Nonlinear Dynamics In Musical Interactions

Thesis

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Nonlinear dynamics in musical interactions

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Abstract

This thesis examines nonlinear dynamical processes in musical tools, identifying certain roles that they play in creative interactions with existing tools, and investigates the roles they might play in digital tools. Nonlinear dynamical processes are fundamental in the everyday physical world. They lie at the core of many acoustic instruments, playing a particularly significant role in bowed and blown instruments.

Two major studies are presented that approach these issues from different perspectives. Firstly a set of comparative studies explore the ways in which musicians engage with systems that do and do not incorporate nonlinear dynamical processes. Secondly, interviews with a range of musicians engaged in contemporary musical practices — particularly free improvisation — are used to investigate the role of nonlinear dynamical processes in instrumental interactions in relation to unpredictability and creative exploration.

Evidence is presented demonstrating that nonlinear dynamical processes can be drawn on as resources for exploration over long time periods. An approach to creative interaction that explicitly draws on the properties of nonlinear dynamical processes is uncovered and connected to material-oriented notions of creative processes. Nonlinear dynamics are shown to facilitate a productive "sweet spot" between unpredictability and complexity on the one hand, and detailed, sensitive, deterministic control, coupled with the potential to repeat and develop particular actions on the other. The importance of *timing* in interactions with nonlinear dynamical processes is highlighted as being significant in creating explorable interactions, particularly close to critical thresholds.

A distinction is raised between instantaneous unpredictabilities that emerge from the interaction with the tool (*interactional*), and unpredictabilities that result from the unexpected implications of the conjunction of otherwise anticipated elements (*combinatorial*). While the usefulness of the latter in creative interactions is frequently acknowledged in HCI research, the former is often excluded, or seen as a hinderance or obstruction. Engagements with nonlinear dynamical processes in existing musical instruments and practices provide clear evidence of the utility of both nonlinear dynamics, and interactional surprises more generally, suggesting that they can be of use in other domains where creative exploration is a concern.

Contents

Related Publications

Parts of the research presented in this thesis have been presented in conferences and published in conference proceedings. Formative aspects of the literature review were published in both the 2014 New Interfaces for Musical Expression proceedings, and the 2014 Designing Interactive Systems proceedings:

> Mudd, T., Holland, S., Mulholland, P. and Dalton, N. Dynamical Interactions with Electronic Instruments. In *Proc. New Interfaces for Musical Expression* Conference. Goldsmiths, London, 2014.

> Mudd, T., Holland, S., Mulholland, P. and Dalton, N. Dynamical Systems in Interaction Design for Improvisation. In: *Workshop on Human Computer Improvisation at 2014 ACM conference on Designing Interactive Systems*, June 21st - 25th 2014, Vancouver, BC, Canada, 2014.

The results of the initial exploratory studies and trial study detailed in Sections 4.2 and 4.3 were presented at the International Conference on Live Interfaces in 2014:

> Mudd, T., Holland, S., Mulholland, P. and Dalton, N. Nonlinear Dynamical Systems as Enablers of Exploratory Engagement with Musical Instruments. In: *INTER-FACE: International Conference on Live Interfaces 2014*, 19th - 23rd November 2014, Lisbon, Portugal, 2014.

The key results from the main comparative study detailed in Section 4.4 were presented at the 2015 Sound and Music Computing conference:

Mudd, T., Holland, S. and Mulholland, P. Investigating the effects of introducing nonlinear dynamical processes into digital musical interfaces. In: *Proceedings of the 2015 Sound and Music Computing Conference*, Sound and Music Computing Network, 2015.

The ramifications for music and HCI of considering creative interactions from a material-oriented perspective have been presented as a CHI Workshop paper:

Mudd, Tom. 2016. Material-Oriented Musical Interaction. In: *Proc. of CHI 2016*, San Jose, 7-15 May, 2016.

Chapter 1

Introduction

This thesis examines a particular mechanism in musical interactions: nonlinear dynamical processes. In this context, the term 'dynamical' refers to the temporal development of a system or instrument, as a function of both inputs to that system and the current state of the system. 'Nonlinear' implies that this includes a nonlinear term (more thorough definitions are provided in Section 2.1). Nonlinear dynamical systems may exhibit a wide range of behaviours in response to changes in input: abrupt changes in behaviour, instability, locking into particular states, and potentially producing very diverse outputs for the slightest change in input. Interactions with nonlinear dynamical processes can therefore be potentially confusing, unstable and unpredictable.

Although the use of such processes may sound esoteric, it will be shown that such systems play an important role in many acoustic musical instruments, play an essential role in certain acoustic instruments, govern interactions in many analog electronic musical instruments, and have been deliberately implemented in a range of digital musical instruments. Indeed, nonlinear dynamical processes can be thought of as the rule rather than the exception in our everyday interactions with the physical world (Prigogine and Stengers, 1984; DeLanda, 2002), yet these processes have rarely been explicitly examined from an interaction perspective.

In human-computer interaction (HCI) there is a tendency to make input-output relationships as clear and as simple as possible. This approach carries over into the design of digital tools for music and other kinds of creative activity, resulting in a markedly different kind of creative engagement. The difference between digital and acoustic musical tools is often couched in terms of the complexity of digital systems, and the physicality of acoustic systems. In interaction terms, the latter may sometimes seem simple: a child can pick up a recorder or clarinet and make a sound. By contrast, the same child may struggle to engage with many digital interfaces for music, with the myriad settings, dials, buttons, sliders, numbers and menus. A closer examination of the input-output relations in acoustic systems reveals a surprising amount of complexity, chaos, and potential unpredictability however. Modelling the specific nonlinear and time-dependent behaviours of even relatively simple acoustic instruments is a difficult process, and even some of the most accurate models involve a range of simplifying assumptions. From this perspective, even the most sophisticated digital music system can seem "simple" in interaction terms when compared to an instrument as complex and nuanced as a recorder or clarinet.

The complexity of interaction with acoustic instruments may be linked to the long term potential of such instruments to afford long-term exploration. Magnusson (2009) makes this connection, pointing out that these complexities are inherent in the physical materials: "the physics of wood, strings and vibrating membranes were there to be *explored* and not invented." (ibid., p 174, emphasis in original). Magnusson explicitly relates this to the nonlinear behaviour of such instruments:

> "As opposed to the generic explicitness of the digital instrument, the acoustic instrument contains a boundless scope for exploration as its material character contains a myriad ways for instrumental entropy, or 'chaotic', non-linear behaviour that cannot be mapped and often differs even in the same type (brand and model) of instruments." (ibid. p 174)

It seems likely that there is a link between the nonlinear properties of acoustic instruments and this boundless scope for exploration. Strange and Strange (2001) highlight the complexity of bowed interactions as the aspect of the violin which is still being explored by performers and composers (ibid. p. 1). The stick-slip interaction of the bow with the string contains a range of nonlinearities which are critical in modelling in the behaviours of bowed strings (Fletcher, 1999; Smith, 2010).

It seems like a natural step to explore digital interactions through similar mechanisms. This is the approach taken in this thesis: investigating the extent to which this link between particular kinds of creative exploration and nonlinear dynamical processes exists and how this might be relevant for digital instrument design, and other creative human-computer interactions. It is important to make clear at the outset that the introduction of nonlinear dynamical processes into musical interactions is not seen as a way to somehow improve otherwise impoverished electronic and digital tools, but rather to explore differences in affordances (see Section 2.3.2) that may come about as a result of their inclusion. Do we engage differently with nonlinear dynamical tools?

Examining complex, potentially unpredictable interfaces raises broader questions about the role of surprise in creative interactions. When and how can surprises be valuable parts of the process? This thesis examines particular musical practices in which unpredictable aspects of musical tools and instruments are viewed as valuable resources for exploration and experimentation. The musicians get something back from the tool that cannot be anticipated in advance. This will be referred to as a *material-oriented* approach to creative engagement. This contrasts with what can be termed a *communication-oriented* approach: the idea that creative tools should be transparent conduits for creative ideas, allowing an original plan conceived in the mind to be realised seamlessly and without mediation. This material-oriented mindset is explored in musical interactions, both in terms of uses of nonlinear dynamics, and in relation to existing interaction theories.

1.1 Summary of Contributions

The central contributions made in this thesis arise from blending detailed examinations of specific musical contexts with detailed examinations of particular kinds of interaction. The studies and discussions presented therefore make contributions in both directions. Firstly, the nature of musical interactions, and the relationships between musicians and their tools provide insights for digital musical interactions, and for HCI more generally. Secondly, musicological understandings of specific musical domains — particularly free improvisation — are developed through an examination of tool interactions. A brief summary of the central research contributions made in this thesis is provided here for convenience.

1. Empirical findings on the role played by specific nonlinear dynamical processes in digital musical interactions. See Sections 4.4.2, 4.5 and Chapter 7.

2. Empirical research into the role played by nonlinear dynamical processes in improvisatory musical practices. See Sections 5.3, 5.4 and Chapter 6.

3. Evidenced characterisations of the relationships between surprise, exploration and control in creative interactions, drawn from the instrumental engagements of musicians engaged in free improvisation and experimental music. See Sections 2.2, 5.3, 5.4 and 6.2.

4. Evidence of an approach to creative interaction that explicitly draws on the properties of nonlinear dynamical processes. See Sections 5.4.1 and 6.2.

5. Identifying and addressing a gap in existing HCI theories regarding creative interactions. See Sections 2.3.1, 5.4.2, 5.4.4 and 6.1.1.

6. Implications for creative interaction design and HCI across a range of other domains. See Sections 2.3.4 and 4.5.

7. Recommendations for further research on nonlinear dynamics in interaction. See Sections 4.5, 4.5.8 and 7.4.

1.2 Research Question

This section lays out the initial research question and a list of related questions that must be considered in examining the primary question. The project's wider aims are then discussed, and the proposed methodology is sketched prior to the full account given in Chapter 3. The primary research question is as follows:

Initial Research Question:

How is interaction affected by the inclusion of nonlinear dynamical processes, in particular in the domain of digital musical instruments?

Subquestions:

1. What roles do nonlinear dynamical processes play in existing instruments (whether acoustic, electronic or digital)?
2. How do the properties of nonlinear dynamical processes relate to affordances in musical instruments?
3. How are nonlinear dynamical processes incorporated into existing musical practices?
4. How do people of varying musical backgrounds engage differently with instruments incorporating nonlinear dynamical processes?
5. Is there a link between nonlinear dynamical processes and exploratory approaches to engaging with musical instruments?
6. How can the effects of nonlinear dynamical processes in musical interactions be evaluated?

7. What roles can nonlinear dynamical processes play in human-computer interaction beyond the musical domain?

The questions stated above suggest a wide range of possible avenues of investigation. Four specific domains of interest can be identified in these questions:

1. mathematical understandings of the nature and properties of nonlinear dynamical processes;
2. interaction, and specifically digital interaction (HCI);
3. digital musical instruments;
4. specific musical practices.

Each of these domains are addressed in depth in the literature review: nonlinear dynamics in Section 2.1, HCI and digital musical instruments in Section 2.3, and specific musical practices in Section 2.2. Two of the key terms used in the research questions are discussed briefly below to avoid ambiguity.

1.2.1 Digital musical instruments

What is denoted by the term 'digital musical instrument'? In the context of this thesis the word 'instrument' is used to refer to a system that relates some kind of human input to an audible output. In this sense, instruments are distinct both from input controllers, which generate only data and not sound, and from sound engines, which can generate sound, but do not have a specific, fixed interface. Granular synthesis for example, is a type of sound engine, but only becomes an instrument when a particular input method and a mapping between the input and the sound engine are provided. A change in the input, the output or the nature of the mapping constitutes a change to the instrument.

1.2.2 Potential roles for nonlinear dynamical systems

The word 'role' alludes to the fact that nonlinear dynamical processes may be included in musical instruments in a number of ways and on differing scales, with varying degrees of significance to the overall interaction. The nonlinear dynamical aspects of hammer strikes and vibrating strings in a piano may be seen as relatively minor with regards to most interactions with a piano (if the performer is only using the keys and pedals rather than directly interacting with the strings[1]). The nonlinear dynamical aspects of a reed instrument can be seen as of a greater significance from an interaction perspective, and must necessarily be engaged with even by a beginner starting out on the instrument.

In digital systems, the nonlinear dynamical processes may not even be directly involved in the sound generating algorithm, but may instead form part of a parameter mapping layer placed between the musician's input and the parameters governing the sound engine.

1.3 Studies presented in this thesis

Two distinct approaches to exploring the research questions are presented in this thesis. The first approach involved 28 musicians engaging with four digital musical instruments that were specifically designed for this thesis. To explore the significance of nonlinear dynamical processes in interaction, two of the instruments were designed to incorporate these processes, while the other two were based around other processes. Participants gave quantitative and qualitative feedback regarding their use of the instruments, and their attitudes towards the interaction.

The second study took an ethnographically-informed approach to investigating the musical practices of 24 musicians engaged in free improvisation. Participants were asked about the role of surprise and exploration in relation to their musical practice, and in relation to the tools they used. Thematic analysis of participant interviews was employed, from which a range of

[1]However, see the case study of participant 3598 in Section 5.3.2.3 for an example of when this does become a significant aspect of even key-based interactions.

different kinds of engagements with nonlinear dynamical processes emerged, connecting with attitudes to unpredictability, exploration, and questions of control.

It is difficult to explore interactions with musical tools and instruments without a thorough understanding of the musical and social contexts under consideration. There may be a wide variety of motivations behind a particular use of a given instrument. The blend of methodologies employed here helps to explore the problem from multiple perspectives, triangulating these perspectives towards a nuanced understanding of interaction in such a rich context.

1.4 Structure of this thesis

Chapter 2 presents a thorough literature review, providing detailed background on three central areas for this thesis:

- nonlinear dynamical processes, in terms of formal definitions, example systems and relations to musical practice;
- specific musical contexts, detailing attitudes to instrumental and technological engagement in experimental music, free improvisation, and contemporary computer music;
- HCI research as it relates to the design of digital musical instruments, the design of creative tools more generally, and the role of surprise and exploration in interaction design.

The specific methodology is then described and contextualised in Chapter 3, elaborating on the method of triangulation between lab-based comparative evaluations of specific digital musical interfaces, and ethnographically-informed approaches. The two studies are then presented and discussed in Chapter 4 (the comparative evaluation studies) and Chapter 5 (the ethnographically-informed study). Broader discussions are reserved for Chapter 6, where the implications of the research are related back to the specific theories and literature examined in Chapter 2.

Chapter 2

Literature Review

2.1 Nonlinear Dynamics

This section provides a relatively brief overview of those aspects of nonlinear dynamical systems that are necessary for the discussions in this thesis. Definitions and descriptions of key concepts and terminology are given, along with a more detailed look at three specific systems that provide concrete examples and that have all been employed in musical applications. The wider cultural significance of nonlinear dynamics is then considered with a particular focus on creative practices. Specific musical applications are then discussed, focussing on situations where nonlinear dynamical systems are explicitly implemented in compositions, synthesis processes and circuit design, and where they are embedded in the physical processes governing the behaviour of acoustic instruments.

2.1.1 Background, Definitions and Terminology

Dynamical processes have been studied since at least the 17th Century (Strogatz, 1994). The more complex properties and emergent behaviours of particular interest in this thesis were not examined closely until the second half of the 20th Century with the advent of computers and the ability to quickly model various systems and observe their outcomes (Strogatz, 1994;

Ott et al., 1994). The study of nonlinear dynamics has yielded applications across a diverse array of fields such as ecology, chemistry, fluid mechanics, solid state devices, and biology amongst others (Ott et al., 1994). They have also been explicitly employed in the arts in a variety of contexts, including visual art and music, both acoustic and electronic.

2.1.1.1 Dynamical Systems

Ott et al. (1994) describe a dynamical system as being any set of equations giving the time evolution of the state of a system from a knowledge of its previous history. Ott et al. (1994) utilise the following terminology that will be adopted in this thesis, firstly for continuous time differential equations:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}) \tag{2.1}$$

where:

- $\mathbf{x} = (x^{(1)}, x^{(2)}, ..., x^{(k)})$ denotes k state components, considered as a vector in k-dimensional phase space,
- $\mathbf{F}(\mathbf{x}) = (F^{(1)}(\mathbf{x}), F^{(2)}(\mathbf{x}), ..., F^{(k)}(\mathbf{x}))$ is a k-dimensional vector function of $\mathbf{x}$
- $\dot{\mathbf{x}}$ denotes the time derivative $\frac{d\mathbf{x}}{dt}$

Secondly for discrete time iterative maps:

$$\mathbf{x}_{n+1} = \mathbf{G}(\mathbf{x}_n) \tag{2.2}$$

where $\mathbf{G}(\mathbf{x})$ is a k-dimensional vector function of $\mathbf{x}$. Maps play an important part in this thesis, as the digital implementations considered are necessarily discrete.

Dynamical systems may be of different orders. The example above is a first order system as it only includes the first derivative of $\mathbf{x}$ with respect to time. A second order nonlinear dynamical system would include the second derivative ($\ddot{\mathbf{x}}$ or $\frac{d^2x}{dt^2}$), and so on. Dynamical systems can also be subdivided based on their time dependence. Systems in which **F** or **G** are not dependent on time, such as the Lorenz system for example (Wiggins, 1990), are referred to as autonomous, whereas those that are time dependent are referred to as nonautonomous, as with forced harmonic motion.

2.1.1.2 Dynamical systems terminology

This section gives a brief overview of some particular terminology necessary for discussions of dynamical systems and their behaviours.

2.1.1.2.1 Phase space and state space

The phase space is the set of possible solutions to the equations (e.g. Equation 2.1 above) governing the system. In the case of systems with two or fewer dimensions, this can be plotted on a simple two dimensional graph, but the higher dimensional phase spaces are not easily visualised. Figure 2.2 in Section 2.1.2.2 for example, shows how two variables are interrelated in the Lorenz system, but this image does not constitute the entire phase space as the system has three dimensions. State space is closely related and describes the discrete set of solutions to an iterative map (the difference equation rather than differential equation, e.g. Equation 2.2).

2.1.1.2.2 Trajectories

Changes over time to a particular initial value (or set of values), $\mathbf{x_0}$, represent a *trajectory* through the phase space or state space. Figure 2.4 in Section 2.1.2.3 shows various trajectories in the Duffing system that describe the different kinds of oscillatory behaviours found in a particular region. Figure 2.2 in Section 2.1.2.2 shows a two dimensional view of a particular trajectory in the three dimensional phase space of the Lorenz system. A trajectory represents a single possible progression through the phase space for particular initial values.

2.1.1.2.3 Attractors

Attractors are sets of points that influence the movement of trajectories in the phase space. Together they map out the set of possible behaviours for trajectories in different regions of the space, and are therefore important in understanding the range of possible qualitative behaviours. There are several possible types, including simple fixed points that may be stable (attracting trajectories within their basin of attraction) or unstable (repelling trajectories), periodic and quasiperiodic limit cycles, and chaotic attractors that are highly sensitive to initial conditions and do not produce periodic behaviour (Lakshmanan and Rajasekar, 2003).

Nonlinear systems often contain multiple attractors which may overlap in terms of their basins of attraction (or repulsion) producing potentially complex and chaotic results (Thompson and Stewart, 1986). Figure 2.3 shows the complexity of the different attractors in the Duffing system, and how the number, location and behaviour of these attractors can change abruptly at critical thresholds (discussed further in 2.1.1.3.1 and 2.1.2.3 below).

2.1.1.3 Nonlinearity and Chaos

A nonlinear function is any function that is not linear, that is, the output is not a linear combination of the input. A function, f is linear if the following two criteria are met (Lakshmanan and Rajasekar, 2003, p 7):

- $f(x + y) = f(x) + f(y)$
- $f(\alpha x) = \alpha f(x)$

Nonlinear functions may include terms for the dependent variable for which these principles do not hold, such as quadratic or cubed terms, logarithmic terms, or trigonometric functions. A consequence of the inclusion of nonlinear terms in dynamical systems is that their behaviour may become highly sensitive to the initial conditions ($\mathbf{x_0}$). This sensitivity is the prerequisite for chaotic behaviour. This is depicted in Figure 2.1 where two very similar initial states diverge considerably over time.

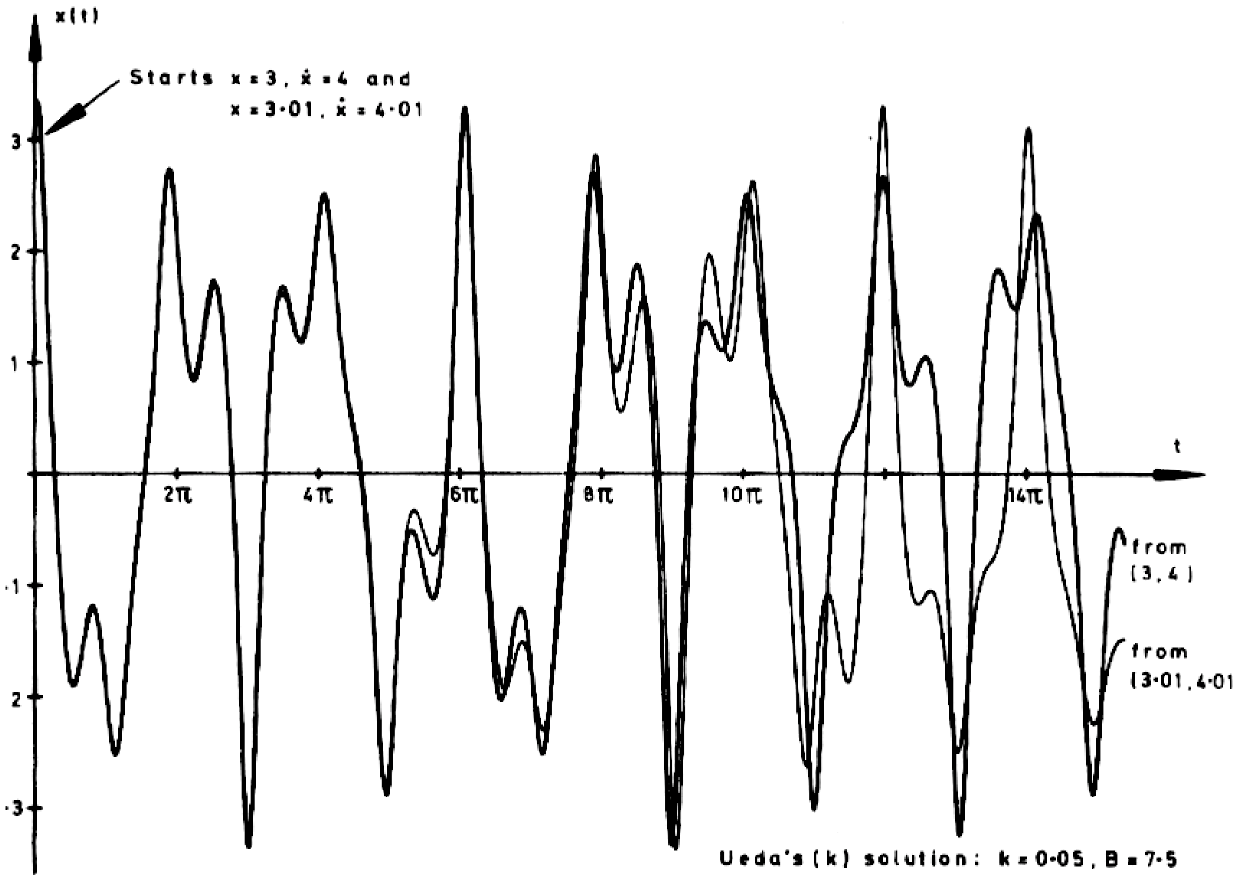

Figure 2.1: Chaotic behaviour in Duffing's equation (see section 2.1.2.3). The diagram is from Thompson and Stewart (1986) based on Ueda (1980). Two very similar initial conditions are given for x and $\dot{x}$, but the results are highly divergent.

2.1.1.3.1 Bifurcation

A bifurcation is a sudden change in the quantity or type of attractors governing the system's behaviour at a critical value of a particular control parameter (Lakshmanan and Rajasekar, 2003, p 75). Importantly, this change is abrupt even while the control parameter is varied smoothly. In many systems, bifurcations are a route to chaotic regimes (ibid.). Such changes can immediately reconfigure the types and locations of the attractors governing the movement of trajectories through the phase space.

Bifurcation points are important in the context of this thesis when considered in terms of interaction. They constitute potentially surprising thresholds where system behaviours (sonic or otherwise) may abruptly change. Moreover, the locations of these bifurcation points may be determined by a complex combination of the various system parameters, making it difficult to know exactly where they arise, and how the system will behave after the transition. Bifurcation points are discussed further in the behaviour of the Duffing equation in Section 2.1.2.3 and in relation to interactions with reed instruments in 2.1.4.3.1.

2.1.1.3.2 Hysteresis

Nonlinear dynamical systems may exhibit hysteresis, where the behaviour of the system is dependent not only on the current input to the system, but also on the prior inputs to the system (Lakshmanan and Rajasekar, 2003, p 23). This is an important property from an interaction point of view, as it means the inputs are not the sole indicators of the motion of a particular trajectory: the way a particular input value is approached is important, and the rate of change of the value may also influence what can occur. This will be examined in discussions of surprise and exploration (Section 4.5.2) and an example is provided in the context of acoustic instruments below in Section 2.1.4.3.1. More specific examples of interactions with nonlinear dynamical processes are traced in Section 6.2.2.1, showing the importance of critical thresholds and hysteresis.

2.1.2 Example Systems

Three specific nonlinear dynamical systems are examined below: the Logistic equation, the Lorenz attractor, and the Duffing oscillator. All three are frequently included in introductory literature on dynamical systems (Sparrow, 1982; Wiggins, 1990; Strogatz, 1994; Upton, 2008; Braun, 1983; Thompson and Stewart, 1986) as they provide relatively clear examples of chaotic properties arrived at through simple equations. All three have also been applied in musical situations and will be referred to throughout this thesis.

2.1.2.1 Logistic Equation

The Logistic system is a one-dimensional nonlinear system often used in simple population models (Braun, 1983), where changes over time in a population x are given by:

$$\frac{dx}{dt} = rx(1-x)$$

where r is a constant. This can be implemented as a discrete map, as is the case in the digital implementations:

$$x_{n+1} = rx_n(1-x_n) \tag{2.3}$$

The system behaves differently depending on the value of r chosen. Lower values of r (less than 3) cause x to converge to a fixed point (independent of the initial value, x_0). For $r > 3$, a range of behaviours can be encountered: sustained oscillations, period-doubling bifurcations and chaotic behaviour (the latter for $r > 3.56995$ approx., May, 1976). The Logistic equation is particularly useful for applications such as audio synthesis as it is bounded: $0 < x < 1$.

2.1.2.2 Lorenz System

In contrast to the Logistic equation, the Lorenz system is autonomous (not time dependent), and interrelates multiple variables into a system of differential equations. The system was originally devised as a model of thermal convection (Thompson and Stewart, 1986), but has since been applied in other areas (Sparrow, 1982, p 4) and has received considerable attention in comparison to other systems (Sparrow, 1982; Wiggins, 1990). Sparrow ascribes this in part to the fact that the system can give rise to a number of complex behaviours, such as chaos, intermittent chaos, and preturbulence (Sparrow, 1982, p v). The continuous time equations are generally presented as follows:

$$\begin{aligned}\frac{dx}{dt} &= \sigma(y-x)\\ \frac{dy}{dt} &= x(\rho-z)-y\\ \frac{dz}{dt} &= xy-\beta z\end{aligned} \tag{2.4}$$

And as a discrete map for use in digital simulations:

$$
\begin{aligned}
x_{n+1} &= x_n + \sigma(y_n - x_n) \\
y_{n+1} &= y_n + x_n(\rho - z_n) - y_n \\
z_{n+1} &= z_n + x_n y_n - \beta z_n
\end{aligned}
\tag{2.5}
$$

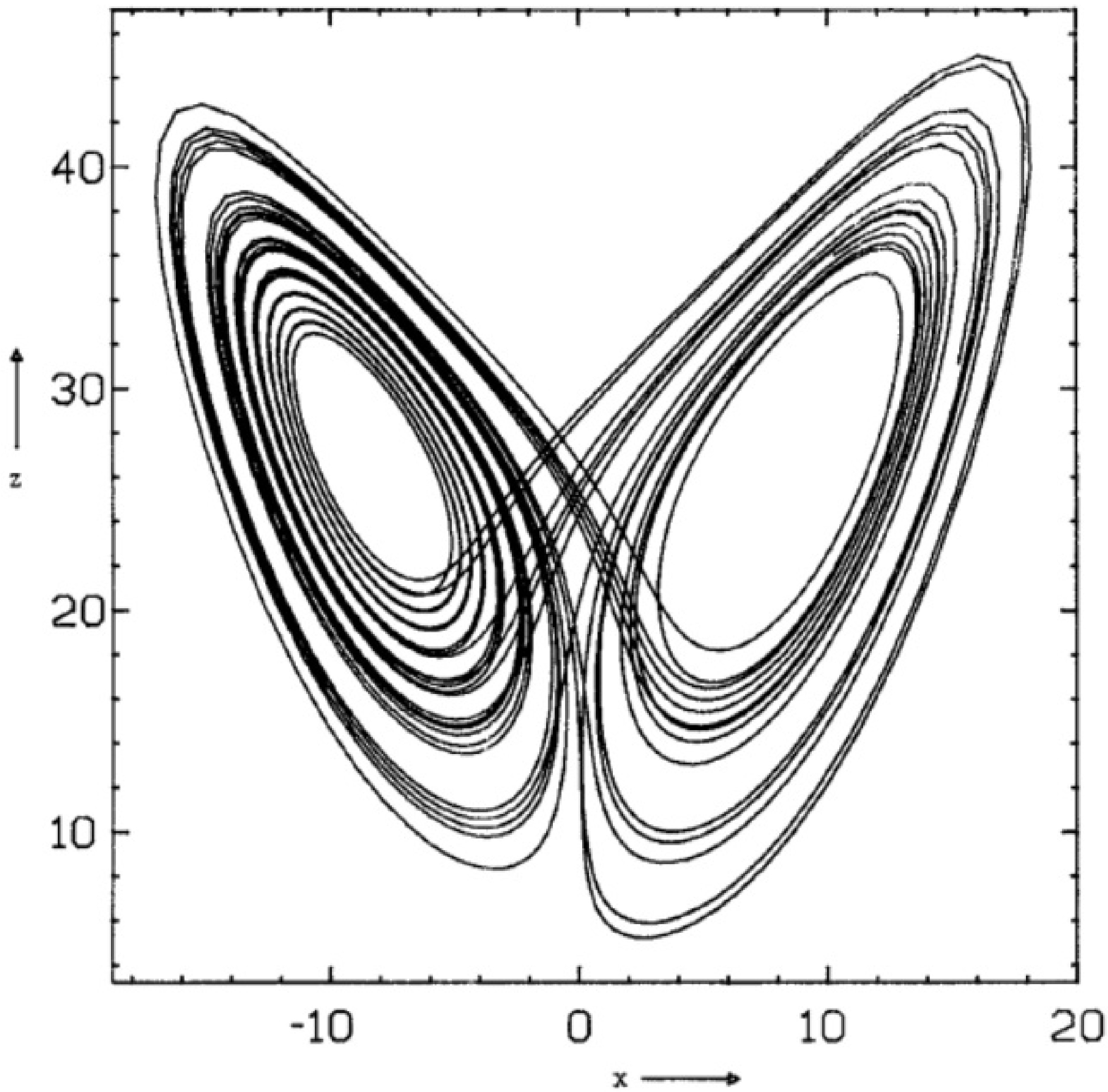

Figure 2.2: Visualisation of the Lorenz equations with $\sigma = 10, \beta = \frac{8}{3}, \rho = 28$, from Sparrow (1982).

Despite the fact that the functions are individually linear and first order, chaos is possible due to the presence of the three interrelated dimensions (Ott et al., 1994). Figure 2.2 shows a typical image of the Lorenz attractor with the particular initial values for the coefficients σ, β and ρ studied by Lorenz. The shape demonstrates visually how close the system can appear to be to repeating itself without actually doing so, showing the minor variations in the orbit. Due to the system's sensitivity to initial conditions, such minor variations can lead to highly divergent results as the system is iterated. These properties have been linked to aspects of music on a variety of scales: such as the structures of waveforms, patterns of notes or events, or longer term structural concerns, as will be discussed in Section 2.1.4.1 below. A detailed descriptive account of the different kinds of behaviours encountered in the Lorenz system is provided by Thompson and Stewart (1986, p. 212–234)

2.1.2.3 Duffing Oscillator

Duffing's equation provides a useful third example of a simple (in terms of the equation) system that can generate a complex range of behaviours. It has been applied across a range of fields, from physics and engineering to biology (Lakshmanan and Rajasekar, 2003). It is particularly useful for this thesis as it has already been the subject of considerable study (Ott et al., 1994; Guckenheimer and Holmes, 1983; Wiggins, 1990; Braun, 1983; Ueda, 1980), is considered to be one of the better understood systems (Lakshmanan and Rajasekar, 2003; Ott et al., 1994), and is frequently used as an introductory example to the rich behaviours found in nonlinear dynamical systems. It is also applied in some of the digital musical interfaces created for the comparative studies in Chapter 4, and therefore merits an extended examination in this section.

Specifically, the damped, forced, Duffing oscillator is considered here, as shown below. The Duffing oscillator includes a nonlinear term, x^3, and is nonautonomous due to the inclusion of a time-dependant driving force, $Bcos(t)$. Its behaviour is described in equation 2.6, and as a map in equation 2.7. The equation can be interpreted physically as a forced spring with a nonlinear (cubic) restoring force (Thompson and Stewart, 1986).

As a continuous differential equation (Guckenheimer and Holmes, 1983, p. 82):

$$\frac{d^2x}{dt^2} + k\frac{dx}{dt} + \alpha x^3 = Bcos(t) \tag{2.6}$$

And as a discrete map:

$$\begin{aligned} x_{n+1} &= y_n \\ y_{n+1} &= -ky_n - \alpha x_n^3 - Bcos(t) \end{aligned} \tag{2.7}$$

Thompson and Stewart (1986) provide a useful diagram (based on Ueda, 1980) of the various steady state behaviours found within the Duffing oscillator, as a function of changes to the damping magnitude and forcing amplitude (k and B respectively in the above equations). This is shown in Figure 2.3. The diagram gives an indication of the qualitative behaviour of the system as it varies with changes to the coefficients in the equation. The various regions denoted by the letters (a) to (u) identify the presence of different types and quantities of attractors. Notable for this thesis is the frequent presence of chaotic attractors and multiple attractors, and the complex layout of the regions. If one were to linearly increment a coefficient such as the forcing magnitude, B, one would pass through a wide range of behaviours. Very different patterns of behaviours would be experienced if this was done with different values of the damping magnitude, k.

The subsequent description given by Thompson and Stewart of interacting with this system is pertinent to the concerns of this thesis, and is therefore quoted at length below:

> "The regions in parameter space are delimited by various arcs. To interpret the meaning of these arcs, it is helpful to think of the parameters k and B as *controls*, like a throttle or rheostat used to adjust the operating regime of a real dynamical system such as an airplane, a motor, or a simulation device. We may then imagine this dynamical system running at high speed while the controls

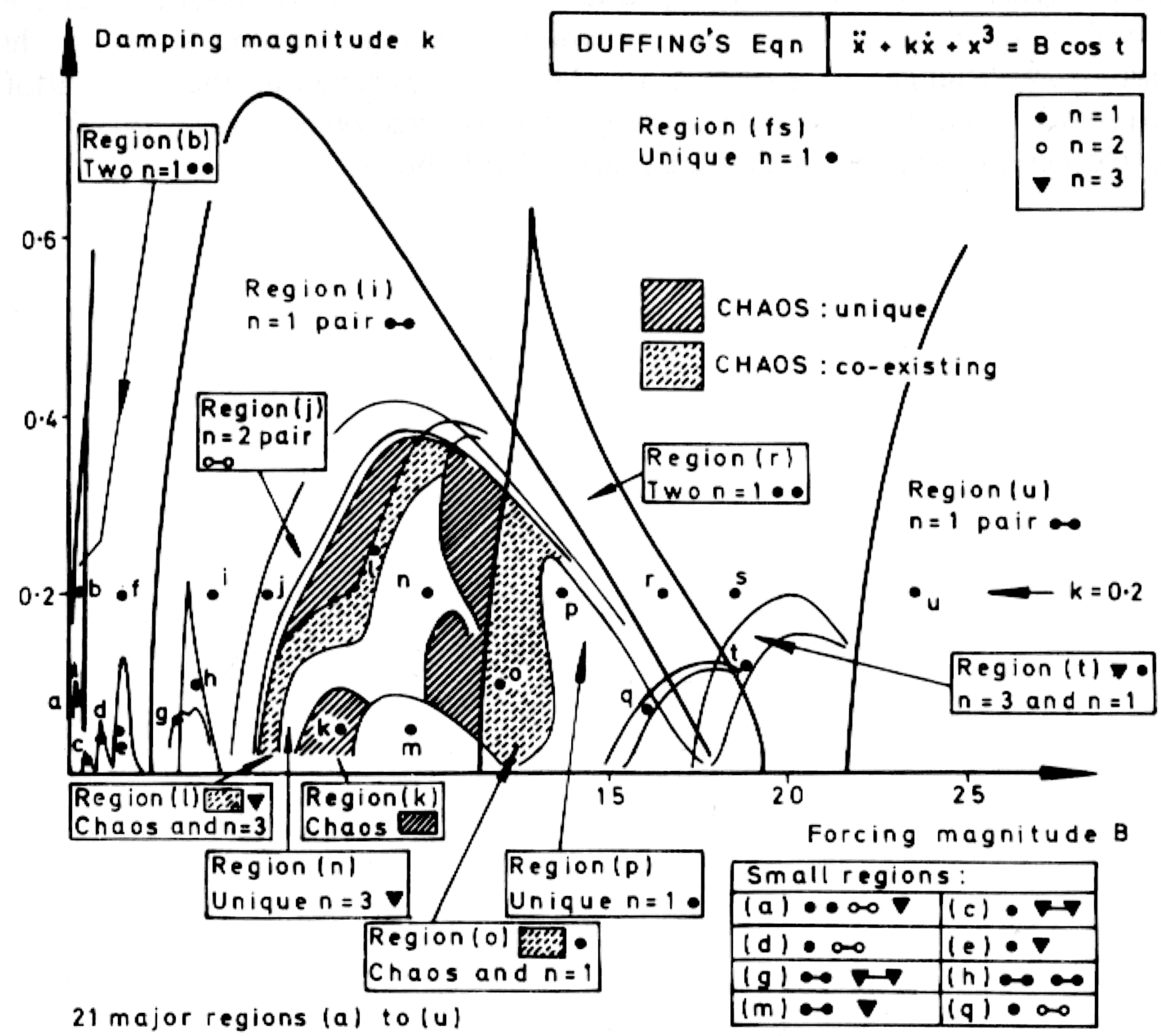

Figure 2.3: Regions of the various long-term behaviours of the damped, forced Duffing oscillator, as a function of damping, k, and forcing, B. Taken from Thompson and Stewart (1986), based on work done by Ueda (1980). n represents the ratio of the periodic frequencies to the forcing frequency. This diagram excludes for simplicity some of the more complex subharmonic ratios identified by Ueda. Copyright ©1986 by John Wiley & Sons Ltd.

> are slowly adjusted; we gradually change the controls, and let the system settle to final behaviour in each new regime. As the control settings cross one of the arcs in Figure [2.3], we observe the system settling to a qualitatively different behaviour: the motion may change from periodic to chaotic, or the previously stable motion may become unstable, in which case the system settles to a different attractor; or the change may be more subtle, as when the subharmonic number of a stable periodic motion changes. In any case, there has been a *qualitative* change in the long-term behaviour, associated with a change in (or disappearance of) an attractor. In theory there is a mathematically precise value of the control settings, lying exactly on an arc in Figure [2.3], at which the qualitative change, or *bifurcation*, occurs.'' (Thompson and Stewart, 1986, p 12, italics retained from original).

As will be discussed below in Section 2.1.4.3, musical instruments would be a highly appropriate addition to their list of ''real dynamical systems'' that may be controlled in this manner.

There are some additional complexities that are not immediately obvious from looking at Figure 2.3. Each point on the graph does not necessarily guarantee a specific behaviour. For example at point (a) where five attractors are present, the initial conditions of the system will determine exactly which steady state behaviour will be exhibited. This is shown in Figure 2.4 with $k = 0.08$ and $B = 0.2$. The initial values of x and y $(= \frac{dx}{dt})$ determine the trajectory's final steady state. Setting the parameters for k and B as described in the Thompson and Stewart quote above therefore does not guarantee a particular behaviour for particular parameter settings, but is rather dependent upon the state of the system at the point of the change.

The Duffing equation is deployed as part of interfaces 1 and 2 in the comparative studies detailed in Chapter 4. Nonlinear dynamics are now discussed in relation to their use and status in music, and artistic and cultural practices more generally.

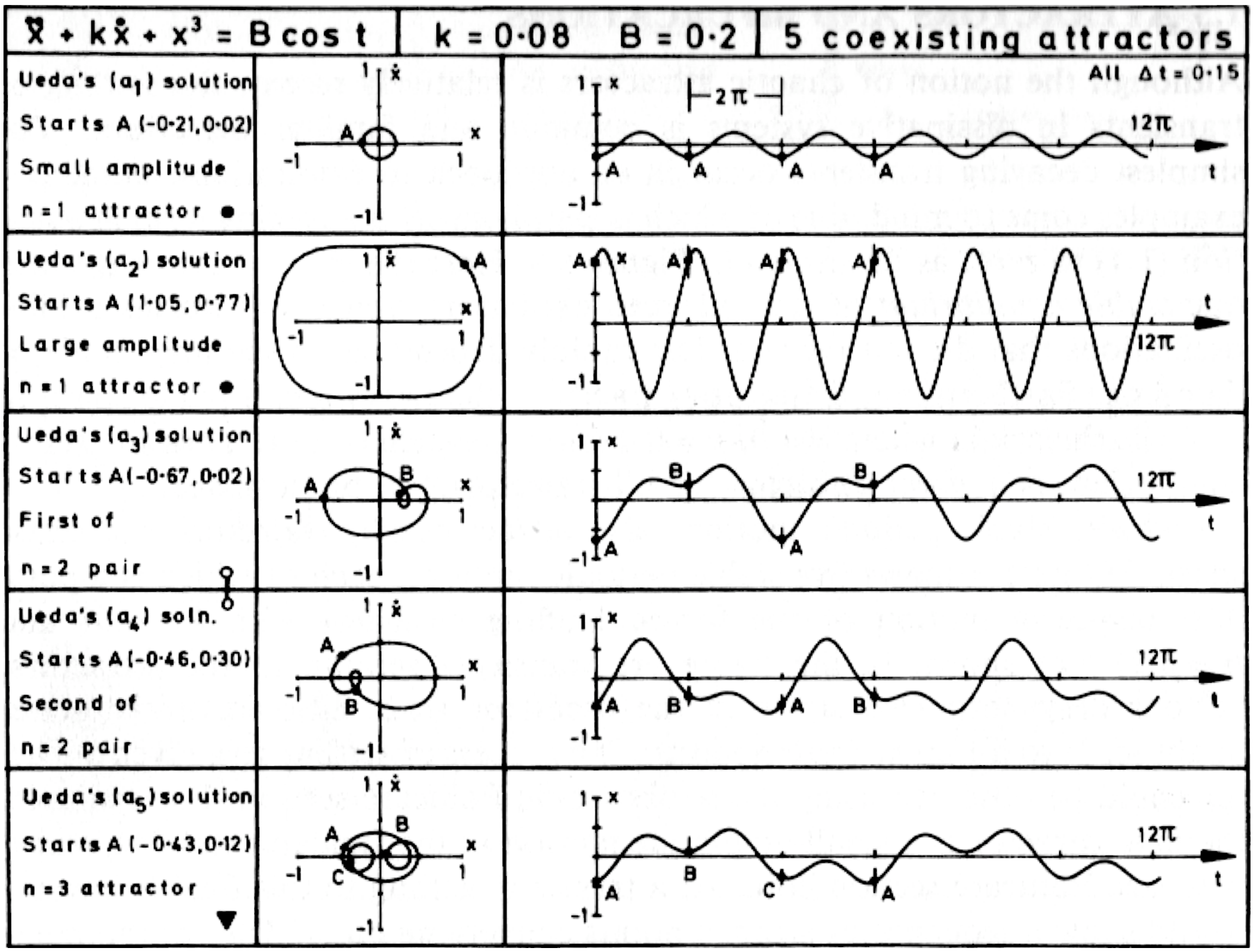

Figure 2.4: The steady state behaviour of five different coexisting attractors from region (a) in Figure 2.3 (from Thompson and Stewart (1986) based on Ueda (1980)). k and B are invariant, but different starting conditions for x and y $(= \frac{dx}{dt})$ lead to the variation in long-term behaviour. Copyright ©1986 by John Wiley & Sons Ltd.

2.1.3 Cybernetics

There is a rich history of crossover and collaboration between art and science in terms of feedback processes and nonlinear dynamical systems. The various activities collectively referred to as Cybernetics highlight this crossover. The description given by Pickering (2010) contains many important aspects that relate to the research questions under consideration:

> “cybernetics [...] tries to address the [problem] of getting along performatively with systems that can always surprise us”

Firstly, using the phrase “getting along with” instead of “controlling” is telling, and seems to relate closely to the material-oriented approaches discussed in Section 2.2.1 where the technology is seen as a collaborator rather than as a passive medium. Secondly, the focus on real-time interaction is clear in the word “performatively”. Finally, the focus on surprise is also a key concern in this research (see particularly the discussions following the ethnographically-informed study in Section 5.4, and the wider discussions in Chapter 6).

Cybernetics has been applied in a variety of ways to a very wide ranging set of disciplines: brain science, city and business management, psychiatry and antipsychiatry, adaptive robotics, biological computing (Pickering, 2010), but also visual art and music. The Cybernetic Serendipity exhibition in London in 1968 is considered a landmark event in the history of computer-based artwork, and has received renewed attention in recent years (Fernández, 2008). It is notable for explicitly blurring the roles played by human agents and mechanical or digital agents in the resulting behaviours of the sound, image or sculpture.

Of particular interest to this thesis are ideas that Hayles (1999) associates with what she describes as the second and third waves of cybernetics, such as the productive role played by feedback, the creative potential of self-regulating behaviours, and relations between stability and uncertainty/chaos. These have passed into musical uses of feedback as discussed in Section 2.2.5 and in Section 2.1.4 below.

The influence cybernetics has had on contemporary music has been noted, particularly by

Griffiths (1995). His book *Modern Music and After: Directions since 1945* begins with a paragraph emphasising this link (''A great deal in music since 1945 seems, if perhaps only in retrospect, to have been leaning towards cybernetics''), noting amongst other things the similarity in attitudes to contingency: ''the concept of the work as a temporary equilibrium of possibilities that could be otherwise realized.'' This attitude is traced further in Section 2.2 in relation to specific musical practices.

2.1.4 Music and Nonlinear Dynamical Systems

This section looks at the inclusion of nonlinear dynamical systems in music, both explicitly mathematically as with algorithmic composition and nonstandard synthesis, and through the often tacit presence of nonlinear dynamical systems in acoustic and electronic instruments.

2.1.4.1 Explicit use of Nonlinear Dynamical Systems

Many composers and musicians have employed nonlinear dynamical systems explicitly in their work, implementing a variety of systems for a variety of purposes. Pressing (1988) describes his use of the systems such as the Logistic map (equation (2.3)) in his own compositions. Several features of such systems are highlighted as being of potential musical interest: fixed points, limit cycles, bifurcations, chaos and strange attractors. Relationships between such processes and musical structures are traced (''musical development or variation of a simple entity (a motive), often followed by some sort of return to the original motive.''). The outputs from the Logistic map and several other nonlinear dynamical systems were mapped directly to particular compositional parameters such as frequency, volume, timing, attack, and so on, and iterated at various tempos to create compositions. Pressing is particularly interested in regions that are only intermittently chaotic, that oscillate between quasi-periodic stability and chaotic states, and thus chooses values of r in Equation (2.3) accordingly (e.g. $r = 3.828$).

The advent of real-time digital musical processes has enabled real-time implementations of nonlinear dynamical systems that can be used to synthesise sound directly. This has been put to use in non-standard synthesis processes, where the output of the system is often rendered directly as audible sample values as in the work of Agostino Di Scipio (Scipio and Prignano, 1996), Insook Choi (Choi, 1994), David Tudor (Warthman, 1995), David Dunn (Dunn, 2007), Dario Sanfilippo (Sanfilippo and Valle, 2012), Ryo Ikeshiro (Ikeshiro, 2012, 2013), Pita, EVOL (Worth, 2011), and many others. David Dunn highlights his approach to designing nonlinear dynamical musical systems as a compositional method:

> "Rather than musical composition as the specification of fixed details of structure over time, it now becomes the design of a generative system of sufficiently high-dimensional complexity from which rich sonic behaviours can emerge." (Dunn, 2007)

Dan Slater has also employed such systems in analog synthesisers, recreating Logistic behaviours using Moog sample-and-hold and VCA modules (Slater, 1998). Running the systems at this rate shifts the limit cycles from producing repetitive phrases (as in the Pressing example) into the audible frequency range to produce actual tones. Chaotic regimes produce noisier results, and the system's behaviour generally has a stronger influence on timbral aspects than structural aspects (although longer term structural elements may still emerge).

Ikeshiro's work combines the synthesis approach with the structural approach taken by Pressing by applying a particular nonlinear dynamical system — such as the Lorenz or Mandlebox systems — at various timescales so that it is responsible for timbral nuance as much as it is responsible for larger scale developments.

As with the cybernetic artistic work discussed in the previous section, the use of nonlinear dynamical processes in music is seen as giving some agency to the tools and systems being created and used: the emergent behaviour of the systems suggest starting points, developments, sounds and structures that the musician can react to. This is a motivating factor for many musicians:

> "[...] due to the emergent nature of the generative systems used, the results cannot be accurately attributed to each agency. Instead, the creative possibilities due to their combination are assessed together. Moreover, this uncertainty in intentionality also contributes to maintaining interest in the works for both the performer and the audience." (Ikeshiro, 2013, p 35)

The wider appeal of working with dynamical systems is suggested by the availability of resources in audio programming languages such as Supercollider (see the chaotic synthesis UGens) and MaxMSP (such as André Sier's A-Chaos library, Sier, 2014). These programs provide access to a variety of chaotic dynamical systems (these are distributed with Supercollider, whereas they need to be manually added in MaxMSP).

In the cases above, the properties of the nonlinear dynamical systems are central to the aesthetic of the results: the music is strongly and deliberately influenced by the behaviour of the system, and the musicians are often content to step back and let the system produce material with only minor modifications. These examples are also very conscious uses of dynamical systems, where the composers have made deliberate decisions to include a particular system (often using simple, well known, 'off-the-shelf' systems such as Lorenz, Logistic, Chua etc.).

2.1.4.2 Embedded use of Nonlinear Dynamical Systems

Many artists work with nonlinear dynamical processes in a more intuitive manner, without necessarily delving into the mathematics or the theory behind them. Feedback, implemented in a number of ways — microphone-loudspeaker (the Larsen effect), mixing desk feedback, digital delays with feedback, etc. — provides a mechanism for musicians to explore emergent phenomena, and has been employed in many areas of music. Jimi Hendrix and the Grateful Dead's use of guitar feedback in performance can be seen as performing with nonlinear dynamical systems, with the feedback from speaker to pickup forming the system's iterative loop, and defining the output as a function of previous inputs, and the distortion working as the nonlinear function. Sanfilippo and Valle (2013) detail a number of approaches to working with various kinds of audio feedback, highlighting the links between the work of influential composers such as Agostino Di Scipio, David Tudor and Alvin Lucier and cybernetic concerns (see also Haworth (2014)).

Kuivilla (2004) notes the link between the kinds of feedback processes employed by Tudor and the mathematical nonlinear dynamical systems described in the first portion of this chapter:

> “Feedback tends to ‘lock’ on a single frequency; allowing the two channels to interfere with one another creates more complex composite behaviours. It is interesting to note that a feedback path using nonlinearity to redistribute energy is the fundamental design approach of such chaotic systems as Chua’s Oscillator”

Section 2.2.5 provides some context for the use of nonlinear dynamical systems in acoustic instruments, feedback electronics, and digital systems by examining musicians involved in experimental musical practices and free improvisation, domains particularly engaged with emergent phenomena.

2.1.4.3 Acoustic Instruments

From a certain perspective, acoustic instruments can be thought of as simple: there is a clear link between human action and sonic result, and the relationship between the two generally corresponds to our everyday experience of the physical world. When examining the specific nature of these relationships however — and particularly when attempting to create models — they appear to be very rich and complex. Rubbing two rocks together is simple in the former sense, but from the latter perspective is a complex situation involving friction between two irregular surfaces. The specific angle, force and speed of the movement combine with the specific physical properties of the two objects in a complex manner to determine the sonic result. Bowed and blown instruments in particular provide very complex relationships between input and output elements. Models of strings and air columns are generally modelled with nonlinear dynamical systems coupled with linear elements (representing impedance spectrums for example) (Smith, 2010).

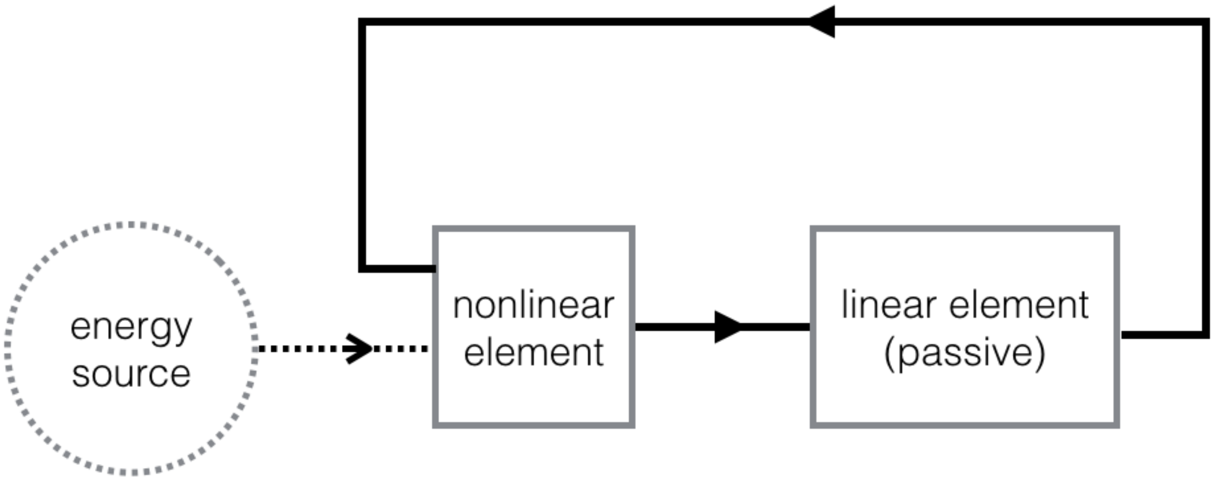

Figure 2.5: An idealised block diagram description of musical instruments as a coupling of a nonlinear element coupled with a passive linear element, as exemplified by brass, woodwind or bowed instruments (after McIntyre et al., 1983).

Figure 2.5 (based on McIntyre et al., 1983) shows a simple block diagram commonly used to represent most woodwind, brass and bowed instruments (McIntyre et al., 1983; Rodet and Vergez, 1999; Smith, 2010; Kergomard, 2016). The nonlinear element may be the bow, reed or air-jet, while the linear element may be a string or a tube, typically with characteristic resonances that may be altered by the musician. The output from the linear element feeds back into the nonlinear element creating a nonlinear dynamical system. Fletcher (1999) makes a useful distinction between "essentially nonlinear" instruments and "incidentally nonlinear" instruments (ibid. p. 725). All sustained tone acoustic instruments are associated with the former (e.g. particularly bowed and blown instruments), whilst the latter is associated with struck instruments (piano, bells, gongs). It is worth noting that instruments termed incidentally nonlinear by Fletcher can be played in ways that move them into the essentially nonlinear category. This can be achieved by finding ways to sustain the sounds of these instruments, either through bowing them (such as gongs, cymbals, guitars or piano strings), or by choosing to focus on the complexity of their nonlinear aspects - e.g. paying particular attention to the spectral content of the sound as the striking position and strength is varied. Instruments and tools that are essentially nonlinear are of particular interest for this thesis, as the nonlinear dynamical processes necessarily affect how they are controlled and interacted with by musicians. While musicians may not necessarily be aware of the nonlinear feedback loop at the core of many common instruments, the effects will certainly have been experienced in interactions with these instruments. The clarinet is explored below to examine how the nonlinear dynamical elements manifest in interaction.

2.1.4.3.1 Nonlinear dynamical interactions with the clarinet

The clarinet and other single reed instruments can be thought of in terms of Figure 2.5, where the reed is the nonlinear component, and the impedance spectrum of the bore is the passive linear element. Pressure changes across the reed lead to pressure changes in the bore, which in turn regulate the behaviour of the reed. The complexity of the nonlinear dynamical interaction in the clarinet and other reed instruments can be experienced by putting slightly too much pressure on the reed, producing an abrupt bifurcation into a higher frequency regime: a squeak (Almeida et al., 2013). Almeida et al. provide a diagram of the changes in the output from a clarinet as a function of breath pressure and lip force, shown in Figure 2.6. This simplified diagram gives some insight into the nonlinear nature of interactions with clarinet-like systems. The diagram would vary considerably when considering other variables, such as fingering, lip position, and reed stiffness. Achieving a stable pitch and volume is therefore a complex task that requires the coordination of a range of inputs. The chart bears comparison with Figure 2.3 above that shows variations in the behaviour of a damped forced Duffing oscillator as two coefficients of the system are varied.

The temporal aspects of the interaction are also important: the system exhibits hysteresis (Dalmont et al., 2003; Almeida et al., 2013), meaning that the behaviour of the instrument is dependent on both the musician's current and past input. For example, blowing with a

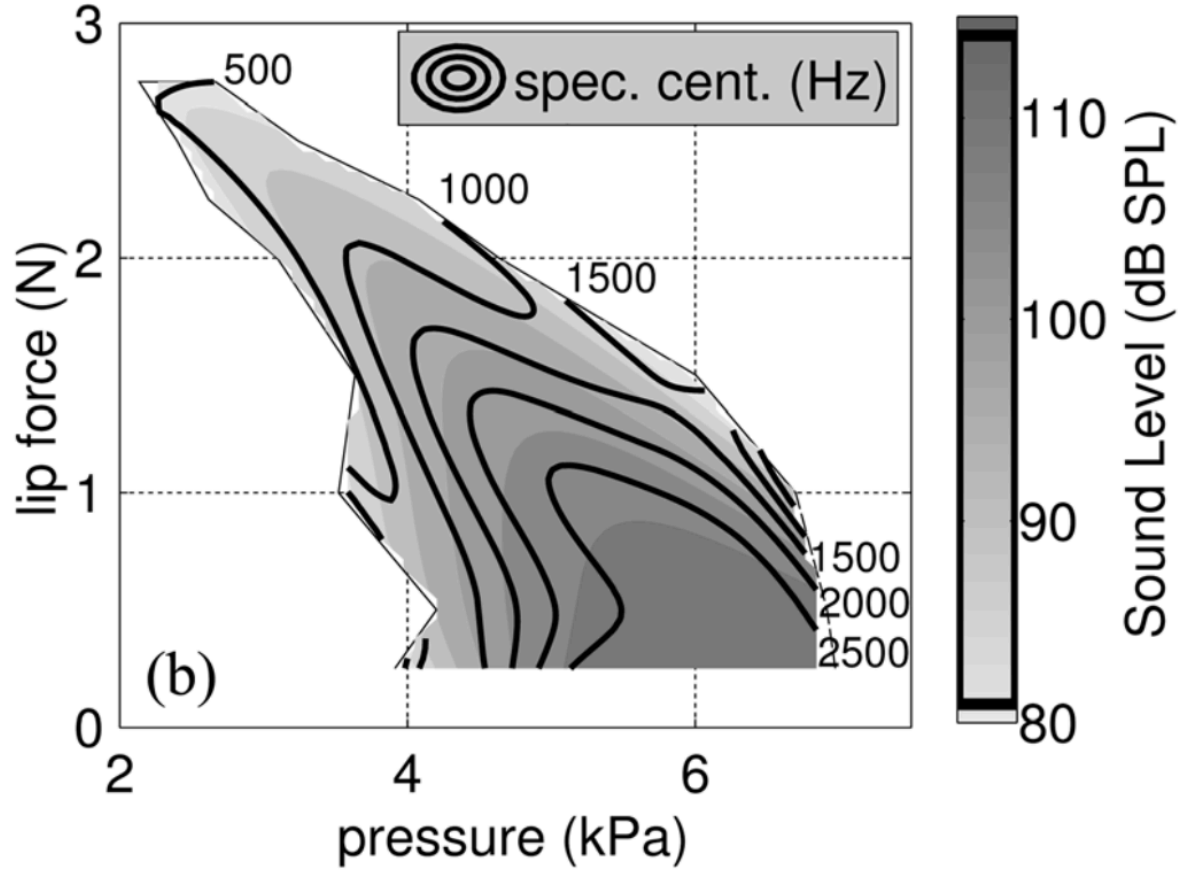

Figure 2.6: Diagram from Almeida et al. (2013) showing changes to sound pressure level and spectral centroid with lip force and breath pressure. The authors also describe how this varies considerably with other parameters such as fingering, lip position and reed stiffness.

particular breath pressure produces a particular note, blowing harder pushes the note into a higher partial, but then returning to the original level of breath pressure does not necessarily correspond to a drop back to the original partial: the system can 'lock' into particular states (McIntyre et al., 1983; Menzies, 2002).

The complexities of the nonlinear dynamical aspects of single reed instruments have been studied and ever more complex models have been conceived (Avanzini, 2001, 2007; Maganza et al., 1986; Almeida et al., 2013; Smith, 2010; Kergomard, 2016). Maganza et al. (1986) view the study of acoustic instruments as a branch of hydrodynamics, and explore the role that the nonlinearities play in instabilities and chaos in the clarinet-like systems. The presence of chaos in such everyday musical interactions should serve to highlight the potential value of studying nonlinear dynamics for creative interactions more generally, and particularly to reflect on the nature of creative interactions with computers. As will be discussed in Section 2.3 however, this approach to interaction stands in stark contrast with many of the established principles of HCI.

2.1.5 Summary

This section has provided the basic mathematical foundations for discussions of nonlinear dynamical systems and clarified some of the necessary terminology. Several important properties of nonlinear dynamical systems have been touched on here, and linked to musical concerns and instrumental behaviours:

- Nonlinear dynamical systems may be highly sensitive to initial conditions, where very small changes to the initial values for a trajectory lead to highly divergent results.
- Boundaries exist where the system bifurcates, transitioning abruptly from one kind of behaviour to another.
- These changes may be dramatic (e.g. from periodic to chaotic), or they may be more subtle (e.g. a change in the subharmonic number of a periodic motion)

- Such systems have the potential to exhibit hysteresis, where the behaviour of the system is based not only on the present state of the inputs, but also on the history of the system.

Musical instruments, tools, and situations have been used to highlight some of the roles that such systems can play, and have played, in practice. Nonlinear dynamics are shown to play an important role in a range of common acoustic musical instruments -- particularly blown and bowed instruments -- and to have a significant impact on the nature of the interaction. The following section will provide a wider background on the musical contexts informing this work.

2.2 Musical Contexts

This section explores interaction with musical tools in particular musical practices. Three key areas are considered: contemporary computer music, free improvisation, and experimental music. Although they are listed here as discrete areas of interest, there is considerable overlap between the three, and the borders of each blur into the others, and into many other musical practices. They are explored here as they provide a perspective on interaction that is in many ways at odds with established ideas of creative interaction in the field of HCI (see Section 2.3), even when music is being explicitly considered. Although these practices may be esoteric from the perspective of more mainstream musical activities, it is suggested that elements of the particular modes of interaction presented here manifest themselves in more subtle ways across a much broader range of musical practices. These practices present useful sites for exploring what is referred to in this thesis as a *material-oriented* perspective, an approach to engaging with tools that focuses on their specific properties, and that acknowledges the influence that tools have in influencing creative ideas. This openness to the specific behaviours of tools and instruments allows for interactions which may be confusing, complicated, difficult to control and chaotic. These properties can be seen as material to be productively engaged with, rather than problems to be surmounted.

Following an outline of this perspective, and three relevant areas of musical practice, material-oriented concerns are linked to the frequent use and exploration of nonlinear dynamical processes in these musical areas, where the instabilities and unpredictabilities inherent in such systems may be welcome. A final musical context is considered that blends aspects of improvised, experimental and computer music practices is then introduced: the “ecosystemic paradigm”. This paradigm provides close links between the material-oriented approach and the use of interconnected feedback networks as discussed in Section 2.1.4.1.

The discussions in this section are necessarily limited in scope however. The focus is on the artists’ engagements with tools and instruments, establishing how the material-oriented perspective is borne out in practice. The limited scope excludes the artists’ wider social and political concerns, despite these frequently being central to their attitudes towards their tools[1].

The material-oriented perspective is introduced below in Section 2.2.1. Experimental music, free improvisation and contemporary computer music are then examined individually in terms of interactions with instruments and tools in Sections 2.2.2, 2.2.3 and 2.2.4 respectively. The close ties between these practices and the use of nonlinear dynamical processes are then discussed in Section 2.2.5, and the relations between such processes and specific ideas around control, surprise and agency are considered.

2.2.1 Material-oriented music

This section presents a contrast between two possible perspectives on the role of creative tools: *communication-oriented*, where tools are ideally transparent mediums for communicating pre-conceived ideas, and *material-oriented*, where ideas are developed through exploration of the specific properties of tools[2]. This distinction is sketched briefly and discussed in the context of musical practice. A proposal for making use of the concept of material-orientation in HCI is developed in Section 2.3.1.

The pragmatic grounding of creative activity in the specific properties of the materials being engaged with, has been a wide-ranging concern over the last century. Although there are undoubtably many roots for these developments, John Dewey's pragmatic epistemology and his account of the role of *experience* in engaging with the world (Dewey, 1980) has been particularly influential. His influence can be traced in visual art practices (Leddy, 2016), musical practices (Worth, 2011), HCI (McCarthy and Wright, 2004; Schön, 1983), education (Bauer, 1992), healthcare (Rolfe et al., 2010), and beyond. Creative acts are seen as rooted in an engagement with objective materials, with the creator necessarily responding to the

[1] The references given in this section provide more information on these aspects however, particularly Cox and Warner (2004) and Saunders (2009) for wider discussions around experimental music practices, Bailey (1992) and Prévost (2008) for free improvisation, Worth (2011) and Haworth (2015) for digital musical practices, and Waters (2007), Green (2011) and Haworth (2014) for the ecosystemic paradigm.

[2] The terms *material-oriented* and *communication-oriented* are introduced here, but are based on the language used by Worth (2011)

nature and behaviour of this material:

> “As the painter places pigments upon the canvas, or imagines it placed there, his ideas and feelings are also ordered.”[3] (Dewey, 1980, p. 80)

The bidirectional nature of the engagement is foregrounded: the material “kicks back” (Perry, 2015) and contributes to the development of ideas. This can be related to a rising scepticism towards the possibility of “neutral” tools (Feenberg, 2002): tools necessarily have tendencies and biases embedded within (Suchman, 1985; Sengers, 2010). Feenberg (2002) provides an account of how technologies are both a product of society and a driver of societal change, contrasting this with what he lays out as the dominant “common-sense” view that technology is neutral until it is put to use. The latter is termed an *instrumental* approach to technology. Green (2008) traces this perspective in attitudes to technology in music, highlighting how musical works came to be seen as transcendent, idealised and separated from the specifics of any individual performance.

However, in opposition to these perspectives, he notes the rising influence of ideas that emphasise closer integration of humans and technologies and that acknowledge the mediating role played by technology (Green, 2011). More recent ideas around technological integration are shown to find their way into musical discourses around composition, instrument design and electronic musical culture more broadly, drawing on — to name but a few — Andy Clark’s ideas around extended mind (Clark, 1998), Lucy Suchman’s focus on *situated* action (Suchman, 1985), phenomenological attitudes to human-technology relations (Dreyfus and Dreyfus, 1986), and Feenberg’s philosophy of technology (Feenberg, 2002). These strands are considered further in relation to HCI in Section 2.3.

Ihde (1990) presents related distinctions in examining attitudes to embodiment and technology. He identifies a contradictory tendency to want both the super-human abilities technology affords (for example viewing the stars as if they were much closer than they are),

[3] There are strong links here between Dewey and Donald Schön’s conception of Reflection-in-Action, discussed in the following Section, 2.3.

but to simultaneously remove any technological mediation:

> "I want the transformation that the technology allows, but I want it in such a way that I am basically unaware of its presence. I want it in such a way that it becomes me. Such a desire both secretly rejects what technologies are and overlooks the transformational effects which are necessarily tied to human-technology relations" (ibid. p. 75).

In a more specifically musical vein, Worth (2011) differentiates between a communication-oriented view of composition and what he terms a more literalist perspective. The former is typified by the view that a composer has a musical idea, and then seeks to communicate this idea through musical instruments and tools[4]. In this scenario, any influence that the technology has on the musical output is seen as negative, detracting from the realisation of a pure idea. This is seen as synonymous with an idealist/rationalist approach, and links closely to the instrumental view of technology noted by Feenberg above. By contrast, the literalist perspective follows Dewey in accepting the role that practical experience plays in shaping ideas and is characterised as pragmatic and experimental. This approach opens the door to an engagement with the specifics and nuances of instruments and technologies, and to an approach which views the creative process as a *collaboration* between the artist and the material, an approach which can be seen clearly in the musical contexts discussed below (see particularly Section 2.2.3.1). This approach acknowledges the inevitable technological mediation, acknowledging, as Ihde notes, that:

> "The actual, or material, technology always carries with it only a partial or quasi-transparency, which is the price for the extension of magnification that technologies give. In extending bodily capacities, the technology also transforms them" (ibid. p. 75).

[4]The term 'communication' denotes the sender-receiver model as described by Shannon and Weaver (1949), where the idea is something to be transmitted into sound, and any instrumental interference is regarded as unwanted noise (see also Fell, 2013b for this link between communication-oriented perspective on musical creation and the Shannon and Weaver sender-receiver model)

This binary distinction presented in the section between material- and communication-oriented attitudes is not to be taken as absolute. Both positions are presented here as ideal abstractions, whereas in practice, many musicians, composers and artists combine elements of both (see Gelineck and Serafin (2009) discussed in Section 2.3.3.3.2 for an example of how the two may be combined in electronic composition). Nevertheless, it is useful to highlight the material-oriented perspective as much of the existing work in HCI, and at the intersection of music and HCI has fallen much closer to the communication-oriented model.

Gurevich and Treviño (2007) demonstrates this point, highlighting a tendency to revert to more romantic, communication-oriented conceptions of the creative process in much of the literature surrounding new digital instruments, particularly in regard to HCI and the New Interfaces For Musical Expression (NIME) conference:

> ‘‘According to this model, an expressive performance should cause the listener to experience the intended emotions or at least understand the expressive intentions of the composer and performer.’’ (Gurevich and Treviño, 2007, p. 107)

Gurevich and Treviño argue that this model has dominated at the expense of other possible models, and show that experimental music and improvisation provide alternatives that can broaden the discussions around digital instrument design. This debate on expression in the NIME community is discussed further in section 2.3.3.2.

The following sections will outline attitudes from communities of experimental and improvising musicians that provide potential insights into approaches to digital instrument design from a more material-oriented perspective.

2.2.2 Experimental music

Experimental music provides a rich site for examining material-oriented musical engagements. As mentioned above, the term ‘experimental’ is used in a fairly specific way in this thesis, denoting musical practices that explicitly engage in processes that have unknown results. As

Gottschalk (2016, p 1) notes, ‘‘it is a position - of openness, of enquiry, of uncertainty, of discovery.’’ A key aspect of experimental music, is a focus on the particularities of any given sound as opposed to a focus on higher level abstractions such as pitch classes. With this broadening of compositional scope, many composers began explicitly exploring the specifics of sonorous objects, musical instruments and electronic devices.

> ‘‘[...] experimental composers/musicians tend to be interested in the materiality of sound rather than its musical meaning.’’ (Cox and Warner, 2004, p 207)

John Cage's compositional practice can be seen as being genuinely experimental in that the specific sonic results are often not known before a particular performance. As such, for many practitioners, notions of success or failure are less relevant (Nyman, 1999, p 1), an aspect that experimental music shares with free improvisation. Keep (2009) discusses the importance of exploring sonic objects in experimental music, coining the term *instrumentalizing*. He highlights the symbiotic relationship between the act of exploration and the sonic material being discovered, and provides a good summary of the key differences in this experimental attitude to the instrument:

> ‘‘For many performers the role of a musical instrument has changed its perspective from being something that can realize a musical language outside or indifferent to its self, to being an object that can create a music responsive to its inherent sonic properties.’’ (Keep, 2009, p. 115)

The composer Scott Mc Laughlin exemplifies this approach. His approach is also notable for this thesis in that he explicitly engages with the ‘‘nonlinear space of acoustic continua,’’ and embraces ‘‘the material agency’’ of the instrument (Mc Laughlin, 2014). For Mc Laughlin, drawing on the nonlinear dynamical properties of the instrumental interaction allows for a balance of human and instrumental agency in performance. This example therefore binds closely a material-oriented approach to composition, and a focus on the exploration of nonlinear dynamical processes in musical instruments. A further account of the close links between nonlinear acoustic phenomena and contemporary music is given by Neubauer et al. (2004), tracing nonlinear phenomena in contemporary vocal techniques.

Adopting a material-approach approach closely associates the creative musical process with the specific nature of musical tools, and therefore also the design decisions made in creating those tools. The creation and/or customisation of the instrument, whether acoustic or electronic, becomes a fundamental aspect in the practice of many musicians, as is the case with many of the musicians discussed in this thesis such as John Cage, David Tudor, Eddie Prèvost, Insook Choi, John Butcher, and John Bowers.

David Tudor in particular links several areas of concern in this literature review. As a pianist he collaborated closely with Cage, Morton Feldman, Christian Wolff and many other experimental composers. As mentioned in Sections 2.1.4.1 and 2.1.4.2, he also designed and performed with a variety of self-built feedback systems, often creating networks of interacting sound generators (e.g. *Rainforest IV*, *Neural Synthesis*). This work is closely connected to the concerns of cybernetics discussed in Section 2.1.3. He would often describe these systems as having inherent intelligence, that needed to be coaxed and then allowed space to emerge (Johnson, 2013). In utilising these self-built systems "advance planning is only partially useful, perfect compliance is impossible, and the concepts of contingency and action are essential in such situations" (Kuivilla, 2004). His attitude towards these devices embodies the material-oriented approach outlined above:

> "In my electronics, I work with an instrumental principle. . . . They become my friends. They have personalities, that only I see, because of my use of them. It's an act of discovery. I try to find out what's there and not to make it do what I want but to, you know, release what's there" (ibid., p 21)

To summarise, experimental music provides an area of practice where nonlinear dynamics are often drawn on as resources for composition or performance. Musicians are particularly open to the specifics of a tool or situation, embracing unexpected events and contingent situations. This openness provides a perspective on human-tool interactions that seems to be neglected in HCI, as will be discussed in Section 2.3.

2.2.3 Free Improvisation

As with experimental music, free improvisation also provides an interesting perspective on the relationship between musicians and their tools. There is a significant overlap between the concerns of improvisers and those involved in experimental music and other forms of contemporary composition, and there are many musicians who sit comfortably across both groups. However, an important distinction between improvisers and experimental composers is that improvisers are often engaged very closely with a single instrument over extended periods of time, practicing daily for periods of many years or decades. An examination of tool use in this context can be informative in considering digital instrument design. Free improvisation should also be distinguished at the outset from free jazz. Free improvisation is often described as being consciously non-idiomatic (Bailey, 1992; Prévost, 2011), attempting to remove any pre-conceived ideas about harmonic relations, rhythmic relations, structural approaches and so on, and to give any given sound equal validity. George Lewis has noted that the term denotes very different attitudes to more traditional, Afrological approaches to jazz improvisation as it eschews the idea of a personal narrative and is more closely related to the ideas of John Cage regarding the absence of intention (Lewis, 2004, p 282-283). However, a continuum exists between free improvisation, jazz and many other musical areas, and many musicians work in multiple areas.

A consistent aspect of free improvisation is the focus on experimentation and a desire to discover and explore new sounds or new ways of working with sounds. Eddie Prévost cites this as an essential aspect of his practice inside and outside of the improvising group AMM (Prévost, 2008), and as an important element in the influential improvisation workshop that he has been convening since 1999 (Prévost, 2011; Clark, 2012). Evan Parker and Derek Bailey, both improvisers who started out in the 1960s, also emphasise a reliance on exploration, investigation, and an openness to unpredictable elements (Hopkins, 2012; Bailey, 1992).

In introducing Prévost's work, Lely (2006, p 4) provides a useful summary of this exploratory aspect:

> “There is a discernible area of music concerned with actively finding and revealing hidden resources of the materials at hand, and practitioners from a wide range of disciplines are converging on this common ground, where the previously clear boundaries of composition and improvisation lose their definition [...]”

The focus on “hidden resources” is particularly relevant here (and is returned to in Section 2.3). This presents an interesting challenge for those involved in creating musical tools: is it possible to design systems with hidden resources? How can instruments be created that have these hidden layers, sounds and behaviours that may be unfolded and discovered across an entire lifetime of playing? This question forms an important consideration in the studies conducted in this thesis, with nonlinear dynamics explored as a possible candidate mechanism for creating tools with this kind of depth. The relationships between improvisers and their instruments are therefore considered in more detail as a short digression in the following subsection.

2.2.3.1 Improvisers and their Instruments

Bailey (1992) discusses two distinct viewpoints on the role of the instrument in improvisation: pro-instrument and anti-instrument[5]. The two are strikingly contrasted. Anti-instrumentalists are described as attempting to remove the influence of the instrument as though it were an obstacle. “[T]echnically, the instrument has to be defeated. The aim is to do on the instrument what you could do if you could play without an instrument.” (Bailey, 1992, p 101). The saxophonist Ronnie Scott is quoted as saying: “I practice to become as close to the instrument, as familiar with it, as possible.”

[5]Bailey does not see this as an absolute split however, pointing out that musicians will likely experiment with both approaches.

This conception of the instrument can be linked with the idea that technology should be transparent. McDermott et al. (2013, p. 30) suggest that "one of the most characteristic aspects of music interaction is the extent to which skilled musicians become one with their instruments", and cite Leman's description of technology ideally becoming transparent:

> "Transparent technology should [...] give a feeling of non-mediation, a feeling that the mediation technology 'disappears' when it is used" (Leman, 2008, p. 18)

This idea of transparent technology and the removal of mediation links closely to the idea of music as the clean communication of a musician's inner impulses. It echoes the instrumental perspective on technology described by Feenberg (outlined in Section 2.2.1), and contrasts with the material-oriented view of interaction.

Bailey's description of pro-instrumentalists is very different however, and he claims that this is the dominantly held view in all areas of improvisation: the instrument is described as a helper, or a collaborator:

> "Although some improvisors employ a high level of technical skill in their playing, to speak of 'mastering' the instrument in improvisation is misleading. The instrument is not just a tool but an ally. It is not only a means to an end, it is a source of material, and technique for the improvisor is often an exploitation of the natural resources of the instrument." (Bailey, 1992, p 101)

This pro-instrumental attitude is common in free improvising musicians: that their relationship with their instruments is bidirectional, with the instrument having a strong influence on the decisions taken by the musician, often leading to descriptions that assign the instrument agency. Evan Parker speaks of the "instrument's intentions" (Hopkins, 2012) and David Borgo describes the way that Parker is "played by the saxophone" (Borgo, 2007, p 57). Taku Unami talks of the difference between commanding an instrument and having a relationship with it (Unami, 2005). Borgo (2013) highlights the "concerted effort to either reduce, deflect or decenter human agency and intentionality" in many improvisatory practices.

This can be related to the potential for unpredictable results even after many decades of playing a particular instrument, as noted by Prévost (2008) in relation to his percussion playing, and by Kopf (1986) in an interview with saxophonist Evan Parker. The importance of an element of unpredictability in improvisation has been highlighted by several authors. Borgo (2007) sees improvisation as a balancing act between "complexity and comprehensibility, control and non-control, constancy and unpredictability." (Borgo, 2007, p. 33). Perkis (2009) talks of finding a sweet spot between control and unpredictability (see also Jordá in section 2.3.3.1.3), a sentiment echoed by John Butcher who works with unstable areas of the saxophone:

> "A lot of the material I work with is right at the border of the instrument — the reed — seizing up and breaking down. It's on the edge of controllable sound."
> Butcher in Warburton, 2001.

Unami (2005) similarly expresses his desire to move away from things that are already known, and embraces "surprises or unknown things".

The attitudes to instruments traced in this section relate closely to the material-oriented view outlined in Section 2.2.1, and suggest alternative perspectives on questions of control and mastery in creative interactions. Openness to surprises and the attribution of agency to the tools are both shown to be common themes. The following section continues to explore attitudes to interaction in free improvisation, and explores a distinction that can be made in the nature of these surprises: between chance surprises and surprises that result from deterministic systems.

2.2.3.2 Deterministic surprises and chance surprises

The distinction between unpredictability and randomness is potentially important. Borgo notes that "randomness does not produce a sense of surprise, but rather confusion, dismay, or disinterest." (Borgo, 2007, p. 1). The distinction between unpredictability and randomness can perhaps be related to repeatability. Keep (2009, p. 119) attempts a nuanced description of repetition in improvised music:

> "Within improvisation sounds are generally emergent or in constant flux, not affording the performer the luxury of contemplation or exact repetition during assessment. [...] As a performer demands more responsive interactions with the object's sonic behaviour it becomes necessary to track the relationship between excitation method or parameter adjustments and the resulting sound. Audible changes can be correlated to physical manipulations. Actions can be repeated to re-access fruitful results, though, as mentioned above, these are often likely to be reactivated sonic behaviours rather than exact events or gestures."

Such conceptions of instruments that allow both for nuanced control and semi-repeatable unpredictable behaviour produce difficult challenges for digital instruments, a theme taken up from an interaction standpoint in Section 2.3.3.1.1. It can be linked closely to the nature of nonlinear dynamical systems discussed in section 2.1 however, as chaotic systems are both completely deterministic, and highly unpredictable. This provides the potential for repeatability which may not be possible in random systems, whilst still allowing for surprises as the system is explored. This topic is reflected on further in the context of the results of the studies conducted for this thesis: in Chapter 4 and in Section 4.5.3.

2.2.4 Contemporary computer music

This section explores the material-oriented perspective in one final musical context: contemporary approaches to computer music. Although, again, it is difficult to define as a distinct, unified area of musical practice, it is nevertheless a useful site in which to examine different views of tool interaction. As with the two musical areas discussed above, a particular subset is examined here where the material-oriented attitude can be found in an extreme form.

This pervasiveness of this attitude is documented by Worth (2011) and Haworth (2015), particularly in relation to an influential set of artists related to Mego, a Viennese record label.

The expectations around new technology for music in the first parts of the twentieth century seem closely allied in places to the communication-oriented view described above in Section 2.2.1. (Griffiths, 1995, p 202) describes Stockhausen as being concerned with realising sounds conjured purely from his imagination. Varèse also envisioned closer links between thought and sound:

> "I dream of instruments obedient to my thought and which with their contribution of a whole new world of unsuspected sounds, will lend themselves to the exigencies of my inner rhythm" (Holmes, 2012)

In terms of the communication/material distinction, this appears to be slightly contradictory: if the instruments are obedient to thought, how can they produce unsuspected sounds? Worth (2011) refers to these attitudes as the "any sound you can imagine" approach, emphasising its surprising pervasiveness[6], and associating it with a traditional idealist stance, concerned with self expression, instinct and emotion. Haworth (2015) traces aspects of this attitude in acousmatic music, showing how composers significantly engaged with digital technology such as Denis Smalley nevertheless attempt to bracket out the technology in the reception of their music. By contrast, Haworth highlights an "aesthetic of radical medium specificity" (ibid. p 44) in the work of underground electronic composers, such as those involved with the Mego label. This focus on medium specificity can be observed in the tendency of many Mego artists to cite the software or hardware being used (and sometimes the designers/programmers) in the track titles or the accompanying texts (ibid. p 47). This emphasises the degree to which the final piece is a collaborative effort between the artist and the technology (and the artists behind the technology). Similar attitudes can be found

[6] see also Fell, 2013a,b; Théberge, 1997. Fell likens this attitude to the Cartesian split between mind and body, and lists a number of high profile cases demonstrating its pervasiveness in contemporary attitudes to music technology, particularly in academia.

explicitly in a manifesto published by the related label Mille Plateaux, which is keen to shine a light on the mediating role played by musical technologies:

> "One has to discuss the medial conditions of digital music, the more user-friendly the software, the less transparent is the medium itself; i.e. the more transparent the functions of a computer or a synthesizer (say, with the use of preset sounds), the stronger the medium proves to be non-transparent" (Szepanski, 2001, p 225)

In tracing the use of a specific piece of software — Andy Pieper's *apPatch* — Worth notes the scope for surprising results, and indeed the presence of nonlinear dynamical processes (the Rössler system of equations). He describes the compositional process as firstly, the creation of a particular set of patch routings (a limited system within the limited system) and then secondly, an exploration of the different possible parameter states within this complex set of interrelations (Worth, 2011, p 129). Although random processes are also made available in these systems, the artist Roc Jimènez de Cisneros (a.k.a. *Evol*) is cited as explicitly eschewing randomness in favour of nonlinear dynamical systems such as the Logistic or Lorenz systems described in Section 2.1.2.

Although a very specific area of musical practice is being examined here, similar attitudes can be traced more broadly in digital musical practices and beyond. Worth relates this medium specificity to aesthetic positions in architecture (e.g. the 'truth to materials' approach found in brutalism), and in materialist/structuralist film (Worth, 2011, p 22 and see Gidal, 1989 on materialist film). Elements of these attitudes can be found in other musical domains too however. Fell (2013a) cautions against considering experimental musical practices as a special case of technological engagement, citing the example of the role of exploration with the Roland TB303 in the creation of "Acid Tracks" by Phuture, a defining acid house release. A study conducted by Gelineck and Serafin (2009) describes a more hybridised combination of the material- and communication-oriented perspectives. The study looked at the compositional processes of 18 digital musicians using a range of established computer music software. Their results highlighted the perceived importance of a *lack* of control, and that the technology played a significant role in the creation and development of the participants' ideas. In contrast to the more radically material approaches described by Worth and Haworth however, as the compositions progressed, after an initial exploratory phase the musicians wanted an increasing amount of control in order to refine and finalise their ideas. This highlights the point made at the outset of this section: that although the musical contexts considered here are perhaps extreme and atypical in their engagements with tools, these approaches and attitudes are nevertheless present to a significant degree in more conventional musical situations.

2.2.5 Material-oriented perspectives and nonlinear dynamics

The discussions in this section on attitudes to musical instruments in areas of contemporary music, and the discussions in Section 2.1 on the behaviours of nonlinear dynamical systems share many similar concerns. Scope for exploration, non-random unpredictability, unstable aspects and the managing of behaviours rather than complete control can be found at many points across all three practices.

This section draws some of this together, finding links between these material-oriented musical practices and the use of nonlinear dynamics. Links with cybernetics are considered, followed by a closer look at the ecosystemic paradigm, an approach that cuts across all three musical contexts described above, and that explicitly draws on dynamical systems. Finally, an example interaction from free improvisation is considered that connects the nonlinear dynamical properties of acoustic systems to the material-oriented perspective.

2.2.5.0.1 Connections with cybernetics

The overlap between cybernetics and attitudes to contemporary music has been highlighted at several points above. The link with material-oriented approaches and cybernetics seems relatively clear:

- a concern with emergent results,

- the potential for surprise,
- the blending of agency between the system and the user.

Eno (2004) links the concerns of experimental musicians to a quote from the cybernetician Stafford Beer:

> "Instead of trying to specify it in full detail, you specify it only somewhat. You then ride on the dynamics of the system in the direction you want to go." (Eno, 2004, p 230)

The "riding" metaphor is particularly interesting, and is examined closely in the results of the ethnographically-informed study in Section 5.4. The term is often used in relation to feedback systems: riding the feedback. The suggestion of an engagement with animals also seems appropriate. They can be herded in particular directions, but have their own ideas, behaviours and agencies which must be engaged with.

2.2.5.1 Performance Ecosystems

A particularly close fit with cybernetics, nonlinear dynamics and material-oriented attitudes to musical tools is presented in the notion of a *performance ecosystem*. The ecosystemic paradigm presents both a practical area of musical activity, and a well developed theoretical approach to considering highly technologized music (Haworth, 2014). This term has been used to denote a collapsing of the distinctions between the performer, the instrument and the performance environment (Waters, 2007). The three become mutually influential, with the boundaries blurring between them. This approach is often explicitly connected with cybernetics (Meric and Solomos, 2009; Haworth, 2014), and highlights musical production as a complex dynamical system (Waters, 2007), in both an acoustic sense and a social sense. Artists associated with the ecosystemic approach (several of which have been mentioned already: Di Scipio, Tudor, Lucier) explore complex feedback systems in their work (Green, 2008; Waters, 2013; Anderson, 2005; Kuivilla, 2004; Sanfilippo and Valle, 2013; Davis, 2011), often setting up unstable situations that can be perturbed and explored by musicians or the public. A central motivation here is the emergent nature of such systems, and the mixture of agency at play between the artists, the instruments, and potentially the acoustic space and the public (in the case of "open" feedback systems as discussed below in Section 2.2.5.1.1).

Again, although this may appear to be a very small musical niche, it serves as a usefully extreme case that helps to explore elements that exist in more subtle ways in a great variety of situations. For example, Waters (2007) describes how site specific performance was closer to the rule than the exception in pre-19th century music. This openness to variety, and willingness to respond to the specifics of the situation (e.g. acoustic space) shares concerns with with the material-oriented perspective.

Figure 2.7: Eddie Prévost exploring the complexities in the interactions of a bow, a cymbal and a bass drum. Photograph: David Reid, 2003.

2.2.5.1.1 Improvisers and nonlinear dynamics

Section 2.1.4.3 demonstrated the important role that nonlinear dynamical processes play in interactions with acoustic instruments. It is useful to consider how these aspects are engaged with in the context of free improvisation, where improvisers often seem to seek out nonlinear dynamical interactions even where their instrument may not easily facilitate such interactions. Eddie Prévost's engagement with regular percussion objects such as drums and cymbals provides a useful example. These objects are combined in creative ways to create unpredictable and unstable interactions. A method frequently employed is the use of bowed cymbals to excite drum skins as pictured in Figure 2.7. The nonlinearity of the bow friction (Smith, 2010), the nonlinear dynamical nature of the cymbal's response (Chaigne et al., 2005), and the complexity of the interaction between the cymbal resonances and the drum resonances all combine to create a very complex musical system that can be explored, and that can yield unpredictable-yet-deterministic behaviours. Many other such examples can be found of improvisers finding and exploring particular areas that bring the nonlinear dynamical aspects of the interaction to the fore:

- the frequent use of feedback in amplified instruments,
- exploration of multiphonics and other unstable regions in wind instruments,
- pianists interacting with the strings inside the piano rather than using the keys, enabling a more direct engagement with the dynamical behaviour of the strings,
- the use of unorthodox bowing techniques to explore complex timbres in bowed strings,
- the use of instrumental alterations in string instruments that create new time-varying behaviours and that interfere with the natural oscillations of the string (e.g. rulers inserted between guitar strings, extra strings tied to violin strings).

The distinction made by Sanfilippo and Valle (2013) between open and closed feedback systems is important here however, in distinguishing between many of the systems discussed here and digital implementations of nonlinear dynamical systems. The authors distinguish between open feedback systems where the surrounding environment may influence the system (e.g. through a microphone connected to the system, possibly in conjunction with a speaker, forming an open loop through space), and closed systems, where the system is shutoff from external influences other than pre-defined control inputs (e.g. dials, switches, faders). Complex acoustic situations such as Prévost's bowed cymbal/drum skin combination can be easily expanded and explored by introducing new objects into the situation. For example, merely placing another object on the drum may dampen the resonance of the skin, which in turn may effect the behaviour of the cymbal and the bowing interaction[7]. The whole system is open, and can be easily interfered with[8]. This is not the case with closed, digital systems[9]. Any interaction points must be added to the system in advance. Nevertheless, even such closed systems may still be significantly explorable.

2.2.5.2 Summary

This section has laid out attitudes from contemporary musical practices and their relevance to the design of digital musical instruments. In particular, a material-oriented perspective to creative engagements with tools is sketched that foregrounds an attention to the specific behaviours of tools, and acknowledges the influence of the tools in the formation of ideas. This perspective complicates the idea of 'control' in musical interfaces, allowing the interface to kick back, to surprise, and to enter into a dialog with the musician. The three intersecting musical areas explored in this section — experimental music, free improvisation, and contemporary computer music — highlight a range of approaches to interaction that celebrate a more bi-directional relationship with musical tools, embracing unpredictability and chaos but not necessarily randomness. Explicit links between these practices and the exploration of nonlinear dynamics are traced, highlighting the potential role that such processes may play in material-oriented musical practices.

The following section examines the field of human computer interaction in relation to

[7]this kind of combinatorial exploration is explored by Bowers and Villar (2006) in the context of Prévost's approach to improvisation

[8]Giaccardi and Fischer (2008) provide a more HCI-specific perspective on the notion of designing open systems that can be user-modified, linking this approach to the possibility of emergent outcomes

[9]Although it is not difficult to open up these systems by incorporating microphones and loudspeakers into the system (as with Di Scipio's pieces (Anderson, 2005)) or by using transducers and contact microphones (as with Tudor's *Rainforest* pieces (Driscoll and Rogalsky, 2001)).

both nonlinear dynamical systems and material-oriented attitudes to creativity.

2.3 Human-Computer Interaction

This section examines the research questions in terms of existing literature from the field of human-computer interaction (HCI). The present thesis is concerned with issues at the border of HCI and music, making potentially useful contributions in both directions. It is therefore helpful to contextualise the research in both a musicological context, as the previous section has done, and in an HCI context as this section will do. Music presents a rich, productively challenging context for HCI research (Holland et al., 2013), particularly in terms of aspects such as live performance (Hook et al., 2012) and improvisation (Bowers and Hellström, 2000; Taylor et al., 2013). Reciprocally, HCI methods — particularly 'third wave' HCI (Harrison et al., 2007) — have been drawn on in attempts to develop and refine research methods and evaluation strategies for musical interfaces (Wanderley and Orio, 2002; Kiefer et al., 2008; Stowell et al., 2009; Hook et al., 2012). In this thesis, interactions with nonlinear dynamical processes are examined in specific digital musical devices and specific musical communities providing useful insights for interactions in fields beyond music. Conversely, musical communities and artefacts are examined from an interaction perspective, providing musicological insights into engagement with tools in these musical communities and potentially beyond.

The material-oriented perspective on creative engagement elaborated in Section 2.2.1 is explored in relation to HCI theories with similar perspectives (Section 2.3.1). This leads on to an examination of the concept of affordances in relation to tool engagement, and more specifically to musical tools (Section 2.3.2). The concept of 'affordances' is helpful as it acknowledges that although musical tools may embody particular aesthetic ideas, they also interact in different ways with musicians' differing experiences, ideas and approaches to interaction.

Section 2.3.3 then engages with some of the vast literature that sits at the intersection of music and HCI research. A particular area of interest is research that engages with *mapping*: how human input corresponds to sonic output. Section 2.3.3.1 introduces existing approaches to researching how different mapping designs influence the ways in which musicians (and non-musicians) engage with musical systems. Links between complex mappings and exploratory, material-oriented engagements are highlighted and developed further in the context of linear dynamical mappings (Section 2.3.3.1.2), and nonlinear dynamical mappings (Section 2.3.3.1.3).

The notion of 'expression' is examined in the context of the communication-oriented/material-oriented distinction to engaging with musical tools (Section 2.3.3.2.1), with the common understanding of the term seeming to be more appropriate for the communication-oriented perspective. The term 'exploration' is highlighted in Section 2.3.3.2.2 as a useful alternative that aligns more closely with material-oriented approaches. Studies of exploration in digital musical instruments are then discussed in Section 2.3.3.3.

Questions around how engagement alters over longer time periods are posed in Section 2.3.3.4, including questions of learning curves and how these ideas fit in with the musical contexts discussed in Section 2.2.

Finally, in Section 2.3.4 interactions with nonlinear dynamical processes are considered in domains beyond music, such as computer graphics and computer games.

2.3.1 Material-oriented attitudes in HCI

As discussed in Section 2.2.1, Dewey's ideas around the role of action and experience in engaging with the world have had a notable impact in HCI literature. A range of authors have discussed similar ideas and related them to design and digital interaction. Four key ideas are considered here: Donald Schön's reflection-in-action (Section 2.3.1.1), Lucy Suchman's situated action (Section 2.3.1.2), reflective design as described by Sengers, Boehner, David and Kaye, and Bill Gaver's ludic design (both in Section 2.3.1.4).

There are important parallels between the approaches to interaction discussed by these authors and the kinds of musical interactions discussed in the previous section. These parallels are examined in more detail in the light of the studies conducted for this thesis, particularly in the individual study discussion Sections 4.5 and 5.4, and then in the final discussions in Section 6. Important differences emerge, highlighting how these musical contexts provide notably different models of interaction that require different considerations, and offer useful perspectives on these established HCI concepts.

2.3.1.1 Reflection-in-Action

Donald Schön's notion of reflection-in-action highlights the contribution made to the creative process by the tools and materials being engaged with. He describes how the material "talks back" to the user (Schön, 1983, p 79), resulting in a "a reflective conversation with a unique and uncertain situation" (ibid. p 130). Initial ideas and plans are revised as a result of surprises encountered during an interaction. Schön has discussed this across a range of situations, such as an architect making pencil sketches (Schön, 1983), psychiatrists discussing patients with supervisors (ibid.), designing and marketing scotch tape (Bennett, 1996), engaging with design software (ibid.), and notably for this thesis, playing melodies with musical bells (Bamberger and Schön, 1983) and the process of improvising with other musicians (Bennett, 1996). In common with the material-oriented musical attitudes to tools and instruments in Section 2.2, surprises in interaction are seen as playing a creative role, as "opportunities to be exploited" (ibid. p 130) rather than merely hindering progress towards a pre-established goal. Both the material-oriented attitude as outlined in this thesis, and Schön's reflection-in-action have roots in Dewey's writing (Visser, 2010, p. 3; Redmiles and Nakakoji, 2004). Johnston et al. (2005) explore reflection-in-action in the context of musical practice, contrasting reflective approaches with an idealist mindset that provides a close fit with the communication-oriented approach outlined in Section 2.2.1. This idealist approach "suggests the performer should picture in their mind what should happen and leave it to the subconscious to take care of the details" (ibid. p. 168). The authors bluntly reject this approach, noting that while it may be desirable, it is not the case in reality. Schön's own descriptions of reflection-in-action also bear many similarities with the material-oriented attitude to musical engagement traced in Section 2.2.1, particularly the improvisatory and experimental musical approaches:

> “[reflection-in-action] is terminated by the discovery of new features which give the situation new meaning and change the nature of the questions to be explored”

The connection between reflection-in-action and experimental musical practices has also been noted by Burraston (2005). Kvifte (2007) develops reflection-in-action in relation to jazz improvisation, noting the role that reflection plays in both moment-to-moment changes, and in the longer-term development of improvisatory skills. For Schön, improvising jazz musicians provide a common, comprehensible example of reflection-in-action, as musicians adapt and respond to developments as they occur. While Schön’s examples are typically of musicians responding to an emerging group situation, Kvifte (2007, p 102) applies this to musicians performing individually, and hence the reflection being oriented towards the response of the instrument. Despite the focus on improvisation however, the fundamental conception of instrumental playing seems at odds with the material-oriented approach to improvisation sketched in the present thesis. Kvifte characterises playing an instrument as “a goal directed activity where the object is to accomplish a specific musical effect.” The reflective cycle is therefore brought to bear on realising that goal, rather than opening up new goals and new questions as described by Schön.

A potential issue with “reflection” is the very broad range of situations that this might encompass. This is particularly pertinent when considering different timescales for reflection: there may be important differences between the kinds of reflection involved in sketching architectural drawings on the one hand, and the moment-to-moment interactions with a complex musical instrument on the other. In latter situation, both the surprise and the reflection are embedded in the interaction, while the former example takes place outside of the specific pencil interaction, taking place instead in the emerging situation created by the unsurprising pencil marks. Even some of Schön’s musical examples are not concerned with the specifics of the musical interaction with the tool, but rather the compositional act combining of separate elements to create a whole from parts (see Bamberger and Schön, 1983 for example). This distinction between surprise and reflection in real-time interaction and more offline compositional situations is discussed further in relation to the two studies conducted in this thesis in Section 6.

2.3.1.2 Situated Action

There are similarities between reflection-in-action and Lucy Suchman's concept of situated action (Suchman, 1985), touched on in Section 2.2.1. Situated action is contrasted with approaches that require detailed initial plans prior to action, with the former instead embracing contingency and ad hoc responses to particular situations as they unfold. Interaction is again seen as a two-way process, and in line with the material-oriented perspective described in Section 2.2.1, the non-neutrality of the tool is taken as foundational:

> "Every human tool relies upon, and reifies in material form, some underlying conception of the activity that it is designed to support." (ibid. p. 3).

The contrast between situated action and more goal-oriented approaches to action can be connected to the difference between traditional approaches to composition and performance, and certain contemporary approaches. While free improvisation presents this in a relatively obvious form — there is no plan by design, with actions and goals being necessarily formed in relation to the unfolding situation — notated approaches to composition also embrace these ideas. Performers are often given the freedom to respond to what develops in the specific performance (see Sections 2.2.2 and 2.2.5).

2.3.1.3 Situated action, reflection-in-action, and goal-oriented interactions

A difficulty that arises in applying HCI and design concerns to musical practices is that the notion of a 'goal' doesn't necessarily translate very well into the musical domain. The goal for some musicians may be to play a very specific sequence of pitches in a very specific way, but often the goal is less well defined. The musical practices discussed in Section 2.2 are particularly open to a wide range of possibilities, and often the ‘goal’ appears to be something slippery and possibly not even well defined to the musicians themselves.

Both Suchman and Schön engage with the problems of goal-directed activity in interaction. Both include the idea that plans may change or be refined in response to the emerging situation. Such an attitude reflects a more open attitude to tools that are not seen merely as means to predefined ends. Suchman begins her book ‘Plans and Situated Actions’ (Suchman, 1985) with a contrast between European and Trukese approaches to navigation. Both have a fixed destination to reach, but the latter is distinguished by not having a concrete plan for how to reach this destination, responding instead to conditions as they arise. Expanding the analogy for musical practices, experimental musicians, contemporary computer musicians, and particularly free improvisers can be thought of more as teams that have set off with the intent only to go on a journey, with neither a destination or a plan in mind. Navigation is still very important, but not as a means to a particular end, but as something to be explored and engaged with in itself. Whilst this is a slightly hackneyed observation, it serves to highlight the difference in contexts and how musical practices — particularly those under consideration in this thesis — may be difficult to represent in terms of conventional HCI frameworks.

Schön’s engagement with goals appears to be a closer fit, with surprises during the interaction potentially leading to the formation of new goals:

> “Problem setting is a process in which, interactively, we name the things to which we will attend and frame the context in which we will attend to them.” (Schön, 1983, p. 39).

Drawing on Schön, Gedenryd (1998, p 69) proposes the impossibility of separating problem setting from problem solving in the design process. Although this is suggested as the nature of the design process rather than necessarily the engagement with designed artefacts, this entanglement of problems and solutions can be linked to similar attitudes to problem finding and solving in musical practices. Holland (2000) uses the term *problem seeking*[10] to characterise the open-ended nature of musical composition and performance.

> “The learning composer must find or create goals or problems to solve, which may need to be revised, modified or rejected as she evaluates intermediate solutions” (ibid. p. 240).

In free improvisation, the creation of goals in the performance can be a primary aesthetic element, with musicians able to consider the situation and forge new directions from what emerges. The way the musicians deal with dead ends and incongruous elements can be an important part of the experience both for the performers and the audience. Whilst these difficult situations may emerge from social interactions between the players, they may also be derived from unexpected results from the instruments themselves, as discussed in Section 2.2.3.1. The unexpected results are a method of creating goals, problems to solve and motivational dilemmas.

Considering interactions with nonlinear dynamical processes provides an interesting perspective in relation to the notions of plans and goals. Advanced planning in engagements with the more complex and chaotic aspects of these processes can be virtually impossible[11]. Nevertheless, as the studies in Chapters 4 and 5 elaborate, they appear to offer a rich world for performers who are happy to engage with and explore their contingent, unpredictable behaviours, in the manner of Suchman’s Trukese navigators, but with only the loosest of destinations in mind.

[10] tracing the term back to Dewey via Matthew Lipman (1991)

[11] The difficulties composers face in attempting to translate the richness of improvised instrumental explorations on essentially nonlinear instruments (such as bowed and blown instruments) into notated pieces using extended techniques and complex notations provide a case in point. Attempting to recreate a particular performance by a musician such as improvising saxophonist John Butcher is a severely daunting task due to the subtleties of the behaviour of the saxophone, the emergence of delicately balanced multiphonics, complex reed behaviours, and so on. While the terrain can be navigated by the improviser, it is difficult to explicitly map out for the composer.

2.3.1.4 Reflective Design and Ludic Design

Reflection-in-action and situated action are brought together by Sengers et al. (2005) in discussing the possibility of reflective design. Reflective design encourages designers and users to reflect on the underlying values and biases contained in the designed artefacts. Here again, surprise plays a creative role. The authors expand on reflection-in-action by not waiting for surprises to occur naturally in interactions, but by deliberately intervening and causing surprises that trigger reflection (both in the design process and in the use of designed artefacts). They also expand the value-aware design process highlighted by Suchman, to encourage both users and designers to reflect on the design of, and their use of, technology. Other ideas drawn on by the authors for this reflective approach are ludic design (Gaver et al., 2004; Gaver, 2009), and ambiguity in design (Gaver et al., 2003). Both ideas similarly de-emphasise external goals, attempting to allow users to find their own meanings in the interaction. Ludic designs in particular are considered to be sites for exploration, rather than achieving something pre-established. In the development of the *Drift Table* (Gaver et al., 2004) — an interface for exploring aerial imagery through a screen embedded in a coffee table — the design team deliberately limit the control options available to the user. In this instance, the user is unable to jump to a particular location in the imagery, but must drift from their current position. This limitation was contrary to users' immediate desires, but nevertheless had an interesting effect on their engagement with the table, encouraging "the exploration of new activities". This can be linked to a relatively common attitude in music and artistic practices more broadly where creativity stems from engaging with limitations (e.g. Gurevich et al., 2010, Zappi and McPherson, 2014, and Tubb and Dixon, 2014, discussed below in Section 2.3.3.3).

2.3.1.5 Summary: Material-oriented HCI

This section identified parallels between the material-oriented perspective outlined in Section 2.2.1 and contemporary concerns in HCI research and practice. Reflection-in-action highlights the role of "talkback" from the material under consideration, and both reflection-in-action and situated action emphasise the ad hoc development of goals, plans and ideas in response to an emerging situation. This links in well with the present research in that unexpected events and deviations from the clear development of an initial idea are seen as productive and often essential aspects in interaction.

These ideas therefore provide a useful parallel in HCI to material-oriented approaches to musical interaction. However there are also important distinctions that are examined in subsequent chapters in the light of the results of the studies conducted for this thesis. A key distinction is in the nature and location of the surprises under consideration. For Schön, the interactions with the tools themselves are generally straightforward and understandable (e.g. pencilled drawings, playing musical bells, using design software). The surprises arise from what he refers to as the "emerging situation". Whilst this also seems to hold in the musical areas discussed here, these areas also involve surprises *in the interactions themselves*, which appear to play a key role in the creative process. The instantaneous result of a particular input to a musical tool yields an unexpected sound or behaviour. This distinction is important both for exploring the subtleties within these kinds of creative interactions (particularly in relation to nonlinear dynamical tools), and in considering aspects that are potentially overlooked by established HCI theories, but that may offer important insights for interaction design more broadly. See particularly Section 4.5.3 on differences in deterministic and chance surprises, Section 5.4.2 on *mechanical* and *compositional* surprises, Section 5.4.1 on making or not making plans, and Section 6.1 that explores important distinctions between different notions of surprise in light of the research presented in this thesis.

2.3.2 Affordances

As has been established above in Sections 2.2.1 and 2.3.1, the decisions taken in designing a particular tool will influence what potential users can and can't do with it. This applies equally with the design of musical instruments: they are not neutral, but will influence the way that musicians create music, the types of musical material they can and can't access, and the relative ease or difficulty of particular musical tasks. Gibson's notion of affordances (Gibson, 1977) provides a useful way of thinking about this problem and has become an established concern in HCI and interaction design (Gaver, 1991; Norman, 1988; McGrenere and Ho, 2000; Gray et al., 2014). The term is developed as an alternative to cognitive approaches to describing engagement with the world that see engagement as a mixture of sense perception and memory that come together to allow subjects to build up a mental model from which the possibility of goal-oriented action can be determined (Gaver, 1991). Affordances are instead associated with a more perceptual approach, where the environment is perceived "directly in terms of its potential for action" (Gaver, 1991, p. 1). There is therefore an important distinction between the inherent material properties of an object, and what is afforded to a person engaged with that object. The former is a material fact, while the latter is an encounter between a tool and a being with their own intentionality (in the Heideggerian sense). Affordances can therefore change over time. DeLanda's distinction between *actual* properties and *virtual*[12] capacities is similar (DeLanda, 2011, p 389): a sharp stone has the actual property of being sharp, and the virtual capacity to cut. This capacity only becomes actualised when beings evolve with the dexterity and the desire to pierce soft animal skins.

The term 'affordance' has been used to think about the capacities of musical instruments and systems by a number of authors (e.g. Tanaka, 2010; McDermott et al., 2013; Armstrong, 2006; Cannon and Favilla, 2012; Green, 2011; Mooney, 2010; to name but a few). Although the nature of a specific design will have a strong impact on the possibilities that it presents to a potential user, these are not the only factors determining how that user will view the potential for action. Magnusson (2009) poses the question:

> "How do computers, as necessarily symbolic devices, enable, produce, maintain, support, augment, but also constrain and limit our cognitive processes and

[12] Virtual in the sense elaborated by Deleuze (DeLanda, 2002, p 34).

therefore creative output?"

Green (2011) responds to this by emphasising the role of the "particularities of the social and historical context at hand." (Green, 2011, p. 139). This is borne out very clearly in free improvisation, where the conventional uses of musical instruments are often avoided, and the instruments present potentially different possibilities. A violin may afford certain methods for melodic and rhythmic playing in the hands of a classical violinist, along with all manner of nuances in bow use and intonation. In the hands of an improviser it may provide a sounding board for scratching, rubbing, brushing, scraping and so on. The instrument takes on a very different character. There are important differences between considering affordances in the acoustic domain and the digital domain however.

Breaking a string shifts the possibilities offered by the instrument into a new area: the loose string can be played in new ways, offering new sounds, behaviours and interaction possibilities. There is generally no readily available equivalent to this in digital instruments; digital inputs such as MIDI controllers tend to have definite limits. Acoustic instruments can be seen as being inherently more explorable in this regard[13].

Bowers and Villar (2006) describe the process of creating ad hoc digital instruments through an examination of Eddie Prévost's improvisatory practice. Prévost is described placing cymbals onto a horizontally mounted bass drum and exploring the interaction between the resonances of the two, and "exploring strategies for beating and damping the cymbals and affecting how they pass their energy to the resonances of the bass drum" (Bowers and Villar, 2006, p. 234, and see also Figure 2.7 and Section 2.2.5.1.1). The authors attempt to create exploratory affordances through the use of dynamically configurable digital systems which allow for performer experimentation beyond their own intentions as designers. A modular approach is also developed in the study by Gelineck and Serafin (2012), discussed further in section 2.3.3.3.2, but it is interesting to note the lack of interest that the study participants (composers) showed in this feature.

[13]although one may consider the physical acoustic properties of digital instruments, as demonstrated by the study conducted by Gurevich et al., 2010

The potentially deep, rich, complex nature of interactions with nonlinear dynamical systems elaborated in Sections 2.1.2.3 and 2.1.4.3.1 may provide another way of allowing musicians to explore a given tool beyond what could have been anticipated by the designer. *Hidden* affordances (developed in section 2.3.3.2.2) can be discovered and explored. Gaver (1991) has seen hidden affordances as a problem in more conventional design situations, as they can lead to mistakes. This may explain precisely why they can be of interest to improvisers and experimental musicians: compare this to the description given by Lely (2006) in section 2.2.3, where he articulates "a discernible area of music concerned with actively finding and revealing hidden resources of the materials at hand". Section 2.3.3.2.2 considers this issue in more detail in a broader discussion of musical exploration, and studies by Gurevich et al. (2010) and Zappi and McPherson (2014) investigating this aspect in relation to digital instruments are discussed further in Section 2.3.3.3.

An overview of parameter mapping in musical HCI is given first however to provide the relevant background to these discussions, along with a reframing of digital instrument design and use in terms of *exploration* rather than *expression*.

2.3.3 Music and HCI

There is a vast array of literature at the intersection of music and human-computer interaction, which cannot be easily summarised for this thesis. This section will look at certain specific areas that relate to the research questions directly. In particular, attitudes to *exploration* and *expression* are considered in this literature (Sections 2.3.3.2.2 and 2.3.3.2.1), particularly in relation to mapping control inputs to sound generation parameters in digital systems (Section 2.3.3.1). Studies of parameter mapping that incorporate both linear and nonlinear dynamical processes are considered and related to the research goals.

2.3.3.1 Mapping

One of the essentially new aspects of digital musical instrument design is that there is no inherent causal relationship between human interactions with input devices (e.g. a mouse, keyboard, MIDI keyboard, or other sensor input), and the sound outputs. Such relationships in acoustic instruments are governed by the nature of the physical system, e.g. the dynamics of strings or of air in cylinders, whereas in digital instruments this relationship — generally referred to as the mapping between a set of input parameters and a set of output parameters — is open and endlessly reconfigurable. Given the same input information (e.g. the rotation of a dial) and the same audio engine (e.g. a single oscillator with controls for frequency and volume), there are limitless approaches to configuring the relationship between the two. It could be as simple as ascribing a numerical value to both the input data and the output parameters, and linking the two directly. The input could also be fed into a complex system that could involve chance, smoothing, complex logic, averaging, or a range of other algorithmic, dynamic, or stochastic processes, which then finally apply values to the parameters of the audio engine.

A common method for classifying mappings involves subdividing them into four categories: one-to-one, one-to-many, many-to-one, and many-many (Rovan et al., 1997; Hunt and Kirk, 2000; Hunt et al., 2003; Kvifte, 2008). A mapping in which each input maps to a separate, single output is called one-to-one[14]; mapping single inputs to multiple outputs is one-to-many (divergent), with the converse being many-to-one (convergent). A mapping that utilises both convergent and divergent mappings can be called many-to-many, or sometimes, complex (Hunt et al., 2003). Mappings can be further described as either linear, where the output parameter increases proportionally with the input parameter, or as nonlinear. A further dimension considered by Menzies (2002) is the inclusion of time-based, *dynamical* mapping processes. This is discussed further in section 2.3.3.1.1 below.

[14]Note that the term “one-to-one” is often used in similar but fundamentally different circumstances, such as by Magnusson (2005) and Schloss (2003), who both use the term to refer to control in acoustic instruments, and the fact that single physical events generally correlate to single sonic events

The design of these mappings is a highly creative act, with different implementations suggesting very different affordances. Wessel (2006) talks of ‘composing instruments’ to highlight the compositional decisions that must be taken in the design stage (see also Schloss, 2003), and Magnusson (2009) emphasises that systems can be thought of as *knowing* things about music through their design. A clear example can be seen with the Theremin, which offers fine control over glissandi and vibrato due to the linear, one-to-one mapping between the performers hand position and the frequency of the oscillator. The musical possibilities afforded would be radically altered if the mapping was stepped and snapped to a pentatonic scale (the Theremin could then be said to *know* about the pentatonic scale) or if the Theremin played different preset melodies depending on the performers hand position, or if the performer had to continually move their arm to sustain a sound. The affordances can be radically altered through the mapping.

In their study of the effects of different mapping techniques on engagement, Hunt and Kirk (2000) lay out a distinction between an analytical mode of engagement with musical instruments and a holistic mode. The former is characterised by goal-oriented, sequential thinking, whilst the latter is linked to what the authors call the “performance mode.” With the latter approach, a performer may “explore an environment in a continuous manner”, rather than “perform[ing] a series of unit tasks,” (Hunt and Kirk, 2000, p. 233). They highlight the interdependence of parameters in conventional acoustic instruments: “where is the volume control on a violin?”, “which sonic parameter does the bow control?” (Hunt and Kirk, 2000, p. 234). Their research involved giving participants a range of musical tasks to be accomplished on different interfaces ranging from systems using simple one-to-one mappings to more complex multi-parametric mappings. Their conclusions were that the more complex tasks were more easily achieved by using the more complex mappings, and further (and slightly more tentatively) that in general the complex mappings often allowed a more “subconscious” control of the interface, were seen as more fun, and had a greater long term potential. These kinds of interactions were related more closely to the holistic mode of engagement, whilst the one-to-one mappings seemed to support single-dimensional accuracy and were more closely associated with the analytic mode. Kiefer (2012), Dobrian and Koppelman (2006), and Kvifte (2008) support these conclusions. The latter goes as far as to claim that complex mappings are "more interesting and rewarding to use than systems of simple one-to-one mappings," (Kvifte, 2008, p. 353).

This distinction in modes of engagement may be related to some of the other distinctions outlined above in relation to material-oriented perspectives in music (Section 2.2.1) and HCI (Section 2.3.1). The focus of Hunt and Kirk's holistic mode on exploration and responding to the particularities of the instrument in the complex mapping example seem to fit well with the material-oriented approach (and with reflection-in-action/situated action). Similarly, the analytic mode shares some aspects with a communication-oriented approach: sonic parameters can be specified with precision, and surprises are unlikely. The links made by Hunt and Kirk between the holistic and analytic modes of engagement and the specific design of the musical interfaces is therefore particularly important to this thesis which seeks to perform a similar analysis for interface designs that incorporate nonlinear dynamics.

2.3.3.1.1 Dynamical mappings

Several authors have engaged specifically with dynamical mappings. The term 'dynamical' is used to denote mappings that include time-based behaviours. Many commonly found interfaces incorporate dynamical elements. ADSR[15] envelopes provide a simple example: releasing a key does not immediately release the sound, but a longer process is set into motion that evolves over time. This section discusses linear dynamical mappings briefly but then moves on to situations in which a nonlinear element is also present.

2.3.3.1.2 Linear dynamical mappings

Menzies (2002) provides an overview of approaches to linear, time-based processes as mapping

[15] Attack, decay, sustain, release - a common approach to managing the temporal evolution of amplitudes in synthesisers.

elements. The article begins with a criticism of the term mapping itself, claiming that it "perpetuates an overly simplistic view of instrument design," (Menzies, 2002, p. 255) and that it tacitly implies an instantaneous function rather than a time based behaviour. The term *dynamic control processing* is suggested as a more general alternative. The author traces a range of dynamic behaviours encountered in interactions with acoustic instruments, both linear and nonlinear: decay dynamics, near-frequency beating and related dynamics, onset dynamics, mode locking (e.g. overblowing - see Section 2.1.4.3.1 for the link with nonlinear dynamics), evolution dynamics, and micro- and macro-unpredictability. The paper details a range of digital implementations of linear dynamics that are embedded in two example interfaces (examined in more detail in Mudd et al., 2014). Despite highlighting the significance of nonlinear behaviours in acoustic instruments, the author limits himself to implementing linear dynamics in digital systems for this paper. It therefore provides a useful overview of linear processes, and a useful point of comparison with the nonlinear systems examined in this research.

2.3.3.1.3 Nonlinear dynamical mappings

Several authors have advocated the exploration of nonlinear dynamical mappings in digital musical instruments. Jordà (2005, p 214) acknowledges the significance of nonlinear interactions both in the acoustic and digital domain, and draws direct links with free jazz and rock:

> "Musicians explore and learn to control these additional degrees of freedom, producing the very intense, kinetic performance styles upon which much of free jazz and rock music is based. If non-linearity is at first intuitively seen as a source of potential uncontrol, it can therefore also mean higher-order and more powerful control"

Simultaneously associating such systems with both powerful control and virtuosity on the one hand, and "uncontrol" on the other may seem contradictory, but Jordà sees important links between the two.

> “Often mappings in acoustic instruments are slightly nonlinear. Blowing harder on many wind instruments not only affects dynamics but also influences pitch, in such control difficulties is where, in fact, the expressiveness may lie for many acoustic instruments.” (Jordà, 2005, p. 143).

Jordà is keen to stress however, that such systems should not mean uncontrollability and unpredictability. The nonlinear elements are seen as areas that can be pushed into, or moved away from, so that the performer can maintain overall control, making the claim that “there is nothing worse in a new digital instrument performance than the performer looking astonished at a computer screen,” (Jordà, 2005, p. 216). The performer being out of control, or creating music that is not wilfully intended is disregarded as a creative approach: “Is it working? Is it not? Is it doing what it is supposed to do?” (Jordà, 2004, p. 4). As discussed in section 2.2, this is not true in all circumstances, and the potential to be astonished in one’s interaction with an instrument is valued in certain musical practices.

Bowers and Hellström (2000) describe two of their own musical systems explicitly in terms of both nonlinear and dynamical elements. Their attitude to control appears to be more relaxed than Jordà’s, and is more in line with the attitudes displayed by improvisers and experimental composers: “we prefer to support *usability at the edge of control*” (ibid. p. 126). They also specifically express an interest in exploration: “we intend an interface which not merely supports exploring a soundscape but incites it,” (ibid. p. 126). Two of their stated interaction design principles are “dynamic adaptive interfaces” and “interaction spaces [where] the significance of movement [...] becomes context-dependent and locales can emerge with different interactive characters.” These interaction spaces are achieved though the use of nonlinear and discontinuous mappings. An example interface described in the paper demonstrates these ideas. It uses the history of the user’s input actions performed on an XY controller to effectively expand or contract the parameter space. If a user spends considerable time exploring a small area of the XY controller, the mapping may magnify that

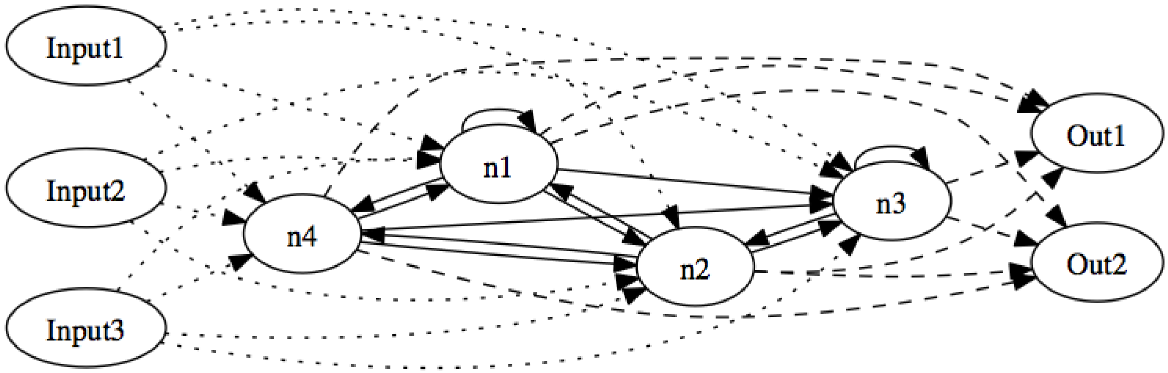

Figure 2.8: Structure of an echo state network, a form of recurrent neural network, from Kiefer (2014).

area so that it is spread across a greater part of the controller, allowing for increasingly subtle explorations. Conversely, it may contract that area, making it more difficult to manoeuvre in that specific area, eventually forcing the performer to explore other territory.

Kiefer (2014) describes a more general method for deploying dynamical control mappings through the use of *echo state networks*. Echo state networks are a specific type of recurrent neural network that consist of a set of input units, a set of output units, and a set of interconnected internal units referred to as the reservoir (see Figure 2.8). As with other neural networks, each connection has an associated weighting coefficient. Echo state networks are unique in that only the output weightings are trained; the other weightings are assigned random values (subject to certain constraints). Thus, the dynamical aspects of the reservoir are exploited through the calibration of the output weights. The system can therefore take advantage of a gradually fading memory of its input.

The degree to which the output is determined by the history of the inputs can be adjusted through scaling the weightings of the internal elements. Kiefer makes this parameter (along with many others) available to control in realtime through a set of Pure Data external objects[16], allowing for real-time interaction with the echo state network. He demonstrates a range of approaches to eliciting nonlinear behaviour from these systems, and shows how they

[16]Pure Data is an open source visual programming environment for audio, see `http://puredata.info/`

may be applied to music. Of particular interest to this research is his description of using the system with a custom mapping which involves taking the rate-of-change of a manually controlled input and applying it to the scaling factor described above. More energy from the input causes the system to be pushed into nonlinear dynamical areas where it will exhibit a range of unpredictable behaviours. This approach is remarkably similar to Jordà's description of his ideal application of nonlinear behaviour in musical instruments:

> "Non-linearity should not mean uncontrollability nor unpredictability! In a good performance, the performer needs to know and trust the instrument and be able to push it to the extremes, bringing it back and forth from the zones of nonlinearity." (Jordà, 2005, p. 216)

Kiefer's description (below) of working with echo state networks in music shares many similarities with the descriptions that improvisers give of their relationships with their instruments (Section 2.2.3.1):

> "The process of perturbing a dynamical system with external input can give compelling, unpredictable and strangely lifelike behaviours for music and interaction." (Kiefer, 2014, p. 297)

This section has highlighted some of the existing work on interaction with both linear and nonlinear dynamical systems, and how they can be incorporated into musical processes. In line with Menzies' desire to reposition mapping as "dynamic control processes", the nonlinear dynamical processes explored in this thesis lead away from the idea of parameter mapping from inputs to musical parameters. The questions posed by Hunt in section 2.3.3.1 — "where is the volume control on a violin?", "which sonic parameter does the bow control?" — can be related to interaction with nonlinear dynamics. Consider the amplitude of the output of a Duffing oscillator as described in Section 2.1.2.3: the amplitude is not controlled directly by a single input. The amplitude is an emergent property. Whether a particular input parameter to the system increases the amplitude of the oscillations is dependent to an extent on the other inputs, and the current state of the system. This can be seen in Figure 2.6 as discussed in Section 2.1.4.3.1, where the output sound pressure level in a clarinet is shown in relation to lip force and breath pressure inputs.

The following section discusses these questions of mapping and ‘‘dynamic control processing’’ in terms of broader ideas of both exploration and expression in musical situations.

2.3.3.2 Expression and Exploration

Although the research conducted by Hunt and Kirk (2000) discussed above in Section 2.3.3.1 builds on that done by Rovan et al. (1997) — who studied the use of convergent and divergent mappings in connecting a Yamaha WX7 wind controller to an additive synthesis engine — the framing is different. Rovan et al. (1997) centre their discussions around the term *expressivity*, an element they claim has been perceived as lacking in electronic music, a concern that runs through the digital instrument building community (Jordà, 2005; Nakra, 2000, p 15; Rowe, 1996; Machover, 1992). Hunt and Kirk talk instead of *exploration*, a term that has significant resonance in free improvisation and experimental music as laid out in section 2.2. The two terms are examined in more detail below.

2.3.3.2.1 Expression

Expression is often viewed very differently by artists from different backgrounds. The composer Alvin Lucier, for example, has distanced himself from the idea of self-expression in music, but points out that music can nevertheless be expressive: ‘‘A river is expressive, but is not expressing anything’’ (Lucier in Rusche and Harder, 2013). Using expression in this sense removes the idea of communication from the artist outwards as described in Section 2.2.1.

The term often has a more specific meaning in literature surrounding the development of digital instruments, notably in the New Interfaces for Musical Expression conference literature, where the term has been the subject of considerable debate.

Jordà (2005, p. 227-228) charts the rise of the term in paper titles from the International Computer Music Conference (ICMC) from 1990 to 2000, showing that the term steadily becomes more significant in the literature. He also points out that the term is used to refer to a range of different ideas, and clarifies what it does and does not mean for him. The observation that "expression is not a matter of reproducing dated romantic clichés or templates, but of finding personal ways to transmit one's own ideas," presents a fairly broad picture of expression, but one that also leans towards a definition based upon the communication of prefigured ideas rather than the more experimental definition given by Lucier. This presents a seemingly common viewpoint on the term *expression* in literature on digital musical instruments, and perhaps in wider musical discussions: it is agreed that expression is highly subjective (Jordà, 2005, p. 163), but it is broadly defined as a mode of communication of some kind.

The term is examined in detail by Dobrian and Koppelman (2006) who link it closely with control and virtuosity. This paper is frequently cited by the communities of researchers around the International Computer Music Conferences (ICMC) and NIME conferences, and it can be closely related to the instrumental ideal favoured by Rovan et al. (1997). As with Jordà, the authors are concerned with "those characteristics of the live performance that enhance expressive communication" (Dobrian and Koppelman, 2006, p. 277). This is then related to control: "control is a precondition for enabling expression", and "for high quality musical expression, an instrument should be mastered; the performer should achieve a level of virtuosity." (ibid. p. 278). Dobrian and Koppelman state very clearly that they are interested in a notion of expression that relates to the performer, and to their capacity for gestural nuance. This is differentiated from expression as it relates to the composer, which they associate with "expressive characteristics of musical materials and their organization" (ibid. p. 277). This latter definition however, is a good description of the concerns of not only experimental composers, but also free improvisers: performers. This suggests that the concerns of such performing musicians are potentially at odds with many instrument designers, or at least many of those centred around musical HCI communities.

Gurevich and Treviño (2007) outline what they see as the potential problems in attempting to create interfaces around particular models of expression, notably what they see as traditional, communication-oriented notions of expression. “Contemporary aesthetic possibilities demand a model that addresses musical creation without necessary recourse to a discourse that assumes a determinate expressive content”. They suggest instead “experimentalism as non-expressive artistic creation” (ibid. p. 107), and propose an “ecological” model of expression in which,

> “[...] expression does not inhere in any specific medium or stage in a chain through which it is passed. The content of music is therefore no longer limited to the text and the expression; rather it becomes a fluid and dynamic outgrowth of the ecology of a given performance.” (ibid. p. 108)

Cannon and Favilla (2012) cite this characterisation of expression in their study of how an instrument’s potential for expression can be linked to the specifics of the instrument’s design. They trace the development of several of their own instruments as they alter the number of sensors, mapping layers (generally only utilising one-to-one mappings) and number of signal routings (more routings would allow a greater number of different audio processes to be combined in parallel). Their study is notable for their attempt to quantify expression by measuring it along eight dimensions, based explicitly on their own musical group’s aesthetic concerns:

1. pitch range
2. pitch style and tuning
3. dynamic range
4. timbre style and tuning
5. articulation
6. ornamentation

7. number of parts or streams
8. spatial

The data for each dimension was gathered from analyses of past recordings (of both the audio and the controller data) made with the instruments. They make no claims for this definition of expression to be universal, but rather are clear that these categories relate only to their own musical ideals.

As noted at the outset of this section, Hunt and Kirk (2000) make almost no mention of expression in their 27-page report on mapping strategies for musical performance (nor do the study participants across two pages of quotes). A word more frequently employed is *exploration*, a mode of engagement that suggests a different way of conceiving the relationships between musicians, instruments and sound that is less communication-oriented and more engaged with the specific materials at hand.

2.3.3.2.2 Exploration

> "Explorative operation means that the user discovers how to control a device by exploring different input control positions and combinations, thus gaining an immediate response from the system. The user may appear to be 'playing around' with the control, but they are actually discovering hidden relationships between parameters within the system." (Hunt and Kirk, 2000, p 233)

Although Hunt and Kirk may intend this as a learning process and as a way to develop skills on an instrument, this model of exploration fits in closely with the attitudes of many free improvisers discussed in section 2.2.3. Exploration provides an alternate way of thinking about control in digital instrument development that is not centred around communication. It relates to the term put forward by Cannon and Favilla (2012), "investment of play", and to Gaver's concept of "ludic design" discussed above in Section 2.3.1, in that the instrument is a starting point for active exploration, and can reward inquisitiveness and long term engagement with continued surprises and developments. Zappi and McPherson (2014) relate a similar idea in their discussions of *hidden* affordances. These are affordances not consciously included by a designer, and not immediately obvious to a user but that nevertheless play a key role in the development of a personal musical style with a given instrument. These hidden affordances are found through exploration of the instrument.

A move from expression to exploration in musical interface design involves a greater acknowledgement of the role played by the interface itself in the creative process. This shift in attitudes is consistent with the attitudes found in many areas of contemporary music as discussed in section 2.2.1. The musicological study of artists on the Mego record label conducted by Worth (2011) makes this kind of shift very clear, and links it to wider shifts in musical ideas: technology is "not seen as a medium for the communication of ideas, but rather as a source of ideas." It also ties in closely with Magnusson's concept of "epistemic" interfaces that contain musical material within them (Magnusson, 2009, 2010) as discussed above in Section 2.3.2.

The following section examines studies that follow on from the work done by Hunt and Kirk, into the relationship between the design of digital musical tools and attitudes to exploration.

2.3.3.3 Studies of exploration in digital musical instruments

This section explores studies conducted since Hunt and Kirk (2000), that explicitly focus on exploration in digital musical systems.

2.3.3.3.1 Exploration of hidden affordances

A study conducted by Gurevich et al. (2010) provides useful insights into the relationship between the exploration of particular affordances of an instrument and the development of a personal style of playing with that instrument. Their study presented participants with a drastically simplified instrument: a box with only a single button, which produces a fixed tone from a speaker within the box. They conclude that in many cases, the exploration of “non-obvious” affordances (which can be linked closely to hidden affordances as discussed in Section 2.3.2) constituted a major aspect of the development of personal playing style. Examples given of these affordances include the odd timbral effect that could be produced by holding down the single button whilst powering the box on and off, or producing a chaotic sound from the usually stable oscillator by partially depressing the button.

Zappi and McPherson (2014) support this conclusion, and attempt to expand the work through a similarly constrained box-based interface experiment. Their box had two inputs: a force sensitive resistor and a multitouch XY surface. These inputs controlled a simple snare-like percussive sound and a drone, with both always being triggered simultaneously. They implemented two mappings which were each given to five participants. The first mapping had only a single degree of freedom providing timbral control over the sounds. The second added continuous pitch control over a deliberately restricted four semitone range. The participants used the devices in two concerts (one public and one private). Both groups of participants explored a range of hidden affordances with the device, found through touching the speaker, licking the sensor, placing objects on the speaker, and so on. They conclude that exploration of such affordances may actually be constrained by the inclusion of the extra degree of freedom. This conclusion would require more investigation however due both to the limited participant numbers, and potentially the specific nature of the mappings that were used. It also does not investigate how these trends may develop over longer periods of use (see Section 2.3.3.4 for more on long term exploration of affordances).

2.3.3.3.2 Composers and exploration

Two studies conducted by Gelineck and Serafin examine exploration with digital musical tools in relation to the compositional process. In the first study (Gelineck and Serafin, 2009), 18 digital musicians were interviewed with regards to their compositional approach and use of tools. A key starting point for the study was a contrast between two approaches that appears very close to the material/communication contrast explored in Sections 2.2.1 and 2.3.1. One compositional approach involves beginning with a clear goal and then attempting to realise that idea with the tools to hand (akin to the communication-oriented approach). The other approach involves deriving inspiration from an exploration of the tools and sound material available, with the composer being viewed as "an *explorer* of musical affordances" (ibid. p 219, emphasis in the original).

The conclusion drawn from the interviews is that often both approaches play a part for individual composers, but at different points in the compositional process. They describe a narrowing of focus: an exploratory, experimental phase is followed by a more structured, editing phase, and finally a pragmatic phase where ideas from the first two phases are brought together and rationalised (although they suggest the possibility of back-and-forth between the three phases). Questions of control were important in these phases, with a lack of control being seen as a positive element in the exploratory phase:

> "16 of 18 [participants] said that finding themselves in too much control can kill the creative process. Most prefer tools that they don't understand fully, tools that are unpredictable in some way, or tools that they can use in unintended ways." (ibid. p 221)

These aspects are therefore closely associated with the material-oriented approach where ideas come out of a process of exploration, and that exploration is facilitated by a lack of control and understanding, and through the possibility of unexpected occurrences.

These ideas were developed in a second study by Gelineck and Serafin (2012). A series of instruments based around physical models were created by the authors and given to three participants for a period of four weeks. The three participants selected were all composers who regarded themselves as electronic musicians, and whose practice involved some sort of "experimental approach" (although this is a use of the term distinct from that employed in "experimental music" as discussed in section 2.2.2; although the term is not defined clearly by Gelineck and Serafin, the participants do not seem to be focused on the explicit materials at hand). The musicians took the instruments away and integrated them into their existing compositional environments. The majority of the four week period was assigned to the free exploration of the tools, with a single week assigned to a specific composition exercise that required the participants to use certain aspects of the instruments. Much of the anecdotal feedback from this study suggests that exploration was a relatively low priority for the three participants (particularly participants A and C; participant B was slightly more open to responding to the particular affordances of the new tools). The choice of subjects is particularly interesting in this study: they were all composers who were concerned with fitting the instruments into wider compositions as one element among many. They therefore appear to be quite goal-oriented in their use of the instruments: “There isn’t really anything that motivates me to turn this knob, if there isn’t an underlying chord it can play together with” (participant A) (ibid. p. 268); “I wouldn’t want to sit and play with anything that wasn’t going to be used somehow” (participant C) (ibid. p. 269). The musical contexts that were of interest to the three participants appear to be largely pitch-focused, leading participant C to conclude that the instruments provide “too much focus on exploration of timbre alone and that without having better control of notes, melody, harmony and rhythmical structure they generally lacked playability” (ibid. p. 270).

This gives a useful insight into the preferences a musician may have for different kinds of system in their work. Notably for the present thesis, the instruments created by Gelineck and Serafin all utilise nonlinear dynamics, but these aspects rarely seemed of interest to the three participants, with only participant B seeming to explore these affordances (who describes finding “a subtle little sound that occurred just as the *frictionPHOX* would be excited before it reached a steady state”, ibid. p. 270). Comments from the other two participants seem to indicate that the complex nature of the control — likely stemming from the inclusion of nonlinear dynamical processes — was a problem rather than a source of inspiration. Even participant B concluded that,

> “Maybe a free jazz musician or others would think that they are fun to take with

> them on stage, but for me, they are not controllable enough . . .. but then that makes it fun in the studio'' (ibid. p. 272)

2.3.3.3.3 Divergent and convergent exploration

Tubb and Dixon (2014) explore particular interface mappings that use small numbers of inputs to control large numbers of audio parameters. This approach is contrasted with an interface where direct control over each of the audio parameters is provided in a one-to-one fashion. They link these two approaches to mapping to two stages of the creative process: divergent exploration, and a convergent narrowing of options towards an ``appropriate solution''. These definitions of 'convergent' and 'divergent' differ from the use of the terms by Rovan et al. (1997) denoting many-to-few and few-to-many mappings respectively. Tubb and Dixon derive the terms instead from Guilford (1967), where they relate to modalities of thought. Divergent approaches are associated with exploration and ``novelty generation,'' whereas convergent approaches constitute a narrowing in on optimal ``solutions.'' Tubb and Dixon make links between divergent mappings (in the sense used by Rovan et al.) and divergent thinking (in the sense used by Guildford)[17]. The divergent and convergent approaches can be linked with the exploratory and pragmatic approaches taken as a starting point for the studies conducted by Gelineck and Serafin, described above in Section 2.3.3.3.2. They also link this research with the studies conducted by Hunt and Kirk (2000) discussed in Section 2.3.3.1, suggesting that the divergent, two-to-many mappings used by Tubb and Dixon support a holistic rather than an analytic mode of engagement.

The musical context for this study appears to share similarities with the context of Gelineck and Serafin's participants in their 2012 study: working towards composed musical pieces in a studio environment (as suggested by the looped, quantised melodic sequences that serve as the backbone to their software). The idea of ``exploration'' in such contexts may be subtly different to ideas of exploration in the musical contexts outlined section 2.2.

[17]Note that one-to-one mappings are linked to convergent thinking, rather than convergent, many-to-few mappings (in the sense used by Rovan et al.)

The focus in the former case is inclined more towards *finding solutions* in goal-oriented situations (they frame the ultimate aim as ‘‘finding the most appropriate solution’’, and see also the comments made by participants in Gelineck and Serafin’s study presented in Section 2.3.3.3.2), whereas in free improvisation and other musical areas, exploration can often be characterised as *problem seeking* as much as *problem solving* (see Section 2.3.1.3).

2.3.3.4 Long term engagement and ease of use

An important aspect of examining affordances and engagement with instruments is gauging how people interact with them over longer time periods. Some instruments may be very enjoyable, stimulating, and rewarding to explore in the short term, but may then quickly become uninteresting or overly limiting, whilst some instruments may be initially frustrating but reward longer term exploration.

In their report on creativity support tools, Shneiderman et al. (2006) lay out a set of design principles to support creative thinking, which emphasises ‘‘easy exploration, rapid experimentation, and fortuitous combinations that lead to innovations,’’ (Shneiderman et al., 2006, p. 10). This list also includes principles such as: ‘‘make it as simple as possible’’ and ‘‘low threshold, high ceiling, and wide walls.’’

The former in particular seems to be at odds with the ideas about musical tools being laid out in the present thesis. This may be a point on which the design of musical tools differs from conventional design considerations, but it may also suggest that complex musical interactions such as the nonlinear dynamical interactions proposed here can provide alternate models for interaction in other domains of HCI (this point is developed further in section 2.3.4).

Kiefer links the list of design principles created by Shneiderman et al. to the concerns of digital musical instrument designers (Kiefer, 2012, p. 32), placing considerable emphasis on having a ‘‘low threshold, high ceiling, and wide walls.’’ This also echoes the often cited call from Wessel and Wright (2002) for instruments to have a ‘‘low entry fee’’ and ‘‘no ceiling on virtuosity,'' (Wessel and Wright, 2002, p. 12). The influence of this paper is highlighted by its inclusion in the 2017 NIME reader: a compilation of significant papers from the 16 year history of the New Interfaces for Musical Expression conference (Jensensius and Lyons, 2017). In this publication, Wright states that this is the most cited aspect of the paper.[18].

The conclusions reached by Hunt and Kirk (2000) discussed in Section 2.3.3.1 seem to point to a connection between complexity and initial difficulty, and long term reward and satisfaction however. Cannon and Favilla (2012) and Marshall and Wanderley (2011) also explicitly contest Wessel and Wright's assertion. The authors suggest that there may be links between initial difficulty and long term reward. Marshall and Wanderley express a concern that instruments that are easy to use may be seen as toys (ibid. p 404). Cannon and Favilla's notion of ''investment of play'' is introduced in opposition to designs that focus on ease of use that can potentially lead to a lack of long term potential, something they associate with ''disposable'' instruments (Cannon and Favilla, 2012, p 459).

Improvisation provides an interesting perspective on this debate. Learning curves tend to apply only when there is a goal in mind. For example, in learning a violin, what constitutes an improvement is relative to a task to be achieved: holding a steady note, playing scales, accurate pitch. In free improvisation however, it is not necessarily important to be able to do any of these things to participate meaningfully. To repeat the quote from Bailey (1992, p 101) given in section 2.2.3.1:

> ''Although some improvisors employ a high level of technical skill in their playing, to speak of 'mastering' the instrument in improvisation is misleading. The instrument is not just a tool but an ally. It is not only a means to an end, it is a source of material, and technique for the improvisor is often an exploitation of the natural resources of the instrument.''

Viewing the instrument in this way challenges the idea of a ''low entry fee''. Although the

[18]The 'low floor, high ceiling' metaphor used by both Shneiderman et al. and Wessel and Wright may share a common root in Sidney Papert's book, *Mindstorms: Children, Computers, and Powerful Ideas* (Papert, 1980).

violin can be considered a very difficult instrument to learn in terms of playing conventional repertoire, or even a simple tune with acceptably steady pitch, rhythm and timbre, in free improvisation it presents a very broad range of affordances to even a novice player. Anyone can pick up a violin and easily explore a wide array of sounds and textures once the goals of accuracy and stability are removed. The nature of a low entry fee is therefore context dependant.

Long term engagement can similarly be seen as context dependant. The Theremin discussed in section 2.3.3.1, despite its simplicity, has been engaged with over a lifetime by performers such as Clara Rockmore. It affords nuanced control over conventional expression parameters such as subtle pitch articulation, vibrato and tremolo that suit the interpretation of the particular repertoire that she engaged with: Rachmaninoff, Tchaikovsky, Ravel, etc. This enabled her to develop and refine her abilities over many years of study and to find new ways to interpret such pieces. In free improvisation however, the use of the Theremin over a similar period may not be as rewarding, and it is very rare to find a Theremin used in free improvisation for an extended period of time without modification or combination with other tools (as with players such as Grundik Kasyansky, Tom Mills and Nahum Mantra). Conversely, musicians interested primarily in pitch may find very little long term potential in an instrument such as the Cracklebox (Waisvisz, 2014), whilst those interested in timbral exploration may develop and refine their approach over longer time periods. To declare objective design criteria for fostering long term engagements with musical instruments would therefore necessitate second guessing the musical contexts in which the instruments were to be used.

This thesis nevertheless takes inspiration from the kinds of instruments and systems that provide long term engagement for those working in experimental composition and improvisation. The popularity of nonlinear dynamical processes in such areas discussed in Section 2.2.5 suggests that they may play a role in fostering long term engagement for these musicians. The time-dependence and hysteresis found in nonlinear dynamical processes (see

Section 2.1.1.3.2) can mean that even with very few degrees of freedom, a very wide range of behaviours is possible. Considering pinball from an interaction design perspective provides a very striking illustration of this: two simple on-off push buttons are the only interaction points with a nonlinear dynamical system that can be mastered over a lifetime[19]. The game relies heavily on the dynamical nature of the system, and although the user action is heavily restricted, the *timing* and the *ordering* of the user interaction is critical. Interaction examples from other domains that involve nonlinear dynamical processes are considered further below in Section 2.3.4.

2.3.3.5 Summary: Music and HCI

The above section, 2.3.3, has examined recent research into HCI in relation to music as relevant to the concerns of the present thesis. The studies discussed above lay some important ground work for the discussions of exploration, expression and control in this thesis. They also provide a range of useful methodologies for investigating links between particular interface designs and how they are used (discussed further in Chapter 3 in relation to the specific studies conducted for this thesis). The frequent references to contrasting approaches to engaging with musical tools supports the idea that the material/communication distinction described in Section 2.2.1 applies more widely than the musical contexts being explicitly engaged with in this thesis.

The complex relations between control, mapping and creative exploration are taken forward in examining nonlinear dynamical interactions in other areas of HCI in the following section.

2.3.4 Nonlinear dynamics in other areas of HCI

In the real world — as opposed to the digital world — nonlinear processes are the rule rather than the exception (DeLanda, 2002; Prigogine and Stengers, 1984). Similarly, as highlighted

[19]see for example the World Pinball Championship at http://papa.org

by Menzies (2002), dynamical processes are also part of our everyday experience. Menzies discusses this in terms of everyday physical movement, emphasising that our brains are used to dealing with the complexities of inertia, friction and gravity. Sports are put forward as an area where the management of complex dynamical processes is a central concern. The importance of such processes could be thought through in a range of creative contexts, from painting and pottery to dancing, juggling, vehicle racing, and so on.

2.3.4.1 Nonlinear dynamics in computer games

Computer games in particular provide a common example of nonlinear dynamical processes in human-computer interactions, particularly where simulations of real-world physics are employed.

Max Dirt Bike[20] provides a simple example of a physics based game in which the gameplay is reliant on creative engagements with nonlinear dynamical processes. The player has only four buttons that accelerate and decelerate the player's bike, and that lean the rider forwards or backwards on the bike (see Figure 2.9). Although the game is essentially goal-oriented, meaning that there is a learning curve associated with attaining these goals and progressing, a significant part of the fun consists of doing so in style and the player is free to approach the task in their own unique way[21]. Mastery of the bike and hence the game requires careful attention to the lateral and angular momentum of the bike; holding the buttons for very slightly different amounts of time can lead to very different results, with the bike tipping over in one direction or the other.

The creative freedom offered by this game, and by many other games that use momentum and simulated physics, e.g. driving games — often apart from the achievement of particular goals as in the above example — point towards broader applications of the discussions in this thesis on creative engagements with nonlinear dynamical processes.

[20] playable at maxdirtbike.org

[21] see youtube.com/watch?v=MD35mPL5uSg for examples of users creatively engaging with the games constraints.

Figure 2.9: Max Dirt Bike, a simple game with only four input buttons that hinges on the creative management of momentum.

2.3.4.2 Nonlinear dynamics in painting

A second area where these processes can be seen to pass from real world complexity into digital interactions is in painting. The behaviour of the bristles of a paintbrush is nonlinear and dynamic (Chu and Tai, 2002): as pressure is applied to the brush, the bristles act like springs, interacting with each other to determine where and how they come into contact with the canvas. The paint itself is also a highly complex material: oil and acrylic paints for example are non-Newtonian fluids (Baxter et al., 2004), exhibiting complex nonlinear dynamical behaviours (Chhabra, 2010). A simple swipe of the paintbrush against the canvas is therefore a highly nuanced interaction, with both the current and past brush position and the current and past brush pressure bound up with the complexities of the bristles, paint, and canvas. The difference between a conventional digital drawing application and a physical paintbrush is marked. Digital implementations generally provide precision through potentially pixel-accurate control (the models developed by (Chu and Tai, 2002) being a notable exception), but rarely provide the opportunity for the unexpected. A single stroke of a physical paintbrush contains a myriad of nuances stemming from the behaviour of the bristles, the dynamics of the hand movement, varying levels of paint on the brush, and so on, which can be potentially explored over a lifetime. Whilst the simple digital paint interaction can still yield surprises as lines and shapes are combined, and as an image is slowly formed on the screen, there is an important difference between this kind of surprise, and the kind encountered *in the interaction itself* with the physical (or physically modelled) paintbrush. The distinction is closely related to the distinction made in Section 2.3.1.5 above between characterisations of surprise provided by Schön and Suchman, and those found in the encounters with musical tools in Section 2.2 and explored in the studies in this thesis.

As with many of the musical areas considered in Section 2.2, visual art practices often engage specifically with the material affordances provided in the complexity of the interaction: the complex behaviour of paint is a resource to be drawn on. Analogously with the digital modelling of acoustic phenomena, attempts have been made to incorporate the complexities of paint and paintbrushes into digital interactions. These models move beyond the simpler pseudo brush-like textures employed in many standard paint applications. Although they produce an image that may resemble paint, they nevertheless lack the complexity, variability, instability and nuance of an actual interaction with paint and paintbrushes[22]. These approaches have necessarily included nonlinear dynamical processes (Chu and Tai, 2002).

2.3.5 Summary

The present thesis has been contextualised through an examination of relevant literature from the field of HCI and musical interface research. Broader concerns such as affordances and mapping for digital musical instruments were considered alongside more specific research on nonlinear dynamical processes in music that relates very directly to this project. Discussions were informed by the range of musical attitudes outlined in the preceding section, 2.2,

[22] A comparison might be made between such techniques and the use of sampled acoustic instruments: they produce a result that resembles the real-world instrument, but the interaction with such a process is markedly different.

particularly in relation to notions of expression and exploration. Particular methodologies were examined which inform the proposed approach to this research laid out in more detail in the following chapter.

Section 2.3.1 established connections between the material-oriented attitudes in musical engagements and related concerns in the field of design and HCI. Influential notions such as reflection-in-action, situated action and ludic design provide more general accounts of the nature of interaction that can be brought to bear in considering musical interactions. Conversely, the specific nature of the musical interactions considered in Section 2.2 and examined closely in this thesis, shed light on aspects of interaction that may be overlooked or excluded from these more generalised HCI theories.

Section 2.3.3 engages with established research into HCI and music, relating the present thesis to questions of mapping, ideas of expression, and the relationship between interfaces and creative exploration. Nonlinear dynamical processes were outlined as a both an existing area of research in the field, and an area that requires further examination. These processes were discussed in relation to important questions about control and unpredictability in creative interactions. Established discussions around expression, exploration, long-term engagement and learning curves were also examined in relation to a material-oriented perspective, highlighting points at which this perspective suggested alternate approaches to viewing and designing musical interactions.

This perspective was again linked to the properties of nonlinear dynamical processes. Section 2.3.4 explored nonlinear dynamical processes in material-oriented engagements in painting and computer games, suggesting the applicability of this research beyond the musical domains that form the central area of investigation in this thesis.

Chapter 3

Research Methodology

HCI and interaction design research are necessarily multidisciplinary, as they draw on disciplines such as engineering and computing on the one hand, and the social sciences on the other (Mackay and Fayard, 1997; Blackwell, 2015). A study of interaction includes a focus on specific, concrete, material artefacts, but is concerned with how these artefacts are used and understood by people, how the artefacts' capacities are viewed and put into practice, how different people and different situations affect how the tools are applied, how the tools influence behaviour and how behaviours influence tool use. Mackay and Fayard (1997) describe a framework for HCI research that embraces its multidisciplinary nature, emphasising triangulation between various methods as an effective way to explore a specific area of interest. This thesis engages strongly with this idea: a mixture of methods are used to approach the research questions from different angles, with a variety of outcomes contributing to a more nuanced understanding. As the roles played by nonlinear dynamics in musical instruments and interactions are relatively poorly understood at present, this is seen as preferable to attempting very specific, quantitative studies on the one hand, or very broad, ethnographic studies on the other.

For this thesis, two main approaches were used, preceded by a set of initial exploratory studies. The first approach was comprised of a set of lab-based studies that presented a range of musicians with specific, digital musical interfaces. These interfaces were designed in order to examine how the inclusion or exclusion of nonlinear dynamical processes affected how the musicians engaged with them. The second approach is ethnographically-informed: questioning musicians directly about their attitudes to, and engagements with, musical tools in their own musical practices. The latter is particularly focused on musicians engaged in contemporary musical practices as outlined in Section 2.2.

These two contrasting methods approach the topic from two perspectives: lab-based empirical studies, and a more practice-oriented ethnographically-informed study. Each method can help to fill out aspects that are lacking in the other, and overlapping results between them strengthen the findings of both studies.

An overview of each methodology and the rationales behind them are presented below in Sections 3.2 and 3.3, following an outline of the initial exploratory studies in Section 3.1. Figure 3.1 provides a visual overview of the process. The specifics of each methodology are presented in more detail in the respective study chapters: Chapter 4 for the exploratory studies and the subsequent comparative studies, and Chapter 5 for the ethnographically-informed study.

3.1 Exploratory Studies

A set of initial, exploratory studies were conducted in order to find appropriate methods for studying the particular effects of introducing nonlinear dynamics into digital musical interfaces. The motivation for these studies was threefold: to explore initial ideas relating to nonlinear dynamical processes in musical tools, to explore specific design ideas that incorporate these processes, and to investigate appropriate methods for subsequent studies.

The process for these initial investigations involved the design, creation and iteration of a range of digital musical interfaces. Study participants were presented with these interfaces and various methods were trialled for examining how participants engaged with such systems,

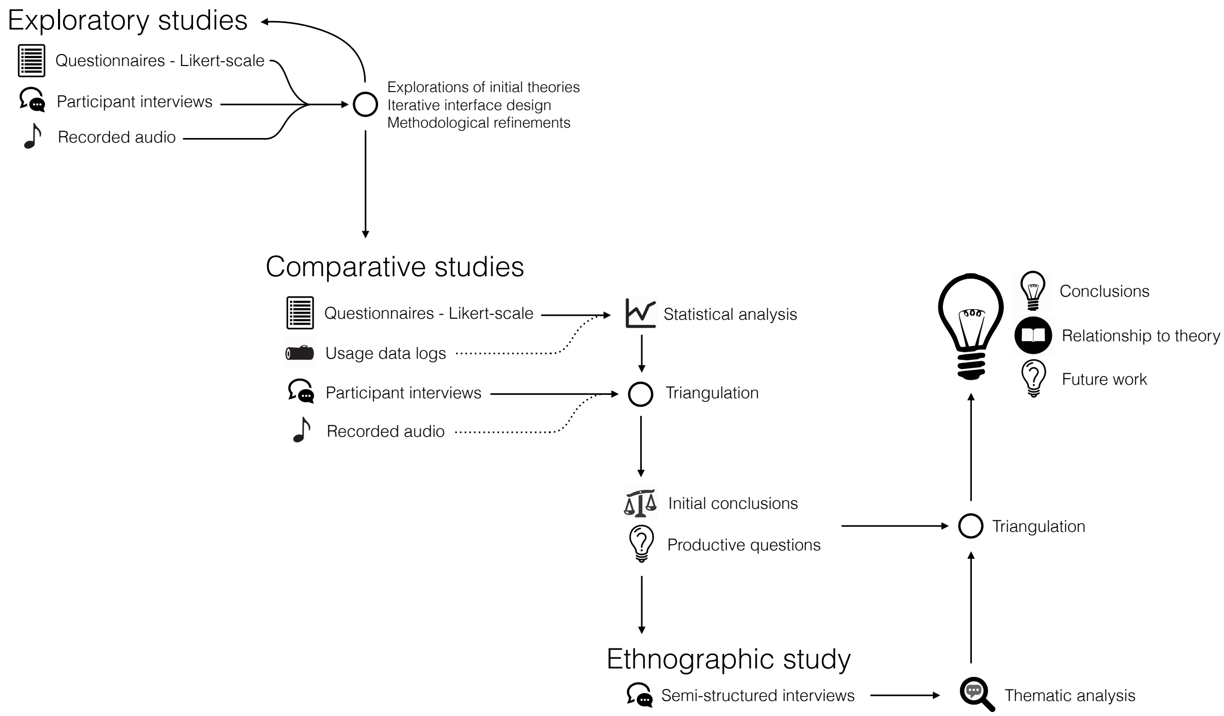

Figure 3.1: An overview of the various studies presented in this thesis, highlighting the data collection methods and the triangulation between different components.

and how the inclusion of nonlinear dynamics affected their engagement and attitude towards the systems.

These studies employed aspects of research through design as described by Gaver (2012): the integration of design methods into HCI research. Such an approach appears appropriate in the domain of music (see particularly research conducted by John Bowers (Bowers et al., 2016; Bowers and Villar, 2006; Bowers and Hellström, 2000)) where clear protocols, procedures and "actionable metrics" (Gaver, 2012) may not be easily found or agreed upon, and findings are not clearly falsifiable in the Popperian sense. Despite this, such a process can help to expose and explore issues, particularly in relation to theory. Carroll and Kellogg (1989) describe a designed artefact as a "theory nexus", suggesting that theoretical insights emerge from the design process: "articulating the system of theories inherent in HCI designs."

While the exploratory studies that provide the starting point for the subsequent studies in this thesis do not attempt a coherent theoretical articulation, the artefacts are deployed to explore some of the initial questions articulated in the introduction (Chapter 1) and discussed in the literature review. In particular, the links between nonlinear dynamics and particular kinds of affordances (see Section 2.3.3.1.3), and broader questions concerning relationships with musical tools (see Section 2.2.1) are examined.

Significantly, these exploratory studies helped to establish some key concerns that arose whilst investigating the use of the designed artefacts. Questions around control, scope for exploration within particular interfaces, and attitudes to unexpected events surfaced as relevant issues. These outline important concerns for studying nonlinear dynamics in both musical interactions and human-computer interactions more broadly. These concerns are therefore taken up in the methodologies applied to both the comparative and ethnographically-informed studies.

The exploratory studies are discussed in more detail in Section 4.2.1, along with their implications for the subsequent methodologies, particularly pertaining to the comparative study methodologies.

3.2 Comparative Studies

The term 'comparative' is used here to refer to the fact that these studies employ a set of specifically designed digital musical interfaces that allow different design components to be compared. The approach to testing and the specifics of the interface designs are developed from the exploratory studies outlined above (see Section 4.2.1.5 for more detail). Musicians with a variety of backgrounds are presented with four digital musical interfaces that vary along two key variables: the presence of nonlinear dynamical processes in the interface, and the presence of discontinuities in the interface. The former implies an engagement similar to that outlined in Sections 2.2.5 and 2.3.3.1.3, where the interaction is nonlinear, time-dependent, may exhibit hysteresis, and may be chaotic. The latter implies that thresholds will exist in the input parameters at which the behaviour of the system may change abruptly.

Interface 1 nonlinear dynamical continuous mapping	Interface 2 nonlinear dynamical discontinuous mapping
Interface 4 static continuous mapping	Interface 3 static discontinuous mapping

Table 3.1: The four interfaces used in the comparative studies differ along two independent variables: whether they include nonlinear dynamical processes (top to bottom), and the nature of the mapping (left to right). The term 'static' is used to refer to the absence of nonlinear dynamical processes in a given interface

While nonlinear dynamical processes are the key element in the study, the discontinuous variable is included to investigate how specific the results are to nonlinear dynamical processes, and whether similar but fundamentally different processes may yield similar results. This approach can be called a *near-miss methodology*: comparable systems are introduced as they have certain related properties that can help to distinguish whether these properties alone are responsible for any change of engagement that emerges in the study results, or whether there is something beyond these specific properties. The comparable system is as close as it can be to the original system, with only the one design aspect varied (hence it is a "near-miss").

The discontinuities in the mapping have a key property in common with the nonlinear dynamical processes: the possibility of abrupt transitions at critical thresholds (discussed in the context of nonlinear dynamics in Section 2.3.3.1.3). A comparison between engagement with and attitudes toward interfaces that include nonlinear dynamical processes on the one hand, and interfaces that instead include simpler discontinuous mappings on the other, can therefore be used to examine in more detail what may be unique about both the nonlinear dynamical processes and the discontinuous mappings. The four interfaces created for the studies therefore differ along these two key variables, as shown in Table 3.1.

This approach to comparative interfaces is informed by a range of HCI and design methodologies. The studies conducted by Hunt and Kirk (2000) into how alterations to the nature of the mapping between human input and sonic output in musical interfaces can affect the nature of engagement are of direct relevance for the comparative approach outlined above (see also Section 2.3.3.1). There are also some key distinctions however. Their methodology was task oriented: participants were presented with three different interfaces that were mapped in different ways to the same audio engine. Each participant was asked to attempt a series of tasks that were assessed in terms of accuracy. The inclusion of specific tasks can help to provide measurable outcomes, but can make it difficult to assess the actual *experience* of using a particular instrument or interface (Kaye et al., 2007; Kiefer et al., 2008; Gelineck and Serafin, 2012). Stowell et al. (2009) make the recommendation that when dealing with complex musical interactions, simplified tasks are unlikely to be appropriate, and more situated evaluation methods may be appropriate. While the studies presented in Chapter 4 draw on many methodological aspects employed by Hunt and Kirk, there has been no attempt to create specific musical tasks that can be objectively measured.

A further, related point (discussed further in Section 2.3.3.4) is that evaluation can be challenging in the context of musical instruments, and to ascribe any kind of success to the instrument involves prior assumptions about what is important in music and musical interactions, assumptions that may not be a good fit for all musicians (let alone the other possible stakeholders involved in an evaluation of musical tools, e.g. composers, audiences, manufacturers, etc. (O'Modhrain, 2011)). For example, Wanderley and Orio (2002) suggest a range of tasks that provide measures of accuracy and control, but as Stowell et al. (2009) note, the authors potentially conflate *controllability* with *expressiveness*. Furthermore, accuracy and control are not necessarily seen as unequivocally positive elements (see the musical contexts outlined in Section 2.2). There can therefore be no straightforward task analysis (as described by Norman and Draper (1986)) as it might exist in more conventional user-centred HCI domains.

The study participants for the comparative studies in this thesis are still given a task however: after spending time familiarising themselves with each interface, they are asked to create a short recording. This attempts to bridge — or at least narrow — the gap between the lab-based study and the participant's own musical practices, encouraging them to think about how the interfaces would or would not fit into these practices, and how they may differ or suggest alternative modes of engagement (similar in kind to the mixture of "free" and "guided" exploration used by Stowell et al. (2009) discussed in Section 2.3.3.2).

As well as the triangulation between this set of comparative studies and the subsequent ethnographically-informed study, a mixture of methods are employed within the comparative studies themselves (see Figure 3.1). These are linked together to build a picture of the *experience* of using digital interfaces with and without nonlinear dynamical processes.

Questionnaires and interviews are used as data collection methods, and are structured in such a way as to permit consistent comparisons between different participants, and analysis of certain quantitative aspects. For instance, questionnaires ask participants to agree/disagree with a range of statements on five-point Likert scales, responses that can then be quantified. Similarly, the interviews are semi-structured with a consistent core set of questions (see Section 4.2.3.2). More concrete quantitative data is provided in the form of input logs from the participants' usage of the various interfaces. While the use of input data logs in the evaluation of musical interfaces can been seen as limited when considered in isolation, they can be useful in connection with interviews and other qualitative elements (Kiefer et al., 2008; Cannon and Favilla, 2012). They are included here with this in mind. This data can be analysed for a range of different metrics (see Section 4.4.2.3) and in combination with the questionnaire data, the interviews and the recorded audio, provide very specific case studies of particular participants (see Sections 4.4.2.3.1, 4.4.2.3.2 and 4.4.2.3.3). A more detailed presentation of the comparative study methodology is provided in Section 4.2.

3.3 ethnographically-informed Study

As discussed in Section 2.2 the presence of a musical community of practice, in which engagement with nonlinear dynamical processes appear to play a significant role, provides a useful resource for this research. While the lab-based studies described above present opportunities to test differences in engagement for very specific interface designs, an ethnographically-informed approach provides the opportunity to explore how musicians think about interaction and their relationships with their instruments in their regular musical practice. This approach is intended to complement the lab-based approach, allowing the issues raised through the lab-based study to be explored in these musical practices. This study therefore explores engagement with instruments and musical tools in these specific communities of experimental musicians who are often playing and exploring musical tools beyond their traditional uses. The focus is no longer specifically on digital interfaces, but engages with musicians using a very broad range of musical instruments.

Ethnographic work in combination with lab-based experimentation has often been put forward as a productive combination in HCI (Ball and Ormerod, 2000; Ormerod et al., 2004; Mackay and Fayard, 1997; Stowell et al., 2009). Many of the characteristic features of ethnography listed by Ball and Ormerod (2000) are relevant and desirable for this study and flesh out elements that are missing from the comparative studies, such as situatedness, richness, participant autonomy, and openness to unexpected issues. As Dourish notes, one of the most useful strategies in dealing with ethnography is to "read for theory" rather than for more specific empirical verification (Dourish, 2007). Although this study is intended to corroborate and expand ideas and questions emerging from the comparative studies, it does not contribute to any straightforward list of "implications for design" (as criticised by Dourish), but is particularly helpful in tracing broader theoretical implications, particularly in combination with the lab-based comparative studies.

Semi-structured interviews (described in more detail in Section 5.2.1) were coded and analysed following a general structure proposed by Braun and Clarke (2006) (the specific approach to thematic analysis is discussed in Section 5.2.2). Although the territory is open and no specific hypothesis is being tested, the approach taken to the analysis is strongly informed by the research questions, and the questions raised during the comparative evaluation studies described above (as shown in Figure 3.1). The analysis contributes to specific ideas around nonlinear dynamics as they manifest in experimental musical practices, and together with the lab-based comparative studies help to provide a more rigorous answer to the research questions. The ethnographically-informed study is presented in more detail in Chapter 5.

Chapter 4

Comparative Studies

This chapter presents a set of studies that examine the effects of introducing nonlinear dynamical processes into digital musical interfaces. Four different digital musical interfaces were created, two of which incorporated nonlinear dynamics, and two of which did not. A range of musicians were asked to engage with all four interfaces and their responses were recorded through input data logs, audio recordings, Likert scale questionnaires and semi-structured interviews.

Section 4.1 provides an outline of the entire set of studies, along with the particular research objectives. Section 4.2 details the specific methodology, drawing on two initial exploratory studies and the more general methodological issues laid out above in Chapter 3. Section 4.3 presents the results of a trial-run study conducted with four participants based in order to test this specific methodology. Section 4.4 then presents the major study that implements this methodology with 28 participants. The results of this study are presented in Section 4.4.2, and are then discussed in depth and related back to the study objectives and more general research questions in Section 4.5.

4.1 Overview, motivations and study-specific research questions

The primary focus of this study as follows:

> *How does the inclusion of nonlinear dynamical processes in digital musical interfaces influence the ways in which musicians interact with and think about these systems?*

This is a more specific formulation of the initial research question laid out in Section 1.2. Of particular interest are attitudes towards control. In engagements with nonlinear dynamical processes, simple, direct control may not be straightforward (see Section 2.1.2.3). In the context of musical instruments, this suggests that the presence of nonlinear dynamical processes can lead cause the instrument to respond to a musician's input in unpredictable ways. A related issue is whether nonlinear dynamical processes can help to create musical systems with depth, that reward continued exploration with the possibility of finding new states, sounds or behaviours.

This initial question can therefore be unpacked to the more specific set of questions listed below:

1. How does the inclusion of nonlinear dynamical processes in a digital musical interface affect the sense of control experienced by a musician using that interface?

2. How is this sense of control (or lack of control) experienced? In a positive or negative light, or are there more nuanced responses?

3. Do the nonlinear dynamical processes yield surprising results? Is this a problem?

4. How is this sense of surprise (or lack of surprise) experienced?

5. How does the inclusion of nonlinear dynamical processes affect the potential 'depth'[1] of

[1] see Section 2.3.3.4

a musical interface? Can they help to establish tools that have hidden depths that can be explored over longer time periods?

6. How do the participants view these questions of control, depth and exploration in their own practices?

7. How do musicians of differing backgrounds respond differently, and in particular, is there a distinction in how musicians from more experimental backgrounds as detailed in Section 2.2 engage with and think about interfaces with and without nonlinear dynamical elements?

4.2 Methodology

The general methodological approach taken in this research is discussed in the previous chapter (Chapter 3). This section lays out the more specific methodology employed in this first set of studies, as informed by the literature review and a set of initial exploratory studies. The studies take the form of comparative evaluations, asking participants to engage with a range of digital musical interfaces that differ slightly in their design.

The two initial exploratory studies are detailed below in Section 4.2.1. These studies were designed to test particular design ideas and data collection methods. Methodological reflections are gathered together in Section 4.2.3, including descriptions of the comparative interfaces, and the data collection methods. A revised methodology is established and tested with four participants via a third study prior to the main comparative evaluation study. The methodology for both studies is considered globally for both the test study and the main study, with specific information on participant recruitment and demographics given separately for each in Sections 4.3.1 and 4.4.1 respectively.

4.2.1 Exploratory studies

This section details two initial exploratory studies that were designed to explore methodological issues for running comparative evaluation studies. The focus of the discussions are therefore primarily oriented towards planning the subsequent larger-scale comparative evaluations, particularly in terms of musical interface design and data collection methods.

For each study, a set of simple mouse-controlled audio interfaces was created. The interfaces within each set are similar to the the others, but vary in terms of whether they incorporate nonlinear dynamical processes, and how they incorporate these processes. Six participants with varying musical backgrounds were asked to spend 5 minutes familiarising themselves with each interface in the set, to record a short 2-3 minute performance with each, and were then asked questions in a semi-structured interview. Most of the participants considered themselves to be musicians in some sense (with one exception), although their specific interests varied considerably (composition, improvisation, songwriting and classical instrumental performance). The format for the study is listed below for the case with n different interface variations:

1. A participant is presented with the first interface, but as little is said about it as possible prior to them investigating it themselves.
2. The participant spends 5 mins getting acquainted with the first interface
3. The participant presses the record button to record a short performance with the first interface
4. The participant spends 5 mins getting acquainted with the second interface
5. The participant presses the record button to record a short performance with the second interface
6. ...

7. The participant spends 5 mins getting acquainted with interface n

8. The participant presses the record button to record a short performance with interface n

9. The participant discusses their experiences of the n interfaces in a semi-structured interview.

The controller for the various instruments was limited to a simple XY mouse interface displayed on the screen (see Figure 4.1). This approach was taken as no external devices were then needed (other than a mouse/trackpad), and it was assumed to be an interaction method familiar to most users and therefore relatively un-intimidating.

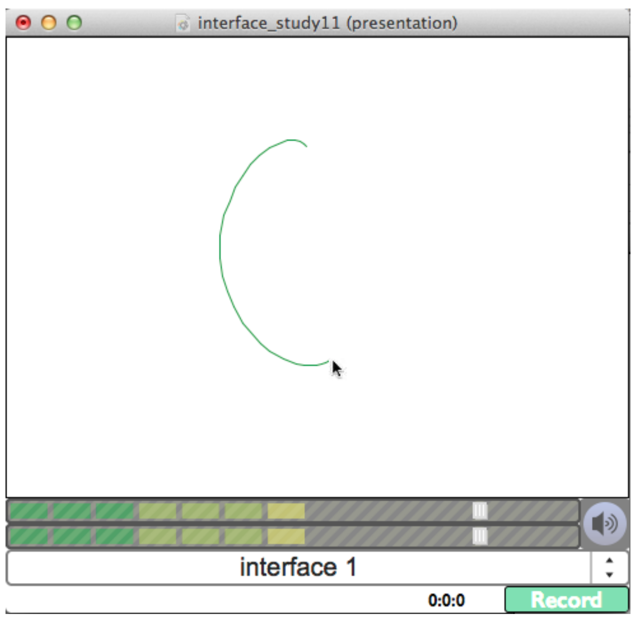

Figure 4.1: A simple XY mouse interface for exploratory studies 1 and 2

The specific interfaces, the particular mapping elements, and the interview and data gathering methods are detailed below. The various interfaces in a given study are distinguished by letter. Interface 2a is therefore the first interface in the second exploratory study, whilst 2b, 2c and 2d are modifications of this interface designed to test different implementations of the nonlinear dynamical element. Preliminary findings and methodological refinements are discussed after both studies have been presented.

4.2.1.1 Exploratory Study No. 1

The first exploratory study was based on a system devised by the author that combines a nonlinear dynamical system (the Duffing Oscillator as a discrete map, see Section 2.1.2.3) with a group of linear resonators in a manner somewhat reminiscent of physical models (Cook, 2002). This study contained only two interfaces in the set: one with the nonlinear dynamical element included (1a) and one without (1b). The XY mouse interface is mapped to the three coefficients in the Duffing system (γ, δ, and ω) and two parameters in the filter bank (resonance and gain). The gain is a function of the mouse position and the mouse button, with the gain quickly dropping when the mouse is released so that sounds are continuous only while the mouse button is held. Interface 1a — the interface containing the nonlinear dynamical element — is shown below in Figure 4.2. The system exhibits hysteresis, meaning that clicking in the same place twice will not necessarily have the same effect, but will depend upon the prior state of the system. This manifests itself noticeably in the behaviour of the harmonics, and has much in common with Larsen feedback: the system will stabilise around a particular harmonic, but if perturbed sufficiently it will move to a different harmonic (limited in this case to the particular frequencies of the resonators). The system is intended to be sufficiently chaotic to permit exploration of different behaviours through the simple XY grid.

Interface 1b was an attempt to create an interface that dealt with very similar sounds to interface 1a, but did not include a dynamical component. This was achieved with a very different system, as it would be very difficult to simply extract the dynamical element in exploratory study 1a without radically altering the nature of the sonic output (this issue is returned to in Section 4.2.3.1). Interface 1b achieves similar sonic results through using a recording of interface 1a as the source material for a simple granular sample player, as shown in Figure 4.3. This gives the participant the impression that they are using a very similar kind of system, as the sonic results are similar, but the actual control relationships are very different. Importantly for this study, the control is linear and non-dynamical.

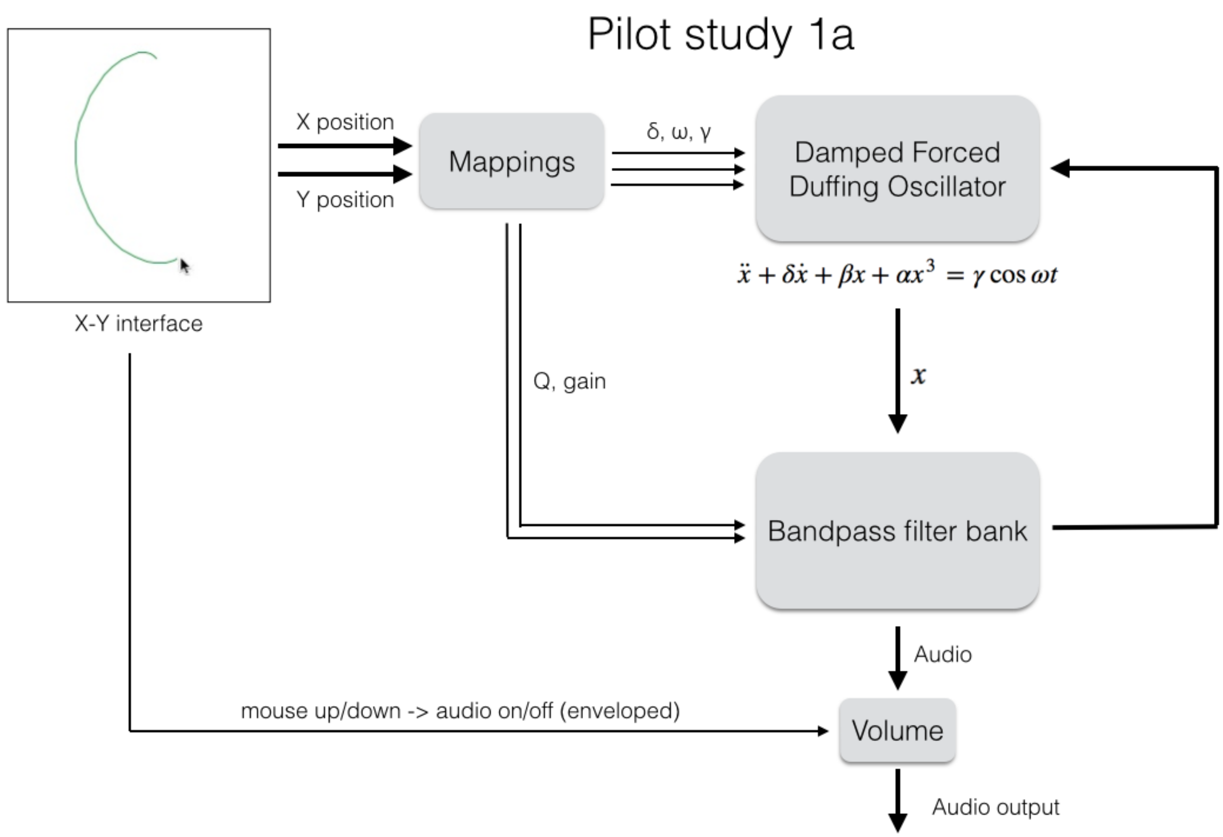

Figure 4.2: Interface 1a for exploratory study 1. A damped forced duffing oscillator (see Section 2.1.2.3) coupled with a bank of linear resonators. This presents a similar situation to that shown in Figure 2.5. The user interacts with the system via the XY mouse interface.

4.2.1.2 Exploratory Study No. 2

The second exploratory study dealt with a different sound engine and different approaches to embedding the nonlinear dynamical processes. Examining the similarities and differences between the first and second exploratory studies sheds some light on the extent to which the nature of the interface and the particular implementation of the nonlinear dynamical system affect the results, and the extent to which it may be possible to reach generalisable conclusions about the inclusion of such systems.

The four interfaces used in exploratory study 2 are comprised of four mappings to a relatively consistent sound engine. This study attempts to compare the use of nonlinear dynamical components in the *mapping* to the audio engine, with nonlinear dynamical elements

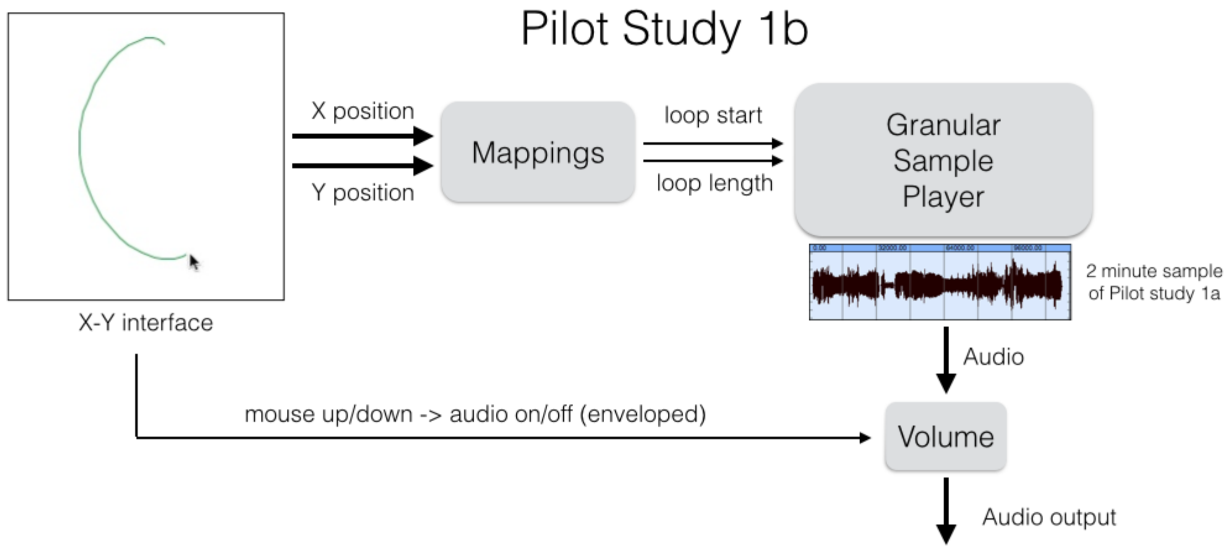

Figure 4.3: Interface 1b for exploratory study 1. A two minute recording of the interface from exploratory study 1a is used as the source material for a granulated sample player. The XY interface controls position and loop length in the sample.

embedded in the audio engine itself. White noise and a low frequency sawtooth wave are used to excite 8 banks of bell-like resonators as shown in Figure 4.4. The volume of the signal sent to each bank of resonators is determined by the users' interaction with an XY interface. Several elliptical regions exist in the XY plane (shown in Figure 4.4), although these are invisible to the user. The proximity of the cursor to the centre of each invisible elliptical region corresponds to the volume of the signal sent to each bank of resonators, shifting both the perceived pitch of the sound, and the timbral properties. The signal is gated by the mouse button, so that upon releasing the mouse, the resonant sound quickly decays. The four mappings differ as follows:

(a) Interface 2a is as described above, and is therefore linear and non-dynamical,

(b) Interface 2b introduces feedback into the system so that the sound evolves over time as the cursor is held down. Particular frequencies may become more prominent depending on the relative balance of the different resonators,

(c) Interface 2c removes the feedback, but the regions are dynamic: they are attracted

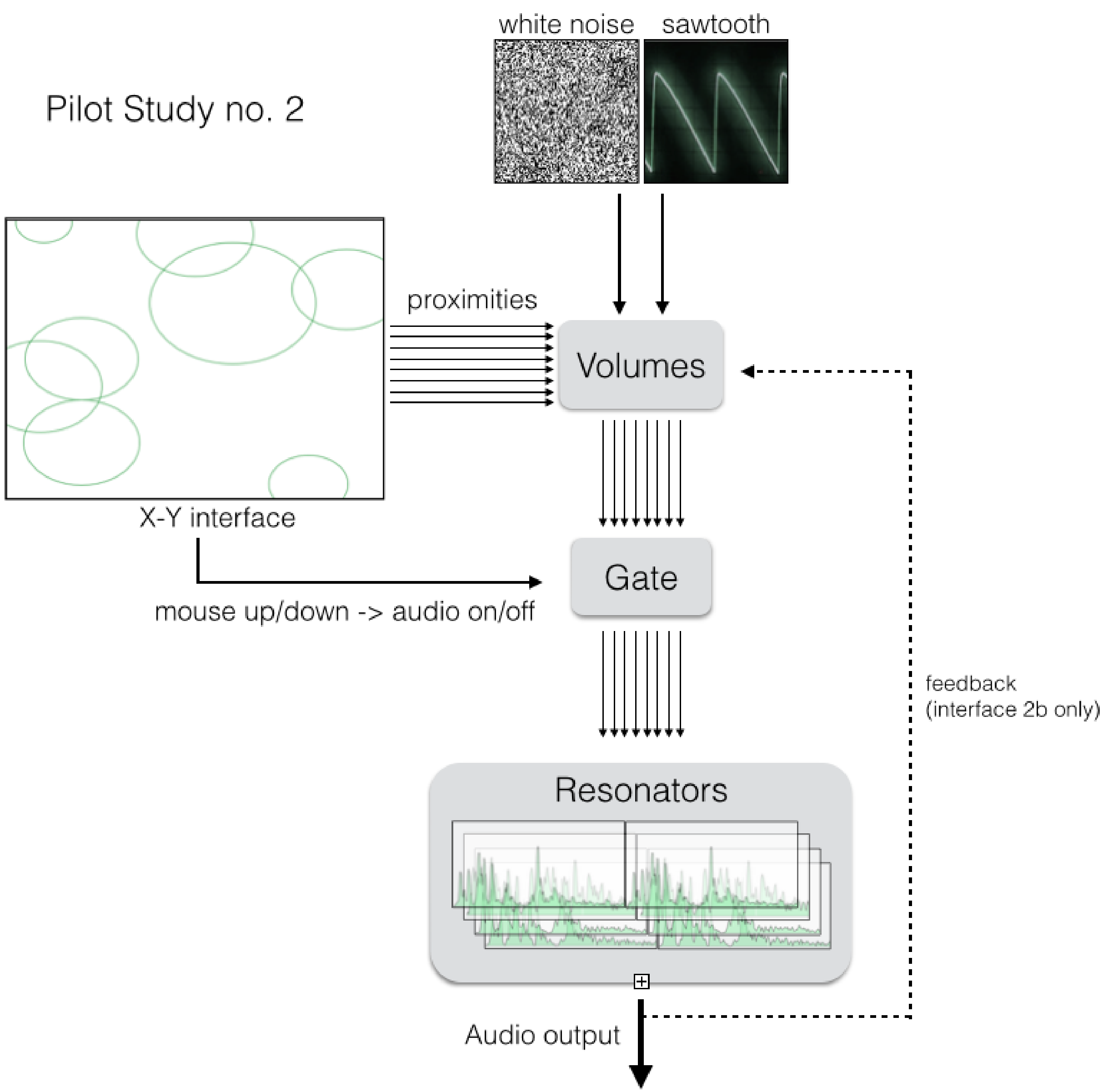

Figure 4.4: System used for the four interfaces in exploratory study 2. The proximity of the cursor to the centre of each elliptical region corresponds to the volume of the signal sent to each bank of resonators. The regions are not visible to the user however: the participants view is identical to that shown in 4.1.

towards the cursor (their acceleration is inversely proportional to the square of their distance from the cursor). When reaching the cursor, they are flung away again, so that the regions do not end up stuck at the cursor,

(d) Interface 2d is identical to 2c except that the regions all reset themselves to their original positions whenever the cursor is released.

Interfaces 2b, 2c and 2d implement the nonlinear dynamical system in different ways. The inclusion of audio feedback in 2b allows for elements of hysteresis and mode-locking where harmonics may become sufficiently prominent that they dominate even when the cursor is moved to a different region, sharing similarities with interface 1a. The nonlinear dynamical processes in interfaces 2c and 2d are embedded in the control-rate mapping layer rather than the sample-rate audio engine. The evolution of sound over time is more noticeably variable due to the shifting resonant regions. The resetting function in interface 2d was included to make it possible to repeat a given sonic event, something that is very difficult in 2c as the regions will be in different positions every time that the mouse is pressed[2].

4.2.1.3 Semi-structured Interviews in the exploratory studies

Semi-structured interviews were conducted immediately after the participants finished using all interfaces in a given study. The questions were a mix of quantitative questions, and more open questions. The quantitative questions asked for values on a scale of 1-10 for each category for the following aspects of their experience:

- their enjoyment of each interface,
- how frustrating they found each interface
- how boring they found each interface,

[2]Two participants did not release the mouse for the duration of their use of interface 4, meaning that it was essentially the same as interface 3. It is interesting to note that participants still felt as though there were differences, and attempted to describe them.

- how limiting they found each interface,
- the degree to which they felt that they understood the underlying mechanisms and logic of the interface,
- how unpredictable they found each interface,
- the extent to which they felt it was possible to repeat a particular sonic event/gesture.

In exploratory study 2, the numerical questions were replaced by rank ordering questions that asked participants to place the interfaces in order rather than assign each a specific value. The participants were also encouraged to elaborate on their response to each question, and to talk about how important each element was for them in their own practice. Questions were also asked about the participants' musical background (if any), whether they played an instrument, whether they saw themselves as a composer, and whether (and if so how) improvisation featured in their practice.

4.2.1.4 Audio and data recordings

The participants' final compositions with each interface were recorded as audio files. The control data from the mouse was also logged and saved both for the practise period, and for the recorded compositions (as separate files). These could then be called up and played back to review the participants' actions and view the mouse movements on screen along with the sound.

4.2.1.5 Findings, discussion points and proposed refinements

The key methodological findings and discussion points from both exploratory studies are laid out below.

4.2.1.5.1 XY mouse Input

Two points were highlighted with regard to the XY mouse-operated input method. The first was that the mouse (and particularly the trackpad) was seen as a slightly awkward input method, and participants complained that it was difficult to keep the button down for longer durations. The second and potentially more interesting point was that several participants were very focused on the visual nature of their interaction. One participant (with little musical background) carefully drew spiral shapes for their recordings, and when asked whether this related to a particular aspect of the sound or control they replied that they “always like to draw spirals”. The visual trails left by the mouse (shown in Figure 4.1) were removed to attempt to engage the users further in the sound, but this point together with the first point demonstrate the influence of the input method on the approach taken.

A less visually-oriented input device, such as a set of sliders may therefore also suggest a different kind of engagement. One participant said that they had felt compelled to continually move the mouse due to the nature of the interface, and had suggested that their engagement might be very different with a different kind of interface. Research into the role of input devices for musical control constitutes a large research area, which is — for the most part — beyond the scope of the present thesis. It is nevertheless important to keep the input device consistent across various studies so that the results may be compared.

4.2.1.5.2 Interview methods

The exploratory studies highlight the difficulty in obtaining concrete data from study participants. Questions such as: “rate your enjoyment of using each interface on a scale of 1 to 10” were met with bafflement from several participants as they felt as though ‘enjoyed’ was not an appropriate term. The rank ordering method tried as an alternative — asking participants to place the interfaces in order for each of the terms listed above, rather than to rate each individually — appeared to be a more appropriate approach, and enabled simple comparisons between the interfaces, despite losing any sense of the proportions of the differences between interfaces.

The questions relating to the relative importance of the various categories in the participants' own practices were often met with unsure and uneasy answers. When a participant was asked the question, ''how much does it matter to you in your practice whether you enjoy using a particular interface?'' the participant understandably replied ''I think I could answer in a thousand different ways.''

Attempting to obtain information about the participants' musical background also proved problematic, as it is difficult to formulate structured questions that are useful both in terms of allowing for comparisons between different participants, and that are open enough not to exclude important details. It would be useful for instance to obtain information about the participants experience with free improvisation, but this proves problematic in practice as each participant may understand the term differently.

Much clearer answers were given to questions about the specific nature of their approach to the interface however: e.g. did they approach the recording with a fixed plan, were they open to changing the plan depending on the results, did they see it as a composition, improvisation, a mixture, etc. Focusing on this kind of data may yield more useful results.

4.2.1.5.3 Transparency

Exploratory study 2 highlighted a question about how much to reveal to the participants about the underlying behaviour of the system. In informal (and undocumented) post-interview discussions that took place after the study session was complete, the participants were shown that there were elliptical regions representing the relative volumes of each individual set of resonators, and that they followed the mouse in interfaces 3 and 4. Three participants felt that they would have benefitted greatly from having these behaviours revealed on screen rather than hidden. This could have substantially altered their engagement with the sounds however, partly as they may become very visually focused as mentioned above, and partly as their mental model of the system may otherwise be very different.

4.2.1.5.4 Overly limited systems

Section 2.3.3.1 discussed how simple or how complicated musical interfaces should be that are to be used in laboratory experiments. This section concluded with the intention to find a balance. Some participants felt that the interfaces used in exploratory study 2 were overly limiting however. Whether it was limiting to the extent that it inhibited the study is not entirely clear, but similar comments were not observed in exploratory study 1. This could also point to the particular deployment of the nonlinear dynamical system not being sufficiently interesting, and not being as endlessly explorable as the kinds of instruments discussed in Chapter 2 and may suggest that the particular method of implementation is critical. This issue is explored further in the eventual study in Section 4.4.

4.2.1.5.5 Defining terms: what counts as 'nonlinear' and 'dynamical'?

The contrast between the two interfaces in exploratory study 1 raises questions about what constitutes a nonlinear dynamical mapping. Although the intention with interface 1b was to create a linear non-dynamical system, it could be seen as both nonlinear and dynamical. The sample position is controlled in a very linear way, but in terms of human input and sonic output, the relationship is highly nonlinear - a small change in a parameter can potentially lead to a large alteration in the resulting sound due to the nature of the audio material in the buffer. It will also change by itself over time (it plays the loop as the mouse is held), so it is technically dynamical. In the short studies, few participants seemed to realise that there was a fundamental difference in the nature of their interaction with the sounds. It seems possible that given much longer time periods, the participants would start to discover more about the underlying systems however, so future studies may benefit from either longer sessions, or multiple sessions. Exploratory interface 1b does lack many of the properties of interface 1a however. Although it can be considered to be both nonlinear and dynamical, it does not exhibit a mode-locking behaviour and only depends on the history of the input to the extent that as the mouse is held, the playhead moves through the sample. Clicking in the same area twice for the same duration will always produce the same result.

4.2.2 Lessons learned from exploratory studies

The discussion points raised in the exploratory studies suggest alterations to the study methodology. Significant revisions include:

- The implementations of nonlinear dynamical processes as parameter mappings to a separate audio system rather than as embedded in the logic of the audio system itself proved difficult (see 4.2.1.5.4 above), and the systems appeared to be too oversimplified to be useful. While a more considered approach to implementation may yield better results, this is a difficult design question, and creating musically interesting interfaces that operate along these lines is seen as a project beyond the scope of this thesis. The subsequent comparative evaluation studies presented in this chapter therefore focuses on nonlinear dynamical processes in the audio engine. However, this is identified as a fruitful area for further research (see Section 7.4).

- As discussed in Section 4.2.1.5.1, any given input device will influence the nature of the interaction. The overly visual nature of the XY input appeared to be a potential distraction, and so is rejected in favour of a simple MIDI controller input for the subsequent studies.

- As participants appeared to be more comfortable answering rank ordering questions than numerical values on a scale of 1 to 10, the subsequent studies uses an ordinal rather than a cardinal approach.

- Interview questions that asked for quantitative information are replaced with questionnaires to ensure consistency.

- The perhaps overly-specific term ‘enjoyment’ is replaced with ‘satisfaction’ in subsequent studies based on feedback from the exploratory study participants.

Some successful aspects of the exploratory studies were retained, such as the use of sampled audio to be able to create interfaces that are sonically very similar to each other, but very different in terms of how they respond to user input. The fact that participants often did not realise just how distinct the systems that they were engaging with were, suggests that this is a useful method for focusing in on the change in interaction rather than broader sonic concerns. Asking the participants to create short recordings also seemed to be a successful approach, providing an incentive to explore the systems, and as a method of bridging the divide between a lab-based study and the participants' own practices.

The revised study methodology is presented in the next section. A final preparatory study was conducted as a trial run for this revised methodology, detailed in Section 4.3. As the methodology for this preparatory study is almost completely consistent with the main study, the methodology for both is laid out first, followed by the results of the trial run, a brief note on minor methodological modifications (Section 4.3.3), and finally, the main study is presented in Section 4.4.

4.2.3 Revised methodology

The main study retains the central approach described above: presenting participants with different digital musical interfaces that employ different kinds of processes, in order to gain an understanding of how participants experience the differences. The main study, along with a further trial run study, both present the study participants with four digital musical interfaces (described below), two of which incorporate nonlinear dynamical aspects into their audio engine, two of which do not. As with the initial exploratory studies, each participant was required to spend a period of 4-8 minutes practising with a given interface before making a short recording of 1-4 minutes, which they were asked to think of as a performance: an attempt to create music that they would stand behind aesthetically. Participants could determine their own duration, but the software restricted the ability to progress before the minimum times had elapsed. Data from the controller input was logged from both practise and recording sessions. Participants then answered a range of Likert scale questions providing feedback on their experience of using the interface, before repeating the process with the

Figure 4.5: A participant interacting with one of the interfaces via the MIDI controller

remaining interfaces (counterbalanced by randomising the order). After completing this process with all four interfaces, they provided information on their musical background, and conducted a short, semi-structured interview, allowing them to expand on and contextualise their questionnaire responses, to comment more fully on their experience with each interface, and to relate these experiences to their own musical practices.

The rationale behind the design of the four digital interfaces is detailed below alongside an overview of each individually (Section 4.2.3.1). This is followed by information about the data collection methods in Section 4.2.3.2, while discussion of the study participants and recruitment process is reserved for Section 4.4.1.

4.2.3.1 Comparative Interfaces

The input method is identical for each interface: a set of three MIDI controls — two dials and a slider — as shown in Figures 4.5 and 4.6. The audio engine, and the mapping to the audio engine from the controls varies across the four interfaces. There are two key variables: whether or not the interface incorporates a **nonlinear dynamical process** as a core aspect,

Figure 4.6: Participants were given the same three inputs to all four interfaces used in the study: two dials and a slider

Interface	nonlin. dynamics	mapping	audio engine
1	Yes	Continuous	Resonated Duffing Osc
2	Yes	Discontinuous	Resonated Duffing Osc
3	No	Discontinuous	Resonated Osc
4	No	Continuous	Audio Sample-Based

Table 4.1: The four interfaces used in this study

and whether the mappings from the inputs to the parameters of the system were **continuous or discontinuous** (summarised in Table 4.1)

Whilst the former is the central concern in this study, the latter provides a useful point of comparison. Discontinuities in the mapping from the controller provide an alternate method of placing unpredictable transition points in the interaction, and allowing for the sonic result of an abrupt transition without utilising nonlinear dynamics (both discontinuities and nonlinear dynamics are suggested as methods for generating more interesting interaction spaces in musical interfaces. See Bowers and Hellström (2000) in Section 2.3.3.1.3). This comparison between the variables is intended to help clarify what is specific to nonlinear dynamical processes in musical interfaces.

As Table 4.1 shows, each of the four interfaces represents a different permutation of the two variables. To be able to focus on the effect of changing these two variables, the interfaces differ as little as possible in other respects. This is a difficult task with musical systems, as a musician's experience and engagement with a particular musical tool may be affected by a wide range of factors: the specific affordances of the tool, the range of sound worlds available (e.g. the possibility for tonal, timbral, and rhythmical control and differentiation), the nature of the input device, the musician's own background, cultural perceptions of the tool, and so on. The individual interface descriptions given below demonstrate some of the measures taken to mitigate the effects of these differences.

Interface 1: Nonlinear dynamical system with continuous mappings

Both interfaces 1 and 2 are based on a damped forced Duffing oscillator (see Guckenheimer and Holmes (1983) and Section 2.1.2.3), shown below in Equation 4.1 as a discrete map (see 2.1.1). This is a nonlinear dynamical system that models the forced oscillations of a beam that is fixed at one end.

$$\begin{aligned} x_{n+1} &= y_n \\ y_{n+1} &= -\delta y_n - \beta x_n - \alpha x_n^3 - \gamma sin(\omega t) \end{aligned} \tag{4.1}$$

This equation is implemented as a discrete map at audio sample rate (44.1 kHz) and coupled with a set of resonators such that the x_n term is passed through the filter bank, and the output of the filter bank is used in its place in the above equation. This combination of a nonlinear function coupled with a linear resonator bears a close resemblance to the structure of many acoustic instruments (McIntyre et al., 1983) and hence to many physical models (Smith, 2010). The specific structure of interface 1 is shown in Figure 4.7.

The mappings from the three inputs are all continuous functions, controlling γ, α, the time step dt, and the filter gain and resonance.

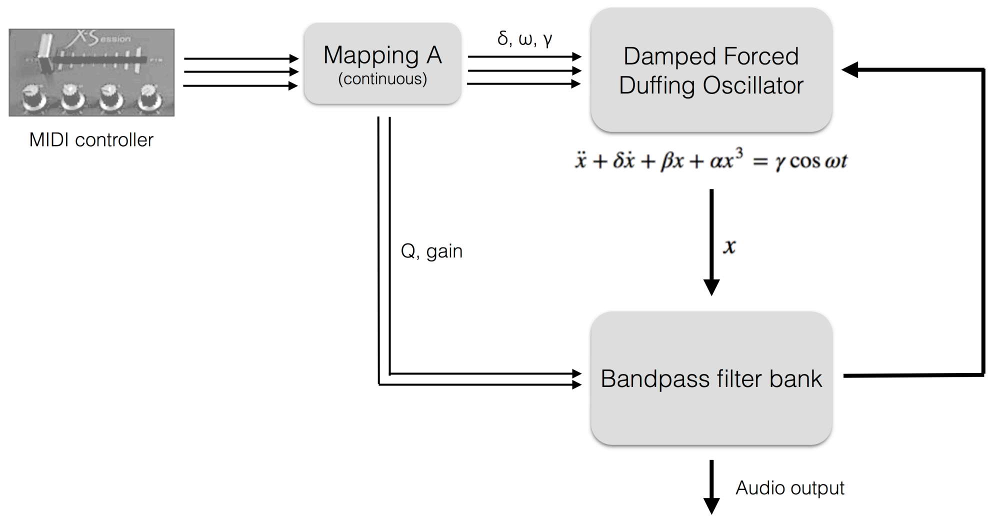

Figure 4.7: Interface 1. A damped forced Duffing oscillator coupled with a bank of linear resonators. The user interacts with the system via three MIDI controls.

Interface 2: Nonlinear dynamical system with discontinuous mappings

Interface 2 differs from interface 1 only in terms of the mapping from the MIDI controls to the system parameters: interface 1 uses continuous mappings, whilst interface 2 uses discontinuous mappings that cause jumps in the parameters at particular points. In other respects this interface is the same as interface 1.

The mappings from the three inputs use lookup tables to provide discontinuities at various points in the dials' ranges. The mapping is continuous in certain regions, but may abruptly jump from one continuous region to another at certain thresholds (see Figure 4.8 for an example). The mappings are many-to-many, in the sense used by Hunt and Kirk (2000), as multiple inputs may influence a single parameