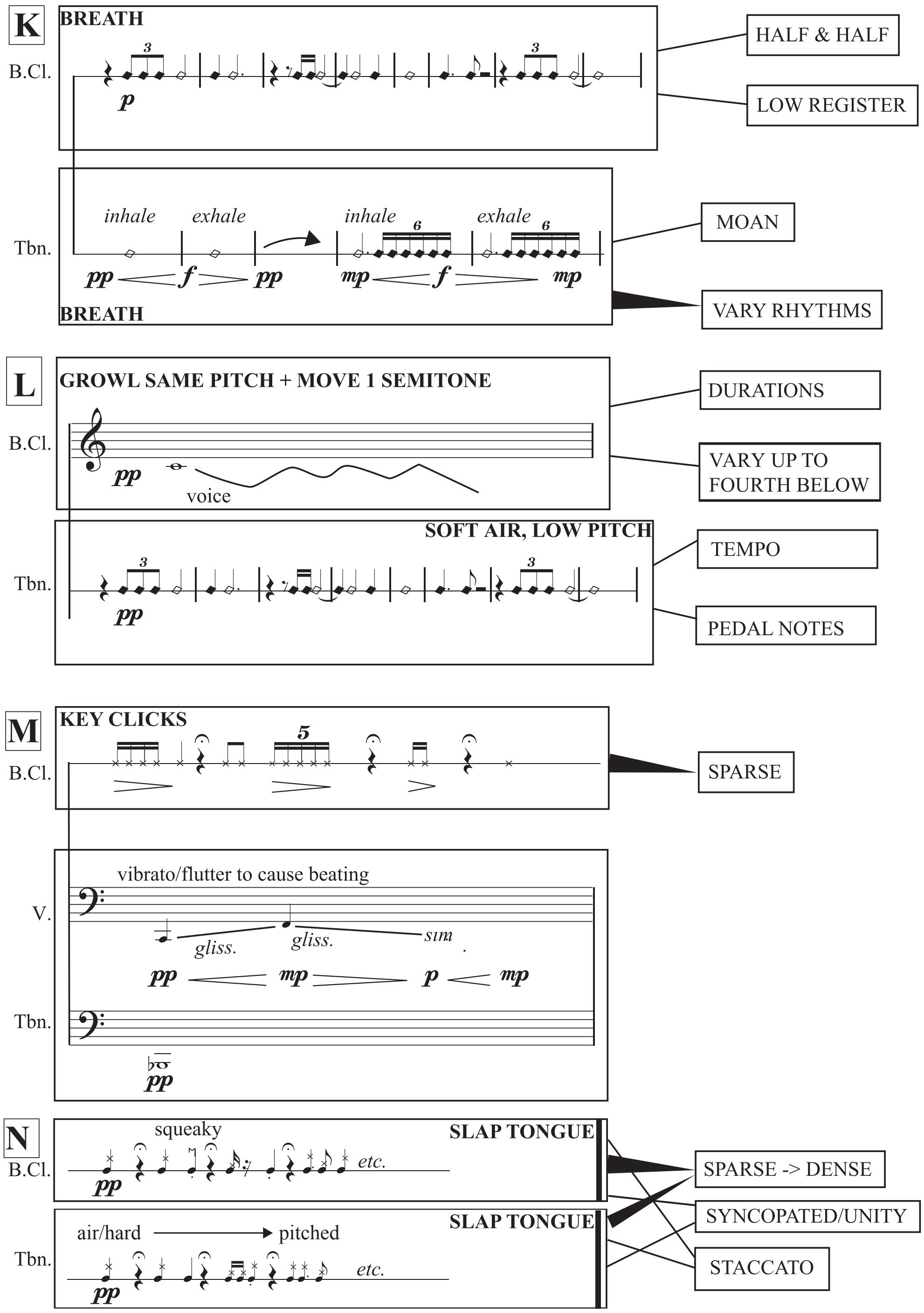
Sungazing

Lauren Sarah Hayes
2012


25
cresc.
31
D
37
E
44
50
flutter
nat.
flutter
nat.


3
56
F
half air/half note
3
mf
ff
ff
pp
nat.
air (vary tone colours)
mf
f
pp
63
half air/half note
mp
pp
air
pp
69
pp
pp
G
subito, noise
Voice
fff
D
D
D
D
Bass Clarinet in B♭
flutter
fff
subito, noise
Voice
ff
D
D
D
BARK
Trombone
flutter
ff


H
B.Cl.
♩ = 140
double tongue
3
ff
squeaky sim.
3
MIX UP RHYTHMS
PITCH ± 3 SEMITONES
sim.
Tbn.
gliss
MID/HIGH REGISTER
VOICE
SPEED UP
I
B.Cl.
♩ = 140
harsh, loud
split tones
sim.
ff mf ff mf ff mf ff
PITCH by maj 3rd BELOW
VARY RHYTHM
by 𝄐 on M
V.
♩ = 140
sim.
f ff
a tempo
accel.
Tbn.
ff
STARTING PITCH
VOICE A or B♭
GET STUCK
J
B.Cl.
M M M M
pp < p pp < p sim.
VARY PITCH
CROSS HARMONICS/LIP MULTIPHONICS
suggestions
Tbn.
p mf mp mf
MUTE HARMON
dim. to breath


K
BREATH
B.Cl.
3
p
HALF & HALF
LOW REGISTER
inhale
exhale
inhale
exhale
6
6
Tbn.
pp
f
pp
mp
f
mp
BREATH
MOAN
VARY RHYTHMS
L
GROWL SAME PITCH + MOVE 1 SEMITONE
B.Cl.
pp
voice
DURATIONS
VARY UP TO
FOURTH BELOW
SOFT AIR, LOW PITCH
Tbn.
3
3
pp
TEMPO
PEDAL NOTES
M
KEY CLICKS
B.Cl.
5
SPARSE
vibrato/flutter to cause beating
V.
gliss.
gliss.
sim
pp
mp
p
mp
Tbn.
pp
N
squeaky
SLAP TONGUE
B.Cl.
etc.
pp
air/hard
pitched
SLAP TONGUE
Tbn.
etc.
pp
SPARSE -> DENSE
SYNCOPATED/UNITY
STACCATO

Appendix E

Figuring-Operated String

This appendix describes the portfolio composition ***Figurine-Operated String*** (2012) for piano and live electronics.

E.1 Portfolio Content

Files are located in `/portfolio/FigurineOperatedString` on the accompanying DVD.

Figurine-Operated String (2012) has received several national performances to date, including INTER/actions (Bangor), Sonorities Festival of Contemporary Music (Belfast), and Interactive Keyboard Symposium (London) (see Section 1.6.1 for the full list of performances. The portfolio contains two versions of the piece: `lsh_figurineOperatedString.mov` is a video recording from a performance in the Reid Hall, Edinburgh, 29th May, 2013. Unfortunately the audio recording was damaged from this performance and so the camera audio has been used. A fully mastered audio version of an alternative performance in the Reid Hall has also been included `lsh_figurineOperatedString.wav`. The piece has been performed in various concert halls using different grand pianos. The electronic samples used in this piece were recorded on the Buchla 200 analogue synthesiser at Elektronmusikstudion (EMS), Stockholm, during an artistic residency in November, 2011.

E.2 Performance Requirements

E.2.1 Gametrak Controller

The Mad Catz Gametrak is the controller used in this piece to provide resistance to the performer and position vectors for control data (see Figure E.2.1). The cheap game controller can be found online in stores and costs around £4. The device requires some simple hacking[1] to allow it to be readable within Max/MSP.

[1] This tutorial illustrates how to hack the Gametrak for use within Max/MSP: http://janoc.rd-h.com/archives/129 [accessed 23rd August 2013].

Figure E.1: Mad Catz Gametrak controller.

The piece also requires the wireless vibrotactile feedback device (see Appendix G), which again enables the laptop screen to be dimmed and pushed aside before the performance.

E.2.2 Technical Requirements

- grand piano
- 2 microphones (condenser, e.g. Neumann KM 184)
- 2 DPA 4061 miniature microphones with BLM6000 Boundary Layer Mount or similar
- 4 channel sound-card
- 2 loudspeakers, plus adequate monitoring for performer
- 2 microphone pre-amps, e.g. API 3124
- mixer
- Gametrak controller
- laptop or computer running Max6
- piezoelectric contact microphone
- wireless vibrotactile device
- objects for extended techniques: 2 bullet magnets, 1 steel guitar slide, 2 bouncing balls, shot glasses, small paint roller, combs or small hair brushes (see Figure E.2.2)

The DPA microphones should be placed underneath the piano with the boundary attachments. These are connected directly to inputs 1 & 2 of the sound card. The piezoelectric contact microphone is connected to input 3 and should be placed inside the piano on the left-hand side of the keyboard, on top of the pegs. All other small items should be placed Monitors should be placed on either side of the

E.2.3 Software Requirements

The Max/MSP patch has been tested on an Intel Macbook Pro 4GB internal RAM using Max6 Version 6.0.7 and can be found as a Max project in `/portfolio/FigurineOperatedString/code` on the accompanying DVD. The vibrotactile device (version 2) should be connected before the patch is opened (see Appendix G for details), as should the Gametrak. To test for correct microphone level, the `ezdac` should be turned on and beginning the piece *sforzando* should trigger the electronic sound. It should not be activated unless *sforzando* is played.

Figure E.2: Objects for extended techniques: paint roller, hair brush, small contact microphone, shot glasses.

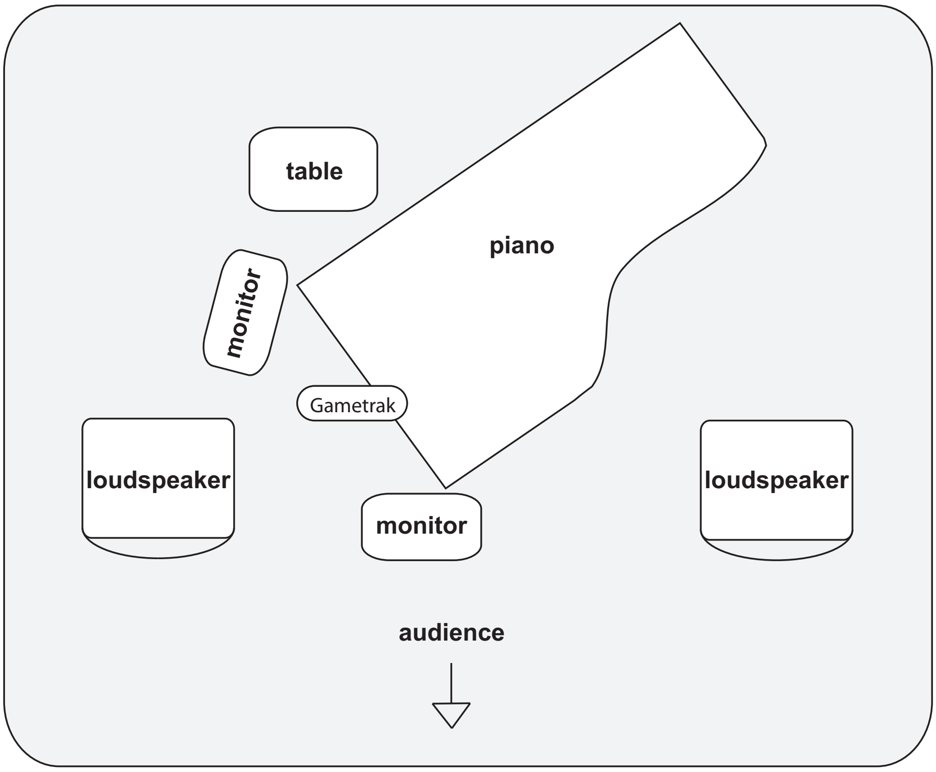


Figure E.3: Stage layout.

E.2.4 Structured Improvisation

As discussed in 3.2.1, due to the individualisation of the performance environments, the portfolio pieces have been built around my own physiology and have not been performed by other musicians. I do not perform these works from scores, and the textual documentation—aside from the technical and software material—is minimal. In Malm(̈o), Sweden, on 4th April, 2013, I performed a work from my master's degree portfolio that was written in 2009. The piece had a documentation similar to the notes written below and yet, due to being largely based around improvisation, was successfully performed. As such I include the informal notes from a sketchbook that I consider to be sufficient detail of the piece as I have no current desire for it to be performed by another pianist. Much of the information is tacit, learned only by feeling the resistance both of the game controller and the sonic material.

Begin with silence, seated on stool wearing gloves and vibrotactile feedback device.

Section 2: trigger with ***sf*** on bass notes, moving between low and high registers.

Continue to 3: to cross over between high and low, freezing on the upper register.

Reach to 4: once a particular stasis has been reached on the upper register, grab paint roller and reach both hands slowly upwards inside the piano. Create harmonics with paint roller in left hand.

Drop right hand down to move to section 5.

Again reach inside after putting down roller with magnets.

Trigger ring modulation on the keys with both hands.

Section 8 is triggered by a clean cut using the piezoelectric microphone to scrape the bass strings.

Move between this and bouncing balls, triggering section 9 my moving around the keyboard.

10 is the only timed section, arriving 2 minutes after section 9.

Reach to the upper right-hand strings inside with the comb to trigger 11 and record the combed strings.

Drop down to start the final section, a cacophony of filtered sounds.

End by gradually lowering arms and then hands down below the keyboard.

Appendix F

subspace

This appendix describes the portfolio composition ***subspace*** (2013) for string quartet and live electronics.

F.1 Portfolio Content

Files are located in */portfolio/subspace* on the accompanying DVD. This piece was workshopped at Heriot Toun Studio, Scottish Borders on 5th February, 2013. The recording included in the portfolio is the last run through of the piece during the workshop, recorded by Ben Seal: `lsh_subspace.wav`.

F.2 Performance Requirements

F.2.1 Software Requirements

The Max/MSP patch has been tested on an Intel Macbook Pro 4GB internal RAM using Max6 Version 6.0.7 and can be found as a Max project in */portfolio/subspace/code* on the accompanying DVD. The vibrotactile devices (version 2) should be connected and switched on before the patch is opened (see Appendix G for details). As this is a work in progress, the patch illustrates only the vibrotactile score. While this requires python libraries and hardware (see Appendix G) which are not available here, it can be used to demonstrate a visual representation of the vibrotactile score in Sections 1 and 3 of the piece.

F.3 Score

The piece is divided into three sections. The first section is based around improvisation seeds, where each performer is instructed to begin in the centre cell (see Figure F.3 and proceed upwards as indicated by the vibrotactile feedback in the form of a short buzz. Regardless of which point they reach along a certain path, when they receive three short buzzes, they must return to the centre cell and proceed along another path. Figure F.3 shows the first violin part arranged in the star formation, which can be seen in more detail at the end of this section.

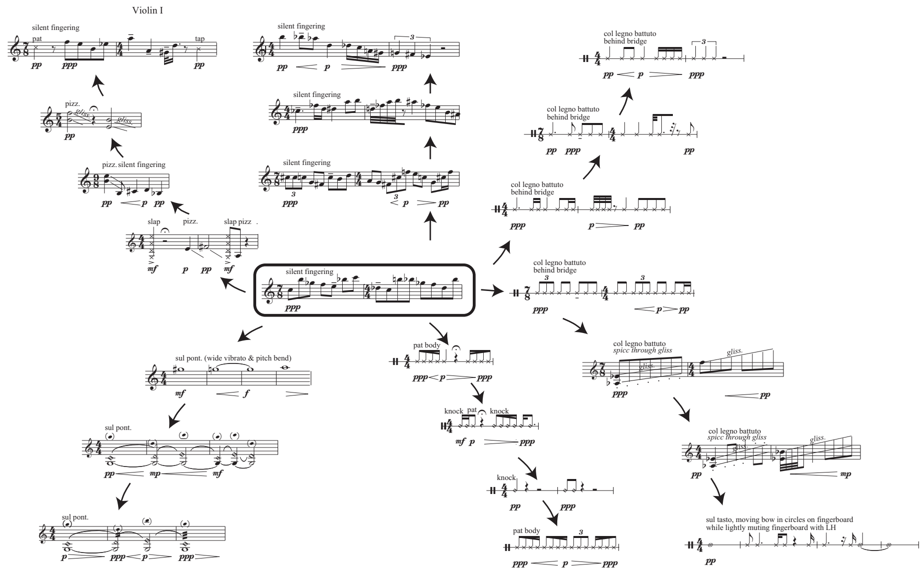


Figure F.1: Star formation score with improvisation seeds.

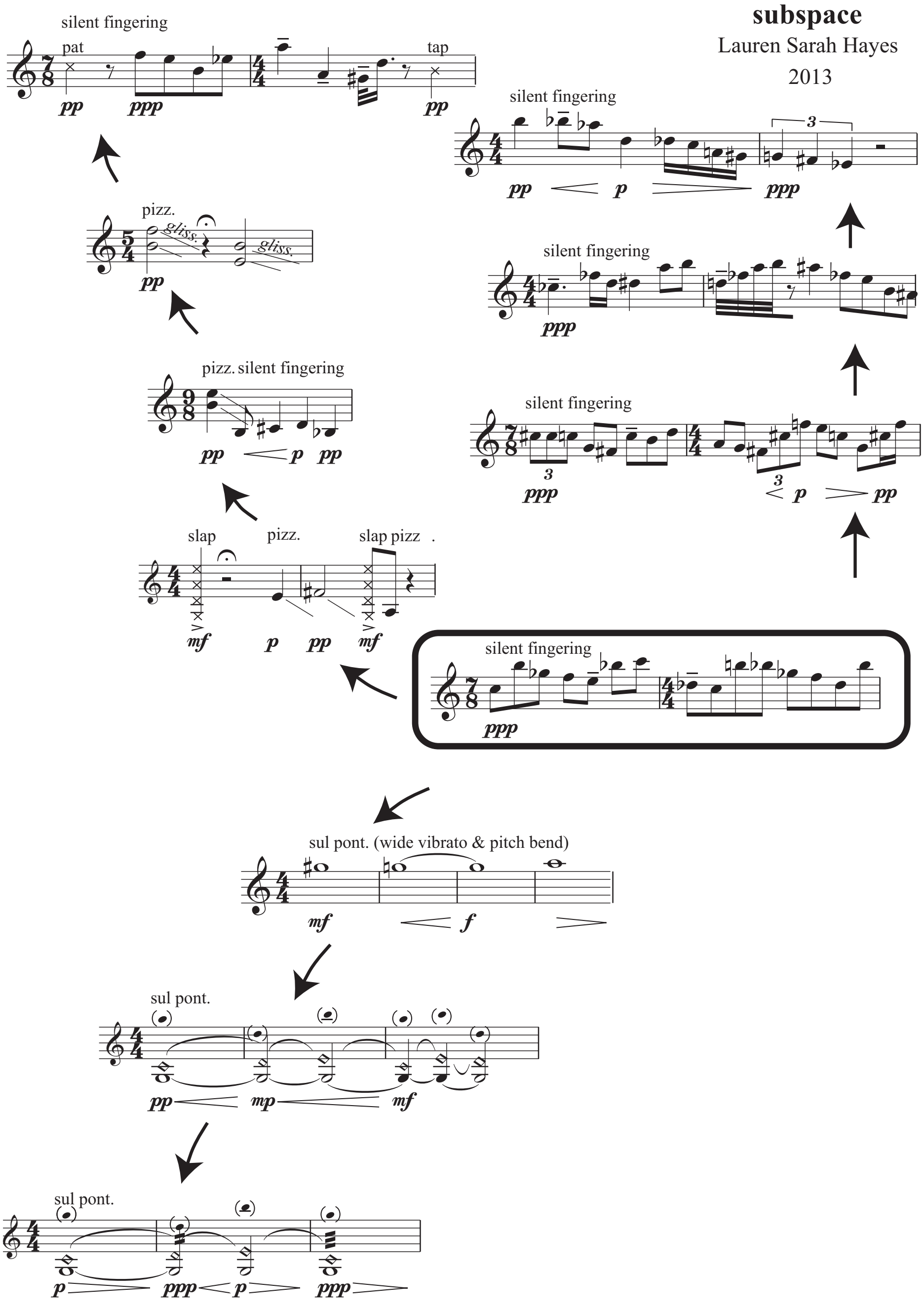
The middle section of the piece was improvised around natural harmonics both on string instruments and the Korg MS20 analogue synthesiser.

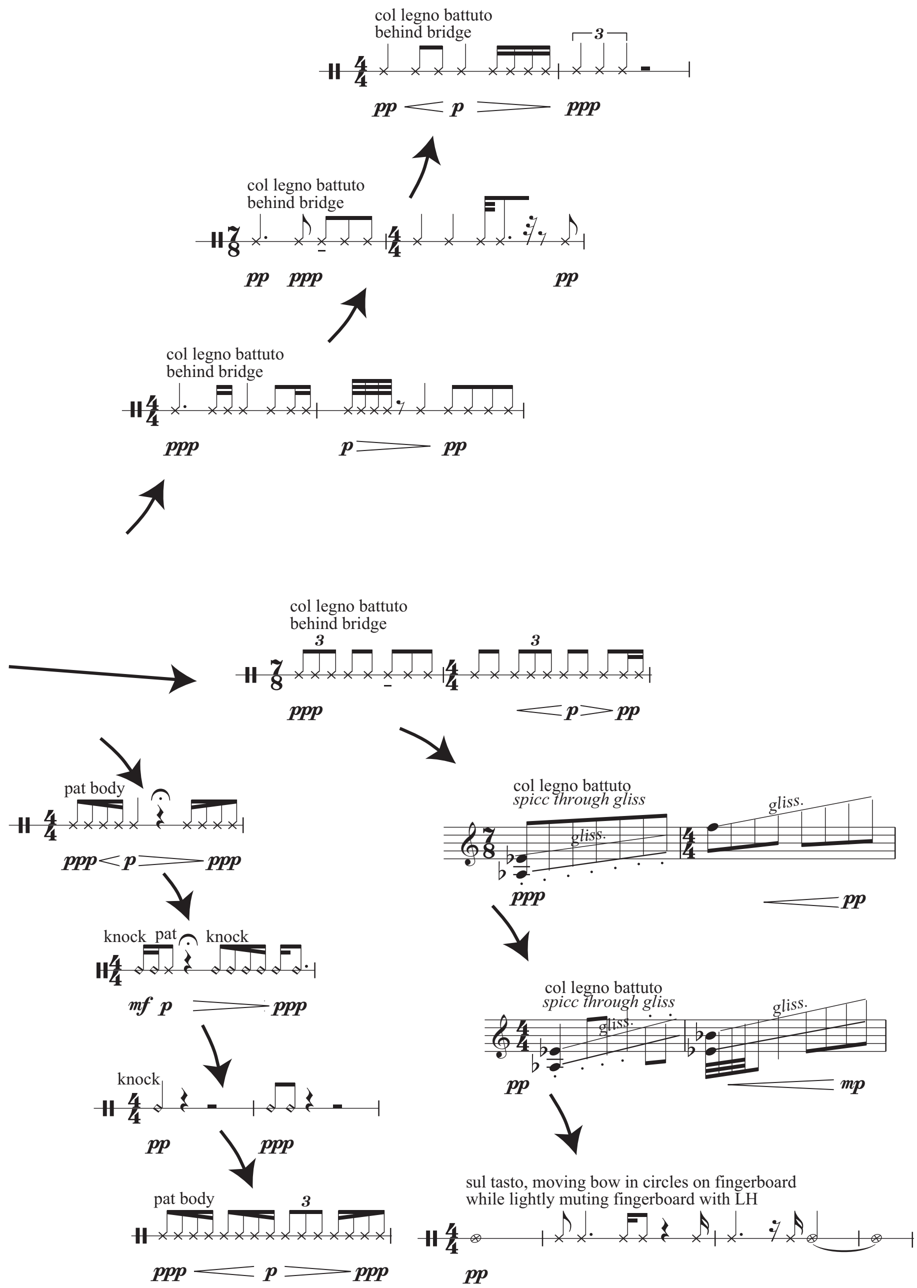
The final section of the piece requires the performers to play loud, short, sharp attack sounds, as directed by strong single buzzes from the vibrotactile feedback. This is discussed in Section 4.2.3.

subspace

Lauren Sarah Hayes

2013





col legno battuto
behind bridge
pp p ppp
col legno battuto
behind bridge
pp ppp pp
col legno battuto
behind bridge
ppp p pp
col legno battuto
behind bridge
ppp p pp
pat body
ppp p ppp
knock pat knock
mf p ppp
knock
pp ppp
pat body
ppp p ppp
col legno battuto
spicc through gliss
gliss.
gliss.
ppp pp
col legno battuto
spicc through gliss
gliss.
gliss.
pp mp
sul tasto, moving bow in circles on fingerboard
while lightly muting fingerboard with LH
pp

Appendix G

Vibrotactile Feedback Devices

This section discusses the technological developments of the vibrotactile feedback system, discussed in Chapter 4.

G.1 Version 1: USB powered

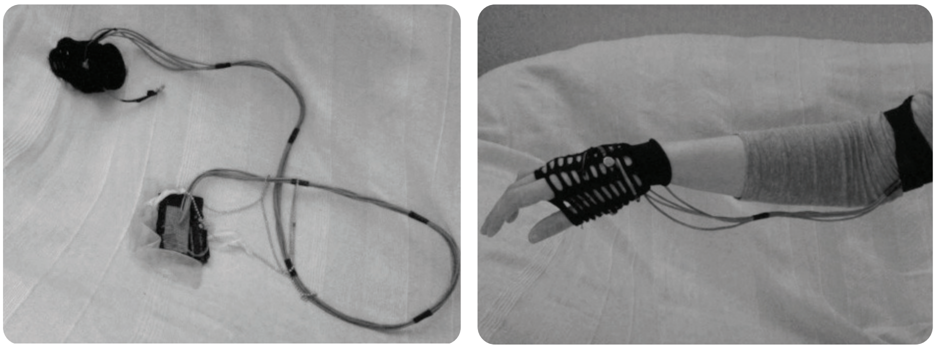


Figure G.1: First version of vibrotactile feedback glove.

The device was built using a standard Arduino, with three pager motors connected across the pulse width modulation pins using a rectifier diode circuit (see Figure G.2).

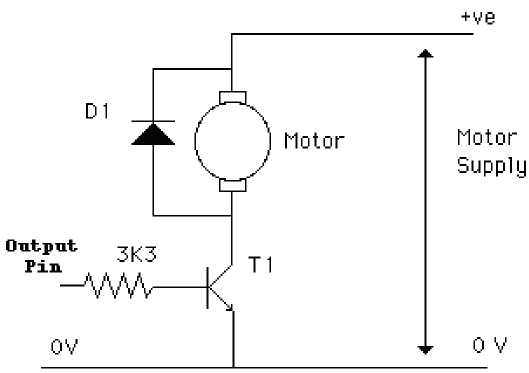


Figure G.2: Motor driving circuit using rectifier diode.

G.2 Version 2: wireless

Due to the restrictions of the USB cable, I wanted to make the system wireless so that it could be used with multiple performers (see Section 4.2.3). In April, 2010, I went back to STEIM, Amsterdam for a residency to work with Marije Baalman to develop the wireless system. We worked with her SenseStage MiniBee system, which can allow up to 50 wireless nodes to be connected[1].

Using a python interface (see Figure G.3), OSC messages can be sent from within Max/MSP out to the different modules.

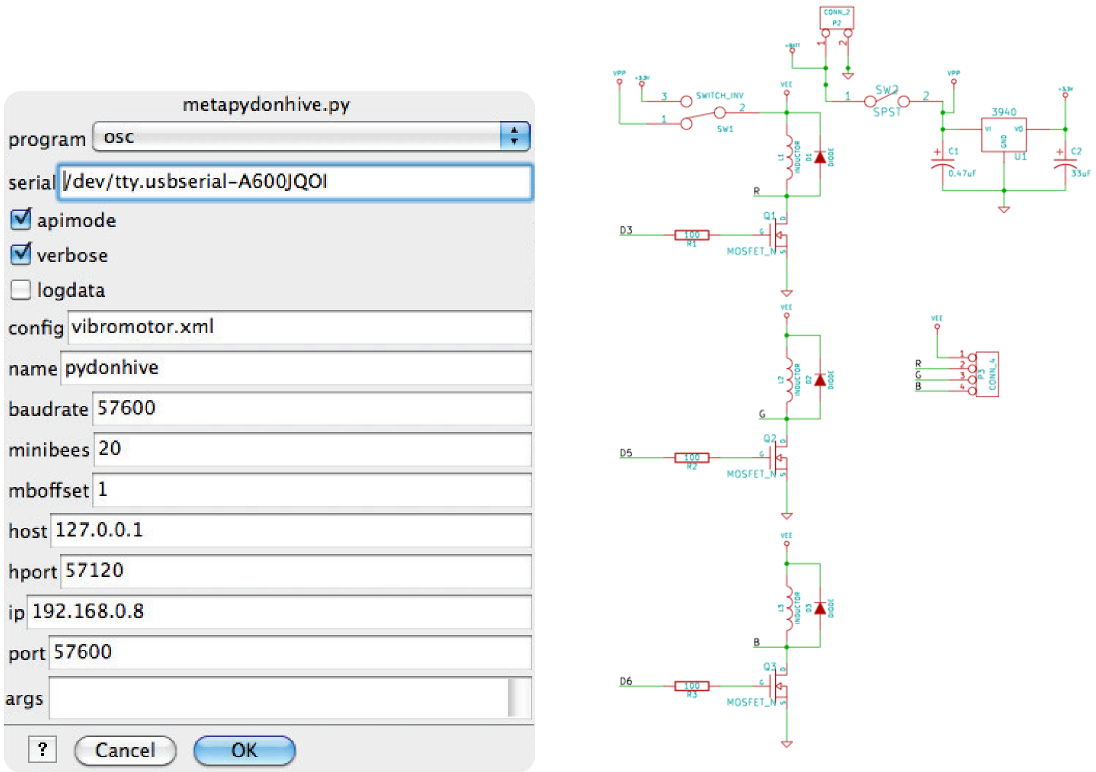


Figure G.3: Python interface for OSC messages and Marije Baalman's updated MOSFET vibration motor circuit

The device casing and wearable technology was designed and created by Tobias Feltus (see Figure G.4 and Section 4.2.3.1).

[1]http://www.sensestage.eu/ [accessed 24th August 2013]

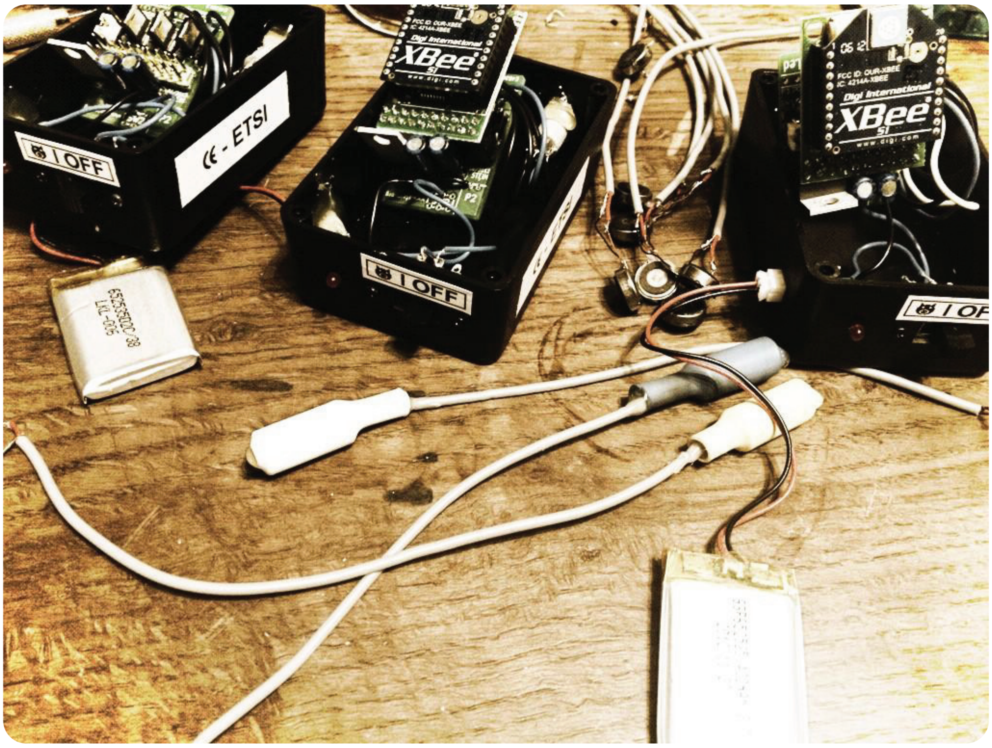


Figure G.4: Tobias Feltus' casing for wireless xBee system.

Appendix H

Publications

H.1 Vibrotactile Feedback-Assisted Performance

Hayes, L. (2011). Vibrotactile Feedback-Assisted Performance. In Proceedings of the International Conference on New Interfaces for Musical Expression (pp. 72-75). Oslo, Norway. http://www.nime2011.org/proceedings/papers/B12-Hayes.pdf [accessed 23rd August 2013]

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Vibrotactile Feedback-Assisted Performance

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ABSTRACT

When performing digital music it is important to be able to acquire a comparable level of sensitivity and control to what can be achieved with acoustic instruments. By examining the links between sound and touch, new compositional and performance strategies start to emerge for performers using digital instruments[1]. These involve technological implementations utilizing the haptic[2] information channels, offering insight into how our tacit knowledge of the physical world can be introduced to the digital domain, enforcing the view that sound is a 'species of touch' [14].

This document illustrates reasons why vibrotactile interfaces, which offer physical feedback to the performer, may be viewed as an important approach in addressing the limitations of current physical dynamic systems used to mediate the digital performer's control of various sorts of musical information. It will examine one such method used for performing in two different settings: with piano and live electronics, and laptop alone, where in both cases, feedback is artificially introduced to the performer's hands offering different information about what is occurring musically. The successes of this heuristic research will be assessed, along with a discussion of future directions of experimentation.

Keywords

Vibrotactile feedback, human-computer interfaces, digital composition, real-time performance, augmented instruments.

1. INTRODUCTION

Being arguably the most highly developed of the senses [5], the importance of touch is often, it will here be suggested, erroneously overlooked in human-computer musical systems. This paper examines some possible advantages in exploring the audio-tactile link for practitioners of digital music, and will propose introducing vibrotactile feedback as a new strategy for improving performance in the field. An assessment will be presented of what has been lost, in terms of interaction, in the move from traditional acoustic instruments to commercial interfaces for digital music. This will be followed by a discourse on using vibrotactile signals, directly applied to the performer's hands, as a means of communicating information about the music and score during a performance. The theoretical ideas are put forth in relation to the creative practice of the author; the output of this work being original compositions and improvisations. Links to audio[3]. and video[4] examples of these works have been provided for reference.

[1]Instrument is used here to encompass the entire system which may include: human-computer interface(s), computer, bespoke software, loudspeakers and so on.
[2]Related to the modality of touch.

2. SOUND AND TOUCH

2.1 Haptics

When hungarian psychologist Revesz first introduced the word haptic, from the Greek *haptesta* (to touch), in 1931 [3], it was used to describe the process of actively exploring a shape or spatial dimension with the hands, discussed in the context of his research on blindness and its profound effects on the other senses. He contrasted this process with the event of indirectly sensing something on the skin (*ibid.*), such as experiencing differences in temperature or feeling something brush against the body. However, when discussed in terms of human-computer interfaces, the word haptics is often used as an umbrella term encompassing both the active information gathering that Revesz described, as well as the tactile sensations that he classed separately, and additionally, kinaesthetic information about the body in relation to space [12].

Haptic devices are carefully designed interfaces that usually involve some type of actuator or mechanical device, such as small vibrating motors. Their purpose is to improve the translation of gesture between the physical world and the digital realm by considering both the body's kinaesthetic system, which detects position and motor control of muscles and joints, as well as the tactile sensors in the skin, which are extremely sensitive and capable of detecting highly complex patterns of information [6].

2.2 Instruments

2.2.1 *Acoustic Instruments*

The skin's sensing nerves are most densely collected in the lips and hands [9], [12]; since most acoustic instruments are constructed to be played with the mouth or fingertips, this distribution of sensors in the skin allows for the maximum amount of information exchange. During engagement with the instrument, the performer receives feedback in the form of various resistant forces and vibrations (for example, the

[3]Audio recording of improvisation for laptop using vibro-tactile feedback device: http://soundcloud.com/elleesaich/multifingeredbodyparts
[4]Video of *kontroll* for prepared piano, self-playing snare and live electronics: http://www.vimeo.com/13493035

vibration of guitar strings, along with the force of the fingers on the strings).

This haptic information supports the auditory feedback received through the ears as sound is made. Hence a closed feedback loop is created: the performer makes a sound, which is heard and also perceived physically, judged, and considered before the next sound is made. This process occurs in a very short space of time and is constantly ongoing throughout musical play: the auditory and haptic feedback is immediate, with the latter signals received perhaps almost subconsciously. Certainly while the amount of force used to strike keys while playing the piano is a conscious consideration, vibrations received through the feet may not be consciously perceived, but are no doubt significant in creating the collective feedback information being received. As Cadoz claims, this bidirectional information exchange 'provides us with manipulation possibilities and even signals the nature of the sound phenomenon itself.' [1] Furthermore, this entire process is uniquely private to the performer, compared to noticeable *visual* exchanges that may occur within a group performance setting.

2.2.2 Digital Musical Interfaces

In general, digital interfaces generally offer significantly less feedback to the performer. A MIDI keyboard may feature weighted keys, but cannot reveal any other information about the physicality of the sound being produced, compared to the great resonating body of an acoustic piano.

2.3 Tactile Feedback Principle

In 1978, Claude Cadoz proposed the tactile feedback principle in conjunction with his work at ACROE[5], Grenoble, France, where along with Jean-Loup Florens, he developed the first Retroactive Gestural Transducers (haptic devices). Their aim was to provide new insights into music creation by focusing on the instrument-performer relationship as fundamental to both the learning of the instrument and the development of the music itself, rather than simply providing improved ergonomics of gestural control in sound synthesis [1]. Cadoz claimed that any musical interface into the digital world must succeed on three levels: the gesture used to manipulate the device must be genuine in that the performer must be familiar with the type of movements being used with the controller. Secondly, the device must be able to accurately sense the characteristic behaviour of the gesture and information must not be lost. Finally, he claimed that the device must offer some resistance to the performer, which is in relationship to the nature of the simulated gesture process [1]. He calls this final aspect feedback, and deems it necessary to achieve mastery or perform with finesse.

2.4 Types of Haptic Devices

Human-computer haptic interfaces may be described as any device that incorporates an element of force feedback through actuators: mechanical systems that can offer a wide range of accurate motion, such as motors. Rovan and Hayward distinguish these devices from what they call tactile stimulators [12], which consist of, for example, small groups of pins that tap at the skin, vibrating at controllable frequencies to achieve different intensities. Thus Revesz's distinction between active and passive perception manifests itself in these contrasting systems: the vibro-tactile systems allow the user to passively experience sensations.

There is a huge amount of evidence to suggest that haptic perception can speed up learning [3], [9], thus allowing the relationship between performer and instrument to develop at a much faster rate than without feedback present. When describing his Modular Feedback Keyboard, Cadoz claimed that the aim was to create a 'synthesis of the instrument' [1], as well as the sound. Thus it would allow experimentation, musical play and would successfully couple the performer, instrument and space [1]. As Pedro Rebelo, researcher and composer at *SARC*, Belfast claims, it is useful to view the link between a performer and instrument as a 'multimodal participatory space (and not one of control)' [11]. The following sections will discuss the author's attempts to realise this idea as both composer and performer.

[5]Association pour la Création et la Recherche sur les Outils d'Expression

3. FEEDBACK-ASSISTED PERFORMANCE

3.1 Developments

There have been a minimal[6] number of instruments designed with vibrotactile feedback in mind. Marshall and Wanderley, CIRMMT, McGill University, describe the *Viblotar* and the *Vibloslide*[8] which each use small inbuilt speakers to produce both vibration, as well as sound, as feedback for the performer. As with acoustic instruments, in both these examples the sound source is located within the body of the physical instrument itself[7], and not dislocated in loud speakers: the physical feedback emerges concurrently with the sonic.

The aim of using of the vibrations of the speakers was to create "vibrations in a DMI [digital musical instrument] that are produced in a similar way to those of an acoustic instrument". Certainly this approach is an important one, in that it uses the paradigm of traditional instruments as a starting point for introducing haptic information to new digital instruments. The following two case studies offer an alternative approach where the vibrotactile feedback is not intended to emulate the feel of playing acoustic instruments, but rather as a signalling and suggestion system for the performer.

3.2 Case Study: Composition for Prepared Piano and Live Electronics

This work arose out of several compositions for prepared piano and electronics, for solo performer, where the performer would be in control of both the piano and the live electronics. As Emmerson claims, digital music interfaces should be both consistent in their response, as well as sensitive, so that even subtle movements and gestures may be accurately detected and used to affect the sound [4]. Thus it seemed plausible that using a touch-based acoustic instrument, namely the piano itself, as the interface into the digital world could be the solution to achieving mastery of the entire system[8]. By controlling all processes from the piano, the pianist may retain their touch-based sensitivity whilst yielding enough useful control data, via various analyses of the sound, to affect the digital signal. From this emerges what pianist Xenia Pestova describes as a 'further continuation of extended techniques' [10].

3.2.1 Score Following

Building on previous work involving a machine-listening system for prepared piano and live electronics, the goal with the new piece, *kontroll*, was to create a situation where the

[6]Marshall found instances of vibrotactile feedback implementation in less than 6% of new instruments at NIME from 2001 - 2008[7].

[7]Although external amplification is also permitted to increase sound quality.

[8]Rather than attaching MIDI controllers to the piano, which may disrupt the performance.

Figure 1: Simple glove with vibration motors, which connects to a laptop via an Arduino.

need to look at a laptop screen for visual feedback would be minimized or completely eradicated. In a previous composition, *transient* (2010) it was necessary to watch for the clock, score position and whether various triggers had been activated on the laptop screen. While certain trigger points were flexible in time, they had to occur within a certain time-window, and thus the Max/MSP interface had to been constantly checked. In the subsequent piece, these obstacles would be overcome by sending haptic feedback, in the form of vibrations, to the hands of the performer, providing the required information via a different modality.

3.2.2 Methodology

The score of the composition was created in Max/MSP, where various preset stages were created which would enable or deactivate different DSP modules, and change how control data derived from analysis of the piano's acoustic signal was used. Advancing to a new section would, in most cases, be triggered by the pianist (either performing a particular gesture at a specified dynamic, or by maintaining a specified amount of silence). Other events would advance according to a fixed timeline. Using an Arduino[9] and three small pager motors attached to the left hand via a simple glove, vibrations were sent to the performer indicating:

- a five second warning for an approaching change in score position, increasing in vibration intensity
- a strong short vibration when the performer had successfully triggered a new section of the piece
- the guide tempo of a section.

The pager motors used were Samsung disk coin-type vibration motors[10]. By selecting extremely light motors (0.99 grams each), no additional noticeable weight would be added to the hands of the pianist. The motors were connected directly across the ground and digital/pulse-width modulation pins of the Arduino, as they operate at a meagre 1.5V. Information was sent to the three motors using the Maxuino helper patch[11] for Max/MSP, allowing all computation to be contained inside a single programming environment. Using pulse-width modulation, a very apparent increase in intensity could be experienced.

Motors were fixed onto the glove (which was extremely thin and elasticated), positioned on either side of the back of the hand, with the third positioned directly below on the wrist. This allowed for discreet observable information to be accurately perceived whilst playing.

3.2.3 Outcomes

The result was extremely beneficial to the execution of the performance: the ease with which I could ignore the screen and concentrate on the performance was immediately apparent. The vibration signals were non-evasive and did not distract from the actual playing. There was a strong sense of being fully coupled to the system as a whole, as the score of the piece was being *applied* directly to the body, offering more security in the often unpredictable world of live electronics, and allowing for a more focussed performance.

3.3 Case Study: Improvisation for Laptop and Game Controller

As a trained pianist, most of my musical expressivity involves working with the hands, and thus for laptop performance I often repurpose generic game controllers as my interface. For the second example, the vibrotactile feedback system that was developed for *kontroll* was used in a more active manner, worn in conjunction with a game-pad for laptop improvisation. While used as a signaller of structure in the previous work, the haptic information was now used to direct the performer with more musical, and particularly rhythmic information.

While many game-pads or rumble-pads do offer resistant force-feedback, this was not present in the one that was used. Instead, it was sought to achieve a high level of control using only micro-movements of the hands and fingers. Thumbs pressed on the two joysticks could freeze and loop the sound, but the slightest movement could throw this off.

3.3.1 Tactile Score

The device alone *without* haptics worked fairly well as a solo improvisational tool, triggering samples within Max/MSP which were sliced into segments of several milliseconds, and then processed in various ways. Yet, to create a more interesting deployment of the gestural rhythmic aspect, the vibrotactile glove provided short pulses of 300 milliseconds to the performer indicating that short sounds should be played. The interval between these bursts was determined algorithmically, and changed over time. Thus the illusion of different paces throughout the improvisation was created, along with more unpredictable intervals between gestures. Similarly, longer signals, which would increase with intensity, were sent to indicate that a section should be repeated for the duration of the physical sensation. A variable timeline was established along which either of these two situations could occur, but this would not be known to the performer prior to the start of the piece.

3.3.2 Development

The next part of this work will be to develop musical suggestion which is dependent, at least in part, on what has been, or is currently being played by the performer. Rhythmic patterns would certainly be an obvious starting point here, as these are perhaps the most easily repeatable events when working with unpredictable digital musical instruments. Furthermore, rhythms can be easily represented by short bursts of vibrations. The problem with translating more complex variables, such as spectral content, is not only

[9] An open-source electronics prototyping platform board: www.arduino.cc
[10] Available from www.pagermotors.com
[11] http://www.maxuino.org/

Figure 2: Vibrotactile feedback used in conjunction with generic game controller.

the issue of how to most meaningfully map parameters, but also where to draw the line between useful information and sensory overload.

4. CONCLUSIONS

It is clear that there is a strong case for utilizing the different aspects of the modality of touch within digital music practice in order to challenge ideas about musical creativity, as well as to address the limitations of current systems used to mediate between the digital performer's gesture and sound synthesis. With careful experimentation and clever coupling of instrument and performer, the possibilities for new musical expression are certainly promising. From the examples shown above, it is clear that using vibrotactile feedback for performance strategies is a largely untapped area that is worth proper exploration.

4.1 Future Developments

Further research in this area will examine different parameters that may be successfully used within this type of feedback system, including:

- testing on different parts of the body
- exchanging information amongst a number of performers in an improvisational setting
- mapping other musical parameters to the feedback.

This last topic possibly deserves the most dedication, and work is in progress to develop ways of representing a more complete musical picture tangibly, looking at aspects such as density and spectral shifts[12], to assist with musical interpretation. Indeed Schroeder et al. describe experiments designed for group interaction, where these parameters are represented visually as an abstract image[13]. Moreover, Chang and O'Sullivan suggest looking toward audio-visual theories, such as those proposed by Michel Chion, to develop ways of linking both the tactile and auditory sensations; techniques such as masking and synchronization[13] are proposed [2].

[12]These are perhaps less consciously perceived, compared to amplitude, frequency etc.

[13]For example, synchronization would involve the sound and the sensation occurring at the same time.

4.2 Concerning the Listener

It is hoped that this type of vibrotactile interface can be used with non-performers, who will listen to music, whilst also experiencing it in the form of vibrations. Indeed Gunther and O'Modhrain, implementing this idea with their *Cutaneous Grooves* project, go so far as to suggest that this is a 'potential new art form' [6].

After developing the tactile feedback system and experiencing the ease with which signals can be transferred to the skin, it is hoped to explore the idea of using this information to enhance the listening experience, by coupling it with various physical sensations.

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H.2 Imposing a Networked Vibrotactile Feedback System for Improvisational Communication

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Imposing a Networked Vibrotactile Communication System for Improvisational Suggestion

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This paper describes the implementation of *NeVIS*, a local network system that establishes communication between individual performers, as well as between laptop and performers. Specifically, this is achieved by making use of vibrotactile feedback as a signalling tool within an improvisational setting. A discussion of the current developments regarding the use of networks within improvisation is presented, followed by an outline of the benefits of utilising the haptic feedback channel as a further sensory information pathway when performing digital music. We describe a case study of the system within the context of our computer-mediated improvisational duo Můstek, involving piano, percussion and live electronics. Here, a cueing system or framework is imposed over the improvisation and is transmitted directly to the skin of the performers via tiny vibrations. Additionally, performers may make use of simple vibrotactile signals to enhance traditional visual cues that are often employed within performance. A new work, *Socks and Ammo*, was created using NeVIS, and was presented at various international conferences and festivals. We also tested the system itself within a group of postgraduate researchers and composers. Qualitative evaluation of the musical outcomes as experienced both by the performers and by the listeners at these events is offered, as well as implications about the nature of collaborative music-making.

1. INTRODUCTION

The motivation behind much of the current laptop-centred networked performance seems to be the construction of enhanced musical relationships within a system comprising performers and instruments. Often, due to the logistics of performing with laptops, where information is displayed on a sizable screen, and the laptop is usually placed on a table along with peripherals, such as soundcards and controllers, the scope to facilitate gestural anticipation, recognisable visual cues, or meaningful physical movements is much more reduced than with performances using traditional instruments. As Seddon observes, ‘when jazz musicians play together they have at their disposal verbal communication, non-verbal communication (e.g. eye contact, aural cues and body language) and musical communication’ (Seddon 2005: 47). When a percussionist hits a drum, the other performers and the audience have a clear idea of the causal agency between the action and the resultant sound. However, in the field of electronic music, and moreover laptop performance, it becomes more difficult to rely on physical gesture to convey, for example, the onset of one’s sound to an audience, or to communicate with other performers. This may be due either to the nature of the interface being used – in the case of mice, keyboards or other devices involving micro-movements of the hand – or to the complexity of the sonic outcome, where it may be unclear how a sound has been produced, or indeed who has made it.

1.1. Networked music performance

Along with recent technological possibilities, these issues of performance and communication have driven musicians and sound artists increasingly to explore various types of networked music performance (NMP). A large portion of this research deals with high-quality uncompressed audio streaming. For example, the *SoundWIRE* project, at CCRMA, Stanford, examines methods of creating networks over the Internet as a means of extending the realm of computer music performance. In fact, one particular concert spanned a geographical distance of over 6,000 miles (Cáceres, Hamilton, Iyer, Chafe and Wang 2008). Such NMPs were emulated in the *Apart Project*, undertaken at the Sonic Arts Research Centre, Belfast, in order to ‘better understand conditions for performance that are created, facilitated and suggested by geographically displaced network performance environments’ (Schroeder, Renaud, Rebelo and Gualdas 2007). Various scenarios were constructed in which performers in dislocated situations received audio and video feeds of each other, both with and without latency, so as to help better understand the complex effects of musical cues. Whilst thoroughly technically descriptive, this project clearly alludes to the power of networks in relation to social concepts, such as community. Moreover, it concludes that rather than trying to recreate that which occurs on the stage, one should ‘rather take advantage of the

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network itself as a medium for performance' (Schroeder et al. 2007: 139).

This idea of using the network as an agent for performance has been realised with the emergence of numerous laptop orchestras, such as *PLOrk*, based at Princeton University. Using local wireless networks and focusing on data transmission of parameter and timing control, rather than audio-streaming (although not precluding wired audio networks), this group has developed strategies for performing with laptops and localised speakers by applying techniques for real-time synchronisation, cueing, scheduling and non-bodily visual communication (Trueman, Cook, Smallwood and Wang 2006). Here, the notion of connectivity within the digital realm is furthered by the introduction of a 'conductor machine'. This can guide the piece by, for example, sending simple text instructions to the performers, or by directly affecting specific parameters such as tempo (Trueman et al. 2006).

Two further projects that draw on this idea of a virtual conductor, but remain within the realm of improvisation, should be mentioned. Anne La Berge and Robert van Heumen's duo *Shackle* consists of a local network between two laptops, over which a series of cueing commands are sent (La Berge and van Heumen 2006). These directions include 'aspects of restriction, either in sound material, timing, dynamics or other musical parameters' (La Berge and van Heumen 2006), and are presented in a somewhat abstracted form to the audience on a projection screen. Additionally, the players may skip past a particular state, if so desired. The ensuing performance presents the two musicians indeed *shackled*, but clearly toying with and struggling against the imposed restrictions. Similarly, external direction is given to a group of four performers in Eric Lyon's *Selected Noise Quartets*, where instructions are generated in real time and sent to each performer via a laptop screen (Lyon 2011). Here, it is noise itself that guides and creates the structures behind the improvisations; the performers must be able to react quickly to the often highly unpredictable changes. Again, a struggle may arise as the instructions are frequently unfamiliar, and may in fact be technically impossible to carry out. Yet, through all the exertion 'the voice of each musician is heard; and behind it, the voice of noise' (Lyon 2011:98).

1.2. The reintroduction of haptic sensation

The *Selected Noise Quartets*, which are performed on acoustic instruments and electric guitar, demand a great deal of dexterity from the players. However, it is arguable that, compared to what can be achieved with conventional instruments, the level of physical sensitivity and control required for such deftness is absent in *digital* musical instruments (DMIs). Most traditional instruments are constructed to be played with the mouth or hands, where the largest number of sensory receptors in the body can be found (Rovan and Hayward 2000). Performing with these instruments provides the player with a wide range of physical forces and vibrations, which create an embodied knowledge about the nature of the sound being produced. Vibrations felt through a percussionist's hands from the mallets and through the legs from the bass drum pedal, as well as the *bounce* that the taut drumskin offers, all inform the performer about, for example, the dynamic, timbre or shape of the sound that is being produced. Hence what is heard through the ears is supported by this physical feedback mechanism, which creates a closed loop of ongoing listening and sensing, playing and readjusting. This all occurs before, and whilst, making each subsequent sound. Thus, by introducing artificial vibrotactile feedback to DMIs, some attempt may be made to restore this vital sensory information.

Generally, interfaces for digital musical offer minimal haptic feedback. They rarely reveal to the performer any tangible information in themselves about the qualities of the sound being made. Working with specially designed haptic interfaces, such as Claude Cadoz's *Modular Feedback Keyboard* (Cadoz, Lisowski and Florens 1990), physical forces, including resistance and pressure, can be carefully introduced to enhance our interactions within the digital realm. Furthermore, as the sensing nerves on our skin are capable of detecting extremely complex patterns of data (Gunther and O'Modhrain 2003), additional *vibrotactile* feedback can be added to DMIs by way of actuators, such as motors. Marshall and Wanderley, at CIRMMT, McGill University, measured the effects of embedding vibrotactile stimuli in DMIs, with varied results (Marshall and Wanderley 2011). They noted that while adding vibrotactile feedback may improve the *feel* of the instrument, the extra sensory load caused some participants to feel less in control of their playing. However, this may in fact be beneficial in terms of creating a *challenging* instrument that could be mastered *over time*. Indeed, it is generally accepted that haptic feedback can assist learning processes (Davidson 1976), and, as discussed above, it is undoubtedly significant in the role of building a performer's perception of sound. Moreover, this experience is uniquely private to the performer, forming an intimate relationship between musician and instrument.

2. BACKGROUND

This section gives a brief contextual summary of the musical activity surrounding this project. The Networked Vibrotactile Improvisation System (NeVIS) arose out of a two-year-long collaboration between the authors, both composer/performers, combining piano and live electronics (Hayes) with percussion and live electronics (Michalakos). Both being practitioners of digital augmentation and hybridisation of our chosen acoustic instruments, we inevitably began to develop strategies that attempted to tackle some of the issues related to performing with augmented acoustic instruments in a collaborative environment. We also both engage in a variety of extended techniques. To give some information about the systems being used: typically, the acoustic percussion or piano sound is amplified, and is also converted to a digital signal for further processing. Analysis of the incoming sound occurs continuously, in real time, and the various parameters derived, including pitch information, density and dynamics, are used to drive assorted processes within Max/MSP[1] and Max for Live.[2] Additional controllers such as foot pedals, sensors and MIDI interfaces are often also employed; these provide hierarchical control over various parameters within the software. While our individual approaches have both favoured hybridisation that makes use of machine listening techniques, we have found ways to integrate these additional devices without losing any sense of flow or agility. In fact, being able to dynamically control the level of one's digital sound is something that we have both found to be a necessary feat.

The creation of the NeVIS project emerged both from ideas developed throughout our experience as the improvising duo Můstek (Figure 1), as well as through individual research exploring on the use of vibrotactile feedback as a performance tool (Hayes 2011). Involvement with large-scale ensembles, such as Edimpro (see Edimpro 2009), a free improvisation group consisting largely, but not exclusively, of students and staff from the University of Edinburgh Music Department, also raised questions about communication strategies within group improvisation. Further influence came from participation in workshops dedicated to the performance of electronic music and improvisation, hosted by, notably, Fred Frith and Christophe Fellay, and the *Converging Objects* workshop by Anne La Berge and Robert van Heumen (2010). Lastly, both authors partake in the yearly roving-researcher-led *Laboratory for Laptop and Electronic-Audio Performance Practice* (LLEAPP), founded at the University of Edinburgh in 2009 by members of Sound Lab Edinburgh (2007), with support from the Roberts' Fund for Researcher-Led Initiative; this workshop aims to highlight and tackle many of the issues related to the live performance of electronic music (see LLEAPP 2009). Now in its third year, LLEAPP provides a framework for collaboration and discussion among postgraduate researchers and music-makers from around the UK.

[1]http://cycling74.com.
[2]http://www.ableton.com/maxforlive.

Figure 1. Můstek performing *Socks and Ammo* at Sonorities Festival, SARC, Belfast, 2011.

3. MOTIVATIONS

The main threads that emerged from the various aforementioned scenarios and improvisations revolved around:

- strategies for structuring improvisations
- strategies for communication between performers
- novel interaction between performers.

One of the most exciting yet possibly troublesome aspects of group improvisation is that, rather than a single-person-led evolvement, ideas may be put forward by any agent present (Edwards 2010). Moreover, new material may be emergent, appearing only as a result of everything that has previously been put forward by the present assemblage. We began to consider new methods that might challenge these characteristics of improvisation, which appeared to be ubiquitous. Furthermore, after performing together for a significant amount of time, performers begin to predict or expect what their well-known partners might contribute in any given situation. On one hand, this is of course an advantage in long-term collaborations, as players become familiar with the sonic worlds of their peers; but, in some cases, it can also lead to a lack of spontaneity, or at least spark a desire for a freshness of sorts. In our case, introducing a third, unpredictable agent into the system was certainly something that was appealing, not only for the sake of newness, but moreover because we would be able to consider its role in the construction of the sound and musical form.

A further motivation for imposing this system was noted during the post-concert discussion of the LLEAPP workshop of 2010 at Newcastle University's Culture Lab. The improvisations of electronic music presented on that occasion generally seemed to settle on an average of fifteen minutes' duration: as participants, it appeared that we were neither daring by performing extremely short works, nor confident in demanding more time, where needed. It was felt that different approaches to structure, in terms of duration, would have helped significantly in nearly all of the pieces presented.

Naturally, the role of structure within improvisation is a complex issue. Analogies have been drawn between improvisation and vocalising, either as monologue, emulating the flowing nature of singing (Sudnow 1978), or as conversational dialogue (Healey, Leach and Bryan-Kinns 2005). The latter types of comparisons suggest that a certain pattern of interaction occurs within group free improvisation, whereby one person provides a new idea and the others listen and respond to it, just as may happen with a new choice of topic in conversation. Analysis of group improvisational sessions seems to confirm this (Healey et al. 2005). However, this phenomenon suggests a certain structure and development to the music: it does not readily facilitate synchronisation points or cues between players. Just as would not typically happen in conversation, a group of performers would not usually move synchronously to a set of new ideas, unless a clear cueing command was given. This was one of the main motivations for creating the imposed framework: these cue points would be suggestions to simultaneously move to new material, without implying a fully precomposed piece. Just as Bavelas and Chovil give extensive evidence that certain 'nonverbal acts are an intrinsic part of language use in face-to-face dialogue' (Bavelas and Chovil 2006: 110), we claim that within musical improvisation, too, nonverbal communication is fundamental, and worth exploiting beyond merely the gestural domain.

While traditional visual cues continue to exist between performers using electronics, there is increasingly a need to find other solutions to some of the problems that arise when working with new technologies. Dislocation of the sound source and the loudspeakers means that stage layouts become complex and often confused, another point raised, and clearly evident, with regard to some of the performances at LLEAPP 2010, and subsequently at LLEAPP 2011, at the University of East Anglia, Norwich. Naturally, the origins of the acoustic sounds of augmented instruments are situated within the body of the instrument. Ideally, any approach to positioning loudspeakers should involve a conscious effort to integrate the electronic audio. However, due to the nature of a particular space or the availability of equipment, often loudspeakers are *not* placed proximally to the acoustic component of the hybrid system, and so discerning what each player is actually doing can become a difficult task. Similarly, it can be difficult to always situate instrument stations so as to maintain an adequate line of sight between performers. As well as engaging with the acoustic instrument, performers will often be manipulating other devices, such as foot pedals or MIDI controllers; this may expend the amount of time available to watch out for cues from the other players. The individual systems that we used for this project were designed to enable as much freedom from the constraints of looking at laptop screens or focusing on interfaces other than the original acoustic instruments, which were employed both as sound sources *and* as controllers. Nevertheless, especially in the early stages, we often felt consumed by the operation of our hybrid instruments.

4. METHODOLOGY

The NeVIS framework was developed in response to the aforementioned issues.

4.1. Vibrotactile device

At the core of the system is a novel device that transmits haptic feedback in the form of vibrations onto the skin of the performers. First used as a solo performance tool for piano and live electronics, and designed to signal sections within a score and rhythmic information, the system's development is fully documented by Hayes (2011). The device was built from an Arduino[3] microcontroller and three small Samsung disk coin-type pager motors (each 1.5 V, 70 mA and measuring less than 1 cm in diameter). These were connected directly across the Arduino's ground and pulse-width modulation/digital pins. The motors were fixed to a glove made of a thin elasticised material, which the performer wore on her left hand. Two of the motors were positioned on either side of the back of the hand, and the third was positioned directly underneath, on the wrist. In this way, the performer, even whilst playing the piano, could accurately perceive three discreet channels of information. The extremely small and light nature of the vibration motors meant that the performance would not be impeded in any way by the device, as no extra noticeable weight would be added to instrumentalist's hands.

Long-length wires were run from the motors to the Arduino, which was connected to a laptop using a standard USB cable (Figure 2). Information was sent to the three motors via the Arduino using Max/MSP, the same software environment that was being used for the digital signal processing (DSP). This allowed the system to be easily integrated with the pre-existing performance patches. By simply toggling between on and off states, vibrotactile pulses were created; but, by additionally using the pulse-width modulation feature, a clearly noticeable increase in intensity of vibration could be experienced. In duplicating the device for duo performance, we found that using a glove was not suitable for the percussionist: when

[3]http://www.arduino.cc.

Figure 2. Lauren Hayes wearing the vibrotactile feedback device.

positioning the motors on the hand, perceivable changes in vibration were ambiguous due to the natural feedback felt from hitting the drums. To rectify this, a further device was created, which was worn on the upper left arm of the percussionist. Here, the motors were positioned around an elasticised armband. Again, we experimented with the positioning of the motors, and concluded that placing them equidistant around the circumference of the arm gave the most discreet and discernable results.

4.2. Structure by suggested cues

A cue-based framework, the core of which is timed event-points, drives the system. That is to say, before a performance, the participants must decide on the number of sections that the piece will consist of, and the duration of each section. This information must be entered within the Max/MSP patch; alternatively, there is an option to allocate an arbitrary number of sections, or to have these sections assigned random durations of a minimum of thirty seconds. Enforcing a minimum section length was an aesthetic choice, used to allow for a moderate amount of time for propagation of musical ideas. The total duration of the piece is also displayed within the graphical user interface, mainly as a guide for concert situations where a predetermined piece length is required. The performers may allocate names to each state, although, as discussed later, this is merely ancillary and optional. The section changes are simply predetermined cues, but the performers do have the option to pause the time-line, by pressing a button on a MIDI controller, and to remain for longer within a certain section if desired.

One of two laptops acts as a conductor, sending the timing cues and other information, which will be outlined below, as OSC[4] messages over a local network connection to the second laptop. The sections and their corresponding durations are shown on the laptop screens (Figure 3). More important, however, is that this cue list should be perceived cutaneously, through the surface of the skin of the performers. Just as how, within a notated or graphic score, different symbols or instructions signal particular musical events, so too is it the *interpretation* of the different vibrational sensations felt by the performers that is crucial here.

As mentioned above, the first layer of the system consists of the section cues; these being points in time during which major musical cuts may occur throughout the improvisation. These changes can be textural or rhythmical, and either in the acoustic or electronic sound worlds. Although the specific moment when these events occur within time-line is predetermined by the cue list (unless, of course, one of the performers freezes the state of play), it is left up to the players to decide whether to acknowledge and respond to these suggested prompts. For this reason, the different sections are also annotated with generic names, which may suggest a musical description understood by both performers (such as *sparse*), but are vague enough to apply to various situations. For example, who should play sparse? Is it rhythmically sparse, or a sparing use of pitches? It should be noted that looking at the screen for such information is optional, and is something that we constantly try to move away from, or completely avoid. Hence, to recapitulate: *how* changes are made and *what* is changed in the musical progression is entirely up to the performers. They will merely receive a signal telling them *to* change, along with a textual suggestion, should they decide to look at the laptop screen.

The only other quasi-predetermined parameter is tempo. This is sent in the form of a pulse, and is included not so as to enforce strict time-keeping, but rather to serve as a foundation around which possible interlocking between parts can be created. Of course, this can occur naturally within playing, but again this is an additional suggestion to be integrated, or not, as desired by the individuals present. The performers must predetermine the tempos of each section within the patch (zero, if undefined), but they do have the option to stop receiving the pulse if it becomes either too distracting, or unfitting to the current state of play. We both use the small and discreet Korg *NanoKontrol* [5]MIDI controller as part of our extended instruments, and so, by simply pressing a button on the interface, we can turn off the tempo vibrations. This was easy to add to the pre-existing systems, and seemed the most logical way to control this parameter: since we were already adept at using these

[4]http://opensoundcontrol.org.

[5]http://www.korg.com/nanoseries.

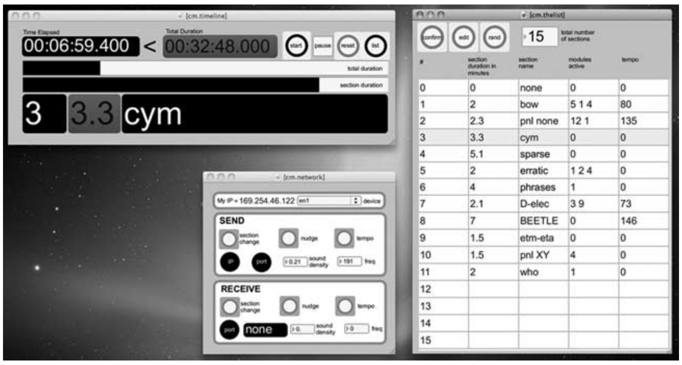

Figure 3. Graphical user interface of the NeVIS interface and cueing system.

controllers it was simply a case of repeating an action that was already learned. An alternative would have been to attach a further button or sensor to the wearable part of the device, but this could have potentially interrupted play. Of course, the situation may transpire where one performer is playing along with the pulse, and the other may have turned it off; this is just one scenario where the *voice* of the system itself may become noticeable. Another advantage of the suggested pulse is that we often slipped into a few standard tempi during previous improvisations, and so the conducting provided a gentle prod towards fresh ideas. Moreover, transitioning synchronously to a new tempo is virtually impossible without some form of direction. This would have to come either from one of the players, or, as in this case, from the cueing system.

4.3. Communication between performers

During performances, we found that we would often drift into a state of semi-isolation, focusing on, gauging and reacting to the specifics of the individual augmented instruments (something also commonly observed within the larger improvisation group, Edimpro). Thus it was often difficult to attract the attention of the other player for visual cues. In order to remedy this, a *nudge* function was built into the system, which served as a tool to enable visual communication. This is initiated by pressing a button on one of the MIDI controllers, sending a burst of three short pulses to the arm of the other musician, over a duration of 1,800 milliseconds. This would simply alert us to make eye contact: the meaning or intent of the actual visual cue given after contact was made would depend, of course, on the ensuing gestures, glances or signals. However, this nudge function certainly helped to *enable* these exchanges.

As an artistic choice, we have always performed in close proximity to each other. However, this system could certainly be used across greater distances and locations providing that a low-latency network could be established. Parker describes a networked performance across three different cities where not only audio, but also control data was exchanged, with a latency low enough to enable real-time performance (Parker 2006). This is an example of what Gil Weinberg terms as 'the Bridge approach' (Weinberg 2005), whereby performers in distant locations attempt to play as if they were spatially together. Certainly NeVIS could be tested in more extreme situations, but our aims were to investigate the effects of the system on the structural outcome of the music, and to enhance our already established communication practices.

4.4. Musical parameters

Although, as stated, the role of the network was limited to signalling and other simple forms of communication, an additional element was added to allow for the exchange of parametric data. The densities of the individual acoustic instrumental sounds, already being calculated in both our patches for internal processing, were sent over the network and mapped to various modules (in the other performer's patch), thus influencing the overall musical texture. Similarly, the spectral centroid of each performer's final output, after all DSP, was also swapped and used in a similar manner. The aim was to explore how parameters less easily perceived than, for example, pitch or amplitude might be useful for affecting the electronic processing. Additionally, each cue point can be assigned up to eight numbers, which will enable or disable sound processing modules within Max/MSP as the piece progresses, creating a more fluid, less disjointed performance during the improvisation. Selections that are displeasing to the performers can easily be overridden using the MIDI controllers. Due to differences in the hybrid instruments, only one of the performers chose to utilise this feature, as it was more conducive to their particular approach.

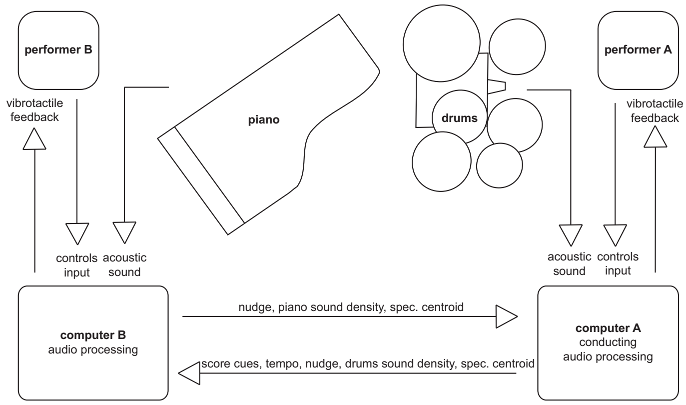

Figure 4. Signal flow of the NeVIS system.

4.5. Choice of modalities

As mentioned earlier, issues of privacy, feedback and creating intimacy with the instrument are just some of the benefits of working with the haptic sensory channels. Furthermore, when working with laptops, using haptics may help to free performers from the constraints of looking at the monitor for visual feedback (Hayes 2011). With this in mind, we decided to use vibrotactile feedback as the method for communicating the signals and cues discussed so far. Within electroacoustic music, in the absence of a conductor, the use of click-tracks for performers is often deployed, whereby a metronome pulse is heard through headphones. Stockhausen's *Helikopter-Streichquartett* (1995) is an extreme, although perhaps apt, example of this phenomenon: four performers play from inside four helicopters, spatially distanced from each other, and directed only through click-tracks on headphones. It was felt, however, that the use of headphones reduces the ability to listen clearly to the overall sonic results: indeed, simply discerning distinct electronic parts in a group setting can be difficult enough. Furthermore, the tempi to be transmitted across the network were only suggestions, which could be easily disabled, and so a constant audible sound would be too distracting. Thus, short continuous pulses (lasting 75 milliseconds) were transmitted to the hands and arms of the performers, allowing the tempo of each section to be adequately perceived.

Similarly, having a visual nudge or alert represented on the laptop screens would not suffice, as we tend not to fixate on the monitor while performing; a signal of three short bursts of vibration was transmitted instead. For the same reason, the section cues were indicated by a vibrotactile sensation that was short enough to trigger an impulsive reaction from performers, but that would also give just enough time to prepare any electronic changes that might be necessary. A ten-second approach signal was used, which increased in intensity over the duration. This length was chosen as it gave adequate time for any musical changes to be made, yet preserved enough of the spontaneity that we wished to arise from the appearance of the synchronisation points.

5. RESULTS

The system (Figure 4) was developed over a six-month period, and the resulting work, *Socks and Ammo* (sound example 1), was performed at various festivals and conferences, which included Sound Thought (Glasgow), Sonorities Festival of Contemporary Music (Belfast), Soundings Festival of Sonic Art (Edinburgh) and NIME[6] (Oslo). With the exception of Soundings, where a guest double-bass player participated in the improvisation without using NeVIS, the system was used in the same format. Not only its usefulness, but also the musical character of the project became apparent the more that it was adopted in performances. The nudge function was immediately utilised as a simple communication tool, and helped to improve our general communication on stage. Moreover, as this is a private method of interaction, it arguably helped to give the audience the illusion of a more integrated and polished performance. We certainly found that it helped to quickly rouse us from the states of absorbed isolation that sometimes occurred, and re-establish any required visual contact. Indeed, at the Sonorities concert in SARC's Sonic Lab, it was noted from audience feedback that a very strong sense of integration and coherence between the performers was evident in the music. Of course, this sense of connectedness may be attributed to our collaborative history, but in comparison

[6]Video performance at NIME 2011: http://www.vimeo.com/26629807.

to performances that we have given without using NeVIS, we believe that this is indeed due to the implementation of the network.

The section changes raised several points worthy of discussion. The knowledge that there was an imminent change very often resulted in a state of self-awareness and anticipation, rather than an engaged performance or progression with musical ideas. This was particularly noted when testing the system with other performers at LLEAPP 2011. Here, participants initially found the system restrictive and counter-intuitive to their former improvisation practice, but after some time they began to comment on the potential usefulness of it. Indeed, after performing with the system many times over a period of several weeks, the anticipatory nature of our own responses receded. At this point, NeVIS became more clearly useful as a tool to shape the improvisations. This can be attributed to the fact that, when we had performed extensively with the vibrotactile feedback, it became an integral part of the performance; and after a certain degree of familiarity was achieved the musical output became the main focus once again. The perceived instructions and suggestions would be taken into account *only* if they served the already established musical material and direction, and, whilst they were very often acknowledged, they could be and *were* ignored too.

Of course, due to the autonomy of the performers within the framework, all cues could potentially be ignored and therefore be rendered meaningless. However, this never happened in performances as we wished to understand how the voice of the system might be heard amidst our own playing. Certainly, it was mentioned in the audience feedback at NIME that the system could clearly be perceived to be influencing the direction of musical progression in ways that would not otherwise have arisen naturally: this was illustrated mainly by the synchronised and often abrupt changes in direction. This feedback was encouraging, considering the context of this performance, as we were unaware to what extent an informed audience (here with explanatory programme notes) would be able to discern the effect of the system. Similar comments were received at Edinburgh performances, from audience members who had heard us perform in both scenarios, with and without NeVIS. When an element of unpredictability and surprise was introduced, the performances, conversely, appeared to take on a stronger sense of direction.

6. FUTURE DIRECTIONS

To date, the NeVIS project has been used with a relatively static predetermined cueing structure. Further developments will focus on creating a real-time non-randomised suggestion system based on machine listening techniques. This will be realised by creating a database of pre-recorded musical gestures, whereby the system will become more familiar with the individual performers the more gestures that it learns. IRCAM's *Gesture Follower*[7] and Fiebrink, Trueman and Cook's *Wekinator*[8] are possibilities that we have started to explore for this purpose. It is hoped that, with the implementation of these systems, the selection of processing modules within each section may become more meaningful. Rather than being selected at random by the system, or pre-determined by the users, the instrument will respond to what is being played. We hope to explore how the emergence of the cues over time might function in a similar manner.

Further exploration into the vibrotactile representation of audio will be undertaken by examining more complex models of analysis of the resultant sonic output. We will investigate which types information can be successfully and usefully integrated into the vibrotactile network. Schroeder et al. created visual avatars from analysis of the incoming signals; the data was recreated as an abstract image from an amalgam of distinct parameters, and was used to assist the improvisations (Schroeder et al. 2007). We will attempt to establish whether similar information can be represented in the form of haptic feedback, and if this enhanced perception of the sound will in any way aid the improviser. Finally, the system will be expanded to multiple wearable devices and be made wireless. It will then be tested with a larger group of performers.

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[8]http://wekinator.cs.princeton.edu.

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H.3 Performing Articulation and Expression through a Haptic Interface

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PERFORMING ARTICULATION AND EXPRESSION THROUGH A HAPTIC INTERFACE

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ABSTRACT

While digital technologies offer a host of new sonic possibilities, we are no longer dealing with the physical vibrations of strings, tubes and solid bodies as the sound source, but rather with the *impalpable* numerical streams of digital signal processing (DSP). As a result, when we perform with digital musical instruments (DMIs), we can no longer make use of haptic feedback provided through the body of the instrument itself. Furthermore, many DMIs are derived from interfaces designed for effortlessly smooth human-computer interaction. Here, however, the struggle afforded by the resistance and physical forces of acoustic instruments, which I will argue is integral to musical performance, is all but lost.

This paper discusses the musical outcomes of an exploration into the use of a haptic interface as an instrument for the performance of digital music. I will argue that it is the reintroduction of these tangible forces that is crucial for the articulation and effectuation of sonic ideas. In particular, the instrument will be discussed in relation to the work *Running Backwards, Uphill (2011)* for piano trio and live electronics, where a potentially high level of sophistication of expression was required that would allow the laptop performer to embody the musical intentions of the piece.

1. INTRODUCTION

> *A violin, played at professional standard, can be likened more to a localised instrument of torture (with its complimentary disciplinary rewards), than a harmonious continuation with human agency. Why is there no impetus to develop a violin that blends ergonomically with the player?* [10]

When playing acoustic instruments, the haptic perception involving both tactile sensors in our skin (especially in the fingertips, hands or lips), as well as our kinesthetic perception of the position and movement of our muscles and joints, is pivotal within the complex relationships between performer, instrument, and the resultant sounds produced. It is precisely these ongoing negotiations and reassessments through multimodal feedback loops that lead to the diversity of achievable musical expression. However, the audio-tactile link has been largely missing in systems of digital music. Instruments can no longer be said to describe only those resonating bodies of physical constructs; indeed the sound sources of DMIs cannot usually be linked to real-world vibrating objects. Emmerson writes that, as performers, we "sense this loss of 'tactile location'"[4]. MIDI controllers are often modelled on the studio paradigm, consisting of knobs and faders, and tend not to offer the types of interaction that make use of physical forces such as pressure, friction, collision, resistance, and so on. Even instrument-based MIDI controllers not only fail to communicate the whole picture in terms of the performer's gestural information, but do not go far enough in allowing the vitally *unharmonious* types of engagement to manifest between performer and instrument, as hinted at by Rebelo and Coyne's quotation.

As research into tangible computing develops, the importance of how we engage with the digital world through our physical interactions is being increasingly highlighted. The incorporation of haptic feedback into mobile phones, and more recently tablet computers, is one such example. Developments in the field of haptic technology directly related to music are steadily increasing. These include ways of using our tacit knowledge of how we interact with physical objects as a means of mapping input gesture to digital audio parameters [8]. Other work specifically uses the already acquired motor-skills of a musician as the basis for haptic instrument design [2]. In related research, I have attempted to reintroduce the tactile sensation of sound to the performer by incorporating vibrotactile feedback within the performer-instrument coupling [6].

In what follows I will attempt to argue the case for employing tangible forces as a means to enhance the potential for sophisticated expression and articulation of performed digital music. I will propose that:

1. Diverse musical expression is achieved through constant multimodal negotiation between performer and instrument.
2. Exploring the resistance of an instrument, either physically or virtually, can help to craft a performance.
3. Haptic technology can help to create shared participation between performer, instrument and performance space.

2. SOUND SCULPTING WITH A HAPTIC CONTROLLER

During his keynote address at the *International Computer Music Conference, 2011*, University of Huddersfield, Simon Emmerson suggested that the idea of sculpting sound was now “a metaphor that could be made ‘real’ through suitable haptic interfaces and three dimensional representation.” [4]. What follows will offer a modest step towards a realisation of this idea, where digital audio can indeed be moulded and articulated through three-dimensional (3D) tactile interactions. In this way, not only do we rely on auditory feedback to navigate between sounds, but we are also guided by ongoing *tangible* exchanges with the instrument.

2.1. Repurposing a Commercial Game Controller

The *Novint Falcon* is an affordable[1] commercial 3D game controller, providing up to 9 newtons of resistant force-feedback to the user [1]. While this is of a much lower bandwidth than, for example, Claude Cadoz’s *Modular Feedback Keyboard* [3], one of the first haptic musical instruments, or “*gestural force-feedback transducers*”, it is nonetheless receiving attention as a low-cost solution to designing haptic DMIs. The *Haptics Lab*[2], at CCRMA, Stanford University, is an audio-interaction workshop specifically based around the Falcon.

Open source software is available from Nonpolynomial Labs[3], enabling the Falcon to operate within musical programming environments such as Max/MSP and Pure Data[4]. Edgar Berdahl, at CCRMA, developed *HSP*, “a simple platform for implementing haptic musical instruments” [1], aimed at making the incorporation of haptic technology into DMIs both inexpensive and easy to programme. The toolkit offers a series of basic force-feedback profiles for the Falcon, including virtual walls and springs. Used and adapted in combination with various DSP techniques, new *instrument* prototypes start to emerge.

The Falcon ball grip can be moved within a 3D space, approximating a cube of side around 11 centimetres. However, depending on design choices, a virtual space of *infinite* size could be traversed. The haptic technology can provide the experience of palpable (but virtual) objects, surfaces, and indeed textures. Thus possibilities for designing interactions based on a host of different gestures arise, where we can imagine not only *bumping* into virtual surfaces, but also being able to move through different *atmospheres*, at various speeds, depending on the viscosity employed[5]. Furthermore, interactions that defy real-world physical relationships can be created through the HSP’s interface. For example, a simple wall model could *disintegrate* after being hit with a particular velocity, and *reform* once the user has passed through to the other side. Of course, meaningful relationships between such interactions and their effect on the musical outcomes must be considered.

2.2. Performance Potential

On trying out the device for the first time, it feels, peculiarly, both new, yet familiar. After initial experimentation within this environment, the possibilities for prototyping new haptic-based musical instruments become obviously clear. The three degrees of freedom gives potential not only for micro-movements of the hand, but for further engagement from more of the body. Thus larger gestural movements can be *transduced* into parametric information, while still allowing for finely focussed articulations. Rebelo refers to performance as a “multimodal participatory space”, somewhere where the performer employs “negotiation of subtlety and the recognition of threshold conditions” [9]. I would argue that by introducing haptic devices, we also increase the potential for this type of engagement.

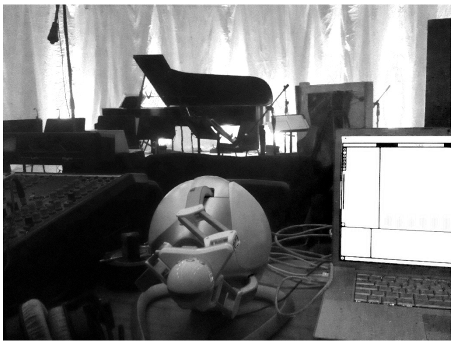

Figure 1. Performance of *Running Backwards, Uphill*, Reid Hall, Edinburgh, 2011.

Emmerson’s idea of sound sculpting suggests that 3D manipulations would enable us to mould multiple aspects of the sound simultaneously. The very nature of the Falcon affords this type of interaction, given that any movement will produce a minimum of three data streams[6]. Thus, the potential for multi-mapping is inherent. The expressive potential of acoustic instruments can, in part, be attributed to the multiple and ongoing negotiations between performer and instrument. For example, playing fast *staccato* scales on a piano requires continuous assessment by the performer about kinaesthetic and haptic information, such as the bounce of the fingers against the keys, and the speed or acceleration of the hand. Thus, simply by nature

[1] Costing around $250 at time of writing, January 2012.

[2] `https://ccrma.stanford.edu/wiki/250a_Haptics_Lab`

[3] `http://sourceforge.net/projects/libnifalcon/`

[4] As well as providing cross-platform functionality to include OS X, which is, at time of writing, unsupported by Novint.

[5] Viscous damping is implemented in the HSP toolkit through a series of biquad filters.

[6] On the most basic level, x, y and z position can be extracted, before even considering force and resistance.

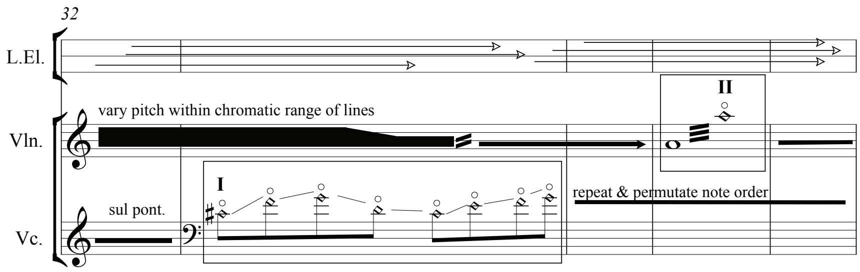

Figure 2. Score with thick black lines illustrating gradual transitioning of sound. Electronic part indicates to play samples with varying speed of playback and dynamic.

of its design, the Falcon already goes some way in offering the qualities necessary to make a convincing instrument.

2.3. Development of an Instrument

After testing the various physical models given within the HSP examples, the virtual wall was used most extensively as a starting point, as the action of striking a surface with different objects and forces could be considered to be one of the most primitive sound-producing gestures.

I implemented a visual rendering of a ball bouncing on the wall using *JavaScript* within Max/MSP, which was initially useful for providing additional visual feedback while developing the system. However, since much of my practice within computer music aims to remove the need to look at a laptop screen while performing (through engagement either with haptic interfaces, or augmented instruments) [7] [6], this quickly became redundant.

One of the most interesting aspects of the instrument was that depending on the different force profiles used, it could rapidly change between allowing wild gestures, to a very resistant, even *secure*, environment where moving through detailed nuances of a sound could be explored. The four buttons on the small ball grip of the Falcon allow rapid switching between different forces profiles and parameter mappings, within a single performance.

3. *RUNNING B CKW RDS, UPHILL*

This section describes the implementation of the Falcon as a performance instrument within a compositional framework.

Running Backwards, Uphill (2011)[7] for violin, cello, piano and live electronics, attempts to explore the relationships between touch, gesture and timbre by examining the sonic qualities of the acoustic instruments, and furthering these through the use of electronics. The performers are directed to lurch and fall off the keys; or, to create the most delicate airy bowed sound. Extended techniques are combined with sound analysis methods, resulting in an informed integration between the two sonic worlds.

3.1. Articulation and Expression

One of the challenges with this composition was to develop a method for articulating the electronic part that could evoke the same expressive qualities within the music as would be expected of the professional ensemble. The musical language of the piece itself is very gestural (see Figures 2 and 3), and thus it was important that the electronic part should also be performed in such a way as to reflect this.

The boundaries of any instrument can be where the most expressive moments emerge, from an unstable clarinet multiphonic, to the point at which a digitally generated pulse turns into pitch. But for instruments within the class of *resonating bodies*, these boundaries are intrinsically coupled with *physical* resistance. As Aden Evens explains:

> *For his part, the musician resists the resistance, which is to say, he employs technique... technique is designed to place the instrument's resistance in contact with the musician, to allow him to feel the many dynamics it offers of force and sound.*[5]

Thus, by working with the haptic device, I could successfully couple physical resistance with these virtual boundary areas, which in turn allowed for a greater range of potential expression in which the performer could employ technique.

In the first part of the score (see Figure 2), the Falcon is used to play short segments of samples of a prepared piano. With the added resistance of the controller, I was able to make micro-movements along the domains of both start and end points of the sample, as well as the speed of playback of the samples themselves. Without the force to play off, the result would have sounded jerky and ill crafted, whereas pushing through the resistance allowed

[7] A live recording of the work can be heard here: `http://soundcloud.com/elleesaich/running-backwards-uphill`

smooth transitions through the various parameters, producing a *legato* effect.

In this section, the string instruments play long tremolo lines in which both the speed of the tremolo, and pitch transition continuously. The dynamics also ebb and flow gradually until the entrance of the piano. I wanted the electronic part to reflect these characteristics by transitioning gradually both in timbre, dynamic and pitch. The haptic device gave the performer a sensation, or *feeling* of moving through the sound, increasing the amount of information available for negotiating the performance.

Figure 3. Score illustrating frenetic, gestural section.

In the middle section of the piece (see Figure 3), the Falcon was used to transduce fast gestural sweeping movements to process various effects (including bit-crushing, feedback and filtering), which were applied to a second set of samples. Here, the piano part leaps through descending cluster chords, in a syncopated manner. The pianist is instructed to play "clumsily, with hands almost falling off keys". The laptop performer uses a different, non-uniform force profile in this section, which facilitates the "jerky" expression marking notated in the score, but which also provides more resistance at the boundaries of the DSP. In this way, the performer is less likely to, for example, hit the more piercing parts of the audible feedback, as the added resistance would prevent them from reaching that part of the instrument's range easily.

4. RESULTS AND DEVELOPMENT

The purpose of this paper was not to detail the technical capabilities of the Novint Falcon, as these are thoroughly described elsewhere [1], but rather to describe how employing a haptic device can manifest imagined musical ideas and *expressive* nuances. Not only through practice, but also by considering the crucial negotiations and feedback loops that take place between performer and instrument, it becomes evident how employing haptic technology can solve some of the problems associated with the performance of live electronic music.

Implementations of different force profiles, combined with viscous damping, allow the performer to *feel* their way through different aspects of digital audio, and sculpt the sound accordingly. In the work described, using resistant forces designed with very simple physical manifestations allowed vastly different types of engagement to be employed within the piece. Through the use of haptics, as a performer, I could more easily position myself within the shared participatory performance space. I will conclude by suggesting that this is a place that we, as composers of digital music, need to more deeply explore.

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H.4 Haptic Augmentation of the Hybrid Piano

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Haptic Augmentation of the Hybrid Piano

Lauren Hayes

One of the most vital feedback systems that has been embedded in musicians for centuries is that of physical response. In the same way that auditory information is available and used throughout a performance, a musician will continuously reassess their playing by making use of not only their specialised sensorimotor skills, but also the tangible feedback that is relayed to them through the body of the instrument. This paper discusses approaches to the development of an augmented instrument, namely the hybrid piano, which focuses on the notion of performance as perceptually guided action. While the acoustic component of the sound energy of the augmented instrument is created within the real-world interactions between hammers, resonating strings, and the soundboard, the digital sonic events cannot be located in a similar palpable source. By exploring notions of multimodality and haptic feedback, the ongoing processes of human action and perception within instrumental performance can be maintained for the player, whilst arguably, also enhancing the experience for the listener.

Keywords: Vibrotactile Feedback; Enaction; Performance; Augmented Instruments

Introduction

Recent shifts in the understanding of human cognition, which suggest that mental processing is grounded in the body, have led to an increased discourse on the role of the body within contemporary music. In the 1960s, Schaeffer (1966) proposed a phenomenological framework for the experience of sound, which was based around the *acousmatic situation*, and the idea of *reduced listening* (Chion, 1983/2009). This encouraged an abandoning of the attempted interpretation of the causal origins of sounds, replaced instead by the formation of musical meaning purely through what is heard: the sound itself. The *enactive* (Varela, Thompson, & Rosch, 1991) approach to understanding and creating music, closely related to embodied music cognition, further builds on this phenomenological perspective by suggesting that our cognitive processes have their roots within the multimodal capacities of the body as a whole, and that meaning can be elicited through our bodily interactions with the world.

These ideas have gradually started to permeate the field of digital instrument design, especially in relation to haptic and tangible technology, where the emphasis on the interdependent relationships between body and mind is taken as key to suggesting improved ways in which novel digital musical instruments (DMIs) might be conceived, in order to create more potential for expression and a more engaged performance both from the point of view of the performer and of the audience. Of particular note are the distinct methodologies that have been proposed by Cadoz (1988, 2009), Essl and O'Modhrain (2006), and Armstrong (2006). These proponents all provide theoretical frameworks, as well as quite different practical approaches to DMI design, yet all are strongly influenced by themes of multimodality and the close coupling of action and perception. Despite the obviously different, yet related, practical outcomes, these approaches all acknowledge the importance of the enactive view, which was formulated by cognitive scientists Varela et al. (1991). It entails that '(1) perception consists in perceptually guided action and (2) cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided'. This non-symbolic approach attempts to redefine cognition as embodied action (enaction). Although born out of the study of the organisation of living systems, enaction was largely inspired by the phenomenology of French philosopher Merleau-Ponty. Specifically, enaction develops Merleau-Ponty's (1945/1962) notion of the body as both biological (outer) and phenomenological (inner), in that we constantly oscillate between these states whilst perceiving and acting (Varela et al., 1991). As Armstrong (2006) explains, 'the enactive perspective takes the repeated *sensorimotor interactions* between the agent and the environment as the fundamental locus of cognitive development' (p. 11). Recent developments within cognitive neuroscience have provided empirical support for this interdependency between action and perception (Leman, 2007, p. 48).

Armstrong suggests that his encountering of an often negative critical reception of computer music in general may in part be due to the fact that many DMIs have failed to provide the potential for an embodied relationship between performer and instrument, due to a lack of fully developed technical and, moreover, theoretical frameworks (Armstrong, 2006). As a result, he argues, the performer often feels disengaged from the instrument and therefore also with the musical content. As a consequence, the audience also perceives this disconnect, and the performance suffers as a whole. Comparably, Essl and O'Modhrain (2006) suggest that we need to consider the various ways in which perceptually guided action might define 'the "feel" and playability of a musical instrument' (p. 294), in the quest to develop a design philosophy for new DMIs; but, they warn that we are only 'at the beginning of understanding when a sensorimotor experience is natural and believable for a performer' (Essl & O'Modhrain, 2006, p. 294). There seems to be an emerging sense of a demand for deeper thought and theoretical rigour with regard to DMI design, in the midst of increasingly inexpensive and ubiquitous technology. These concerns are echoed in recent calls for more discussion into the nature of performance (Schroeder & Rebelo, 2009), and the relationship between body and instrument within a performance environment (Rebelo, 2006).

Instrument–Performer Relationship

In what follows I will explore some of the methodologies related to instrument design that have emerged out of my practice as a performer of piano and live electronics, and have led to the haptically augmented hybrid piano. Before doing so, however, it is important to outline ways in which current thinking in the field of instrument design has influenced these developments, and how this thinking can be shown to support some of the conclusions that have been drawn purely through practice. Certainly, it could be claimed that the subset of DMIs known as *augmented instruments* is inherently suitable as a potential candidate for offering engaging and embodied modes of performative activity, due to the established development both of the acoustic instruments around which they are built, and the corresponding history of performance practice. Indeed, the literature surrounding the design philosophies of those DMIs in which the importance of tactility is emphasised includes a discussion of the favourable multimodal embodied engagement afforded by *acoustic* instruments, and an agreement of the tactile–kinaesthetic action–perception loops that arise during play as being crucial to performance (Cadoz, 2009; Rovan & Hayward, 2000; Vertegaal, Ungvary, & Kieslinger, 1996). This seems to allow for a definition of performance as perceptually guided action:

> Actions necessitate concurrent and consequent perceptions, and perceptions guide and inform actions. Thus the concept of enaction is inevitably dependent upon embodied knowledge, the kind of knowledge that is derived from being and acting in the world, with all its physical properties and constraints. (Essl & O'Modhrain, 2006, p. 287)

However, as we start to modify the instrument and inevitably construct relationships between gesture and real-time sound production, this intrinsic structural coupling between sound and touch can become fractured.

Essl and O'Modhrain's approach to creating an embodied instrument–performer relationship takes as its basis an innovative solution to the problem of how to map input gesture to sound. This relies on the performer's tacit knowledge of real-world objects (Essl & O'Modhrain, 2006). By grouping together sets of actions that afford common types of behaviours, different audible responses, which arise from the similar types of interaction, can be substituted. For example, physical grains, such as pebbles, are used to *make tangible* the process of granular synthesis. Moreover, the sonic result may reflect the acoustic sound of stones themselves, or indeed the sound of colliding ice cubes. Here the *structural coupling* (Varela et al., 1991) between interaction and sonic result is compelling. Armstrong's (2006) approach, on the other hand, looks towards creating adaptive and emergent performance environments through a combination of hardware and software, which employ various types of instrumental resistance to the performer and which engage the rich and dynamic aspects of human behaviour.

It is important to notice that the musical goals in each case are concentrated around engagement, playability, and interdependency, rather than control. This echoes Rebelo's (2006) notion of the 'multimodal participatory space' (p. 29). He argues that when the instrument is thought of as an entity, rather than merely as a functional tool, it carries its own cultural significance, created through the choices of the instrument-maker and elicited through its relationship with the performer. It should follow, then, that when it is the performer who is also the instrument-maker, the resulting instrument can be deeply personalised through prolonged embodied practice. In developing the hybrid piano, the largest amount of time spent on the project was devoted simply to playing, feeling and listening, adjusting, and playing again. Hence, the development of the instrument itself was an embodied activity.

Cadoz warns against classifying every situation that maps gesture to real-time sound processing as *instrumental* (Cadoz, 2009). He starts by defining instruments as real-world objects, which can give rise to both acoustic and visual phenomena through the physical energy exchange that takes place when a human interacts with the object or with the environment through that object. He describes this type of interaction as *ergotic* (Cadoz, 2009). In a musical situation, only the performer experiences the direct tangible interaction with the object; the audience perceives the related visual (gestural) and auditory (musical) information. With regard to acoustic instruments, the interaction is clearly ergotic, in that the action and resultant sound are intrinsically coupled. Cadoz (2009) claims that the subtle variations in how we create and perceive the phenomena of these instrumental gestures 'are of a primordial importance for the study and the understanding of the enactive conditions for the expressive and cognitive activities' (p. 219). The problem for Cadoz arises in DMIs, where the ergotic interaction of the gesture bears no actual physical relation to the resultant sound, even if performed in real time. Here, even sophisticated mapping choices cannot remedy this, as there is no real-world continuum of energy from input gesture to sound processing. As a result, Cadoz advocates continued research into using force-feedback haptic devices, along with physical modelling techniques, as a way to transduce energy from gesture to sound.

Nevertheless, there is an obvious potential for this type of interaction within an augmented instrument. Certainly, it would be extremely difficult to imagine an augmented instrument without this capacity, unless the gestural and sound-producing mechanisms were entirely decoupled. A possible, yet trivial case would be a performance where the body of the instrument was, for example, pressed by the performer, causing no acoustic sound, but triggering, by way of sensors, digital processes. Essl and O'Modhrain (2006) describe the notion of an augmented instrument as one which takes 'traditional instruments and augments them by adding sensing technologies that offer access to aspects of the instrumental gesture' (p. 286). The actual way in which we gain access to this physical energy, and how we use the data that we cultivate from it, must be carefully considered in the design of the augmented instrument. The goal is to create a performance environment that can facilitate a greater potential for expression and an increased sense of engagement. This arises not from creating something that can be easily mastered, but rather by ensuring that the performer's embodied experience of playing continually provides them with 'new forms of embodied knowledge and competence. Over a sustained period of time, these negotiations lead to a more fully developed relationship with the instrument, and to a heightened sense of embodiment, or flow' (Armstrong, 2006, p. 6).[1]

Digital Augmentation

Having established some of the philosophy that continues to influence my own approach to building instruments, I will now outline the two layers of development of the hybrid piano, starting with the original augmentation of the acoustic instrument. The hybrid piano has evolved over the last four years through my ongoing performance practice, which includes the fields of composition and also solo and ensemble-free improvisation. I term the instrument a *hybrid* piano, to emphasise the integration and importance of both the acoustic and digital components, although, of course, it easily falls within the class of augmented instruments. The hybrid piano has been developed as a performance system that enables digital signal processing (DSP) through live sampling, synthesis and sample triggering, and so on, all of which are controlled by the performer alone. Thus, no additional performer is required to oversee the execution of the electronic aspect. The acoustic sound of the piano is usually amplified through loudspeakers, so as to match the dynamic range of the electronic sound, although this is not always necessary, depending on the performance space. It is worth mentioning that the hybrid piano has no real-world unique identity, in that it is designed to be constructed around any piano model,[2] and indeed has manifested on both a Bösendorfer Imperial and an abandoned upright, which was prepared in a Cagean fashion. Whilst continuously evolving through a part-modular software approach, certain aspects of the sonic character of the instrument have remained constant over the years, and as such, it can be recognised as a developing system, and not a series of radically different experiments. For example, partial tracking has been used since inception, either to resynthesise sine waves or, latterly, to generate resonances.

The first appearances of the instrument were in the context of compositions involving live electronics, which explored the notion of using the instrument both as the sound source and as the controller. This makes use of the enactive knowledge already accumulated within the motor skills of the pianist. These early works employed machine listening techniques, in which the acoustic material was continuously analysed by the computer for various information such as pitch, dynamic, phrase length,[3] and perceived silence. Through intimate exploration with the system, there emerged a strong desire to adhere to what I only later learned could be classed as Cadoz' *instrumental gesture*, in the sense that the ergotic interaction and resultant sound should be energetically coupled, as described above. Using the piano as both the sound source and the interface to the digital sonic world would help to facilitate this type of union. This leaves the pianist free from having to operate additional controllers, and hence able to negotiate the instrument and focus on the playing, extended techniques, and general musicality within the performance. In a sense, this is not so far removed in ideology from the approach of Essl and O'Modhrain: in both cases it is the sensorimotor skills already known to the user that are exploited in their relationship to the instrument. The case of a musician using an augmented instrument is simply a subset of the more general case. Similarly, the coupling of gesture to sound in the hybrid piano used the idea of making tangible the type of real-world forces at work. Hence, just as granular synthesis was physically represented through colliding pebbles, the hybrid piano uses, for example, the attack of the hammer on the string to *bring forth* an impulse through a resonant filter.

In the context of the compositions, the use of MIDI foot pedals was avoided. Their use is a commonly encountered performance practice within compositions involving acoustic instruments and live electronics, used either as a trigger for sound file playback or to advance preset sections within the software. Instead, within those compositions that used a timeline, a more fluid approach was employed, which made use of time windows combined with dynamic or pitch-based triggering systems. Thus, realisations of compositions, which often featured improvisational elements, could be more easily moulded into a form more fitting of a particular performance, as determined by the particular environment. So, for example, if the performer[4] feels that the present section needs more development, then they may extend it within the given time frame. In this way, as well as giving the performer more of a sense of value to their movements, there is more chance that the audience will perceive the sonic and semiotic information as resulting from a particular instrumental gesture, which will contribute to the listeners' experience of the music.

Tied into the themes of tangibility and interaction is the idea of the work, or effort, contained within a musical exchange. 'Physical effort is a characteristic of the playing of all musical instruments' (Ryan, 1991, p. 7) is a view that is universally accepted for acoustic instruments, but often neglected when building digital ones. Acoustic instruments resist the will of the performer, and it is within these precarious negotiations that expression is formed. Evens (2005) states, 'Music does not result from the triumph of the musician over the resistance of the instrument, but from their struggle, accord and discord, push and pull' (p. 160). The body of the acoustic instrument already resists the performer: pressing a key takes a small amount of effort; playing rapid *staccato* scales smoothly demands a different type of work; and on plucking a string inside the frame, another set of resistances and forces is felt. The piano, then, could be thought of as a force feedback or *haptic* interface to the computer. The obvious difference in the case of the hybrid piano is that instead of data read directly from physical parameters, such as, for example, the distance that a key is depressed, parametric data are derived from the acoustic properties of the instrument. However, this can certainly still be a useful measure of performance *energy*.

Comparatively, when working with the Novint Falcon,[5] an inexpensive three-dimensional games controller with force feedback, aside from the programmable forces offered to the user, the output data sent to the computer is simply *x*, *y*, and *z* position information. There is no obvious reason why this is a better choice of representing the physical energy put into a system than an analysis of the produced auditory information.

Haptic Augmentation: Perceptually Guided Action

Over an extended period of research, which included regular performance with the hybrid piano, it became apparent that developing a palpable sense of the physicality of the electronic sound was just as important as the analysis techniques, DSP, and the transducing of physical gesture into corresponding changes within the software. It became clear over time that while I was receiving the usual physical vibrations from the acoustic part of the instrument, through the acoustic resonance naturally felt in my hands, along with the more subconscious vibrations felt through my feet in connection with the pedals or floor, for the digital audio there was no analogous tactile feedback mechanism. I had to rely purely on my ears (and eyes via the laptop screen) to receive information about the sonic digital counterpart. The electronic sound would emerge from loudspeakers placed proximally to the piano, when the concert setup would permit this, or on either side of the stage, when this was not feasible, as is an unfortunate reality of many concert scenarios. Even with stage monitors, however, I felt a strong sense of disconnect; a feeling of being literally *out of touch* with what I was playing, despite being able to hear it, to some extent. Furthermore, reliance on the screen is problematic when using augmented instruments (Hayes & Michalakos, 2012), as it can be distracting and interrupt the sense of absorption in the task at hand. When this occurs for the performer, the audience are likely to perceive it too.

Attempts have been made to address the issue of the lack of tangible feedback in DMIs by embedding the vibrotactile feedback in the instrument itself (Berdahl, Steiner, & Oldham, 2008; Marshall & Wanderley, 2011; O'Modhrain, 2001). Collin Oldham's *Cellomobo* is perhaps one of the more established new musical instruments that features vibrotactile feedback. A speaker driver is used to create the haptic feedback and, in combination with a resistive ribbon controller, makes up a virtual bowed string setup (Berdahl et al., 2008). Hence, when the player bows the instrument they are provided with a physical representation of the slip-stick motion of a bowed string, while concurrently providing gestural input data for controlling sound synthesis. It was precisely this haptic information that Oldham felt was lacking in previous instruments. Like Marshall and Wanderley's approach, the vibrotactile feedback is embedded in the DMI itself, to make it *feel* more like an acoustic one. My motivation for the further augmentation of the hybrid piano with vibrotactile feedback was to maintain perceptually guided action through play, by being physically *in touch with* both the acoustic and digital sound worlds.

From a practical perspective, *embedded* vibrotactile feedback would not be appropriate for a piano. Firstly, the pianist is accustomed to the most direct vibrations being felt through the hands and thus would have to be in direct contact with the instrument in order to perceive the embedded feedback. This would work for the direct, instrumental gestures described earlier, but would be problematic for auditory responses that were not directly linked to the performed gesture. For example, a sound with delayed onset, or long duration, would no longer be perceived once the hands had been lifted from the piano. The solution to this was to *embed* the vibrotactile feedback directly onto the skin of the performer, instead of the instrument. This was done by placing small vibration motors on the hands of the performer using a thin, light-weight glove. Other work in the field has explored using vibrotactile rings (Rovan & Hayward, 2000), but it was decided that a fingerless glove would be less invasive for a pianist. By driving the motors with pulse width modulation, a large dynamic range of sensations can be felt, from a barely perceptible tingle to overbearing full vibration. Details of the technology employed can be found in Hayes (2011), although it should be noted that the original system required the performer to be relatively close to the computer, as the motors were sent information from the computer via a microcontroller via USB (Figure 1). The system has recently been improved with the support of Marije Baalman at STEIM,[6] Amsterdam, to allow numerous vibrotactile devices to function simultaneously and, more importantly, wirelessly.

As mentioned earlier, the hybrid piano takes form over numerous acoustic pianos, and thus by developing the technology around the musician instead, it becomes much easier to cater to every possible performance situation. By correlating the haptic

Figure 1. Performing at the Sonic Arts Research Centre, Queen's University Belfast, with the Haptically Augmented Hybrid Piano.

feedback with the produced digital sound through a simple amplitude mapping, the performer of the hybrid piano receives immediate, private feedback about both the acoustic (through the piano itself) and the electronic (through the haptic device) sound worlds. The potential for performance as perceptually guided action is fully enabled through the mutually affecting relationship between performer and instrument. Again, Cadoz (2009), in support of the enactive view, suggests that 'The (ergotic) gestural interaction (which may concern the whole body) … is inseparable from a specific perception, the tactilo-proprio-kinesthetic perception (TPK), and this perception is needed for the action just as the action is needed for this perception' (p. 217). The possibility to play, and to perceive this on the skin, from outside the body, now exists. A consequence of the decision to place the haptic feedback directly onto the performer would suggest a discussion of embodied cognition within the realm of cybernetics, although this is beyond the scope of this paper.

Embodying the Composition

Just as the various structural materials of acoustic instruments, not to mention changes in environment and temperature, will give different sensations to the performer, it is worth exploring the range of perceptual possibilities that the vibrotactile feedback paradigm offers. Firstly, alternative mediations between the digital sonic output and the haptic vibration can be introduced. For example, by feeling the *density* of the sound on the skin, or the amplitude of a *single* process within the electronic part, the performance can differ drastically, especially in the case of improvisation, as the sensory perception will be completely changed. Of course, multiple sensations can be experienced simultaneously, but this quickly results in a sensory overload, which becomes unhelpful to the performer. Since the practice of using sensors to extract information about the gestures and movements of the performer is almost ubiquitous in the world of electronic music, it seems worthwhile to explore different filtering or analysis methods to extract information from the digital auditory signal to send back *to* the performer.

Moving away from purely instrumental gestures, I will extend this notion by proposing that the artificial feedback may be used to convey not only a physical representation of the audio, but other dimensions within the *black box* that we might wish to embody.[7] This idea was explored in the composition *kontroll* (2010) for prepared piano, self-playing snare and live electronics. Here, vibrotactile feedback was used to send the performer information about successful triggering, time windows, and cues within the piece, through a series of symbolic vibrations (Hayes, 2011). In this scenario, the action (the performing) is still very much perceptually guided, but, where direct amplitude-correlated haptic feedback affects action–perception on the near-instantaneous micro-level, this secondary type of information will influence playing on the conscious macro-level of musical structure, influencing aspects of timing or phrasing. For example, if I am guided towards an approaching change in the development of the piece, by way of a vibration that increases in intensity, I may adjust my playing accordingly, building up (or down) towards the change. Perhaps more crucially, the performer is no longer confined to checking for feedback awkwardly on the laptop screen, or worse, worrying about whether a particular trigger was successful or not.

Conclusions

Within the area of digital and electronic instrument design, the focus is overwhelmingly directed towards methods for yielding input data, with minimal attention given to the feel of the instrument for the performer, and the instrument–performer relationship. This paper has attempted to delineate some of the historical thought that has informed current research into the use of haptic technology within this field. By examining various enactive approaches to DMI design, we can see that common threads emerge of multimodal interaction, structural coupling between sound and interface, and the notion of action as guided by perception. The haptic augmentation of the hybrid piano was demonstrated to have evolved out of these ideas, despite already offering what appeared to be a largely embodied mode of interaction for the performer. I will conclude that this feedback system allows the performer and instrument to be more closely intertwined, which in turn significantly influences the musical outcomes, not only in the live performance situation but also within the compositional process, helping the composer to gain insight into how the music actually feels through the process of creation.

Notes

[1] See Dreyfus and Dreyfus (1999) for a description of the various stages of skill development. Even at the expert stage, the performer will make use of their acquired embodied knowledge as they instinctively play by feel.
[2] This will be shown to be of importance in the next section, with regard to implementing haptic feedback.
[3] Phrase length was determined by setting a maximum period of silence between notes before a new phrase was registered.
[4] In all my works involving the hybrid piano, I am the sole performer, but I refer to 'the performer' here, and elsewhere in this work, in the third person, to emphasise the application of these ideas to the more general case of performance.
[5] www.novint.com/index.php/novintfalcon.
[6] www.steim.org.
[7] Although it is beyond the scope of this paper, the vibrotactile system was also used as a method of communication between two improvisers, each playing an augmented instrument (one of which was the hybrid piano) (see Hayes & Michalakos, 2012, for details).

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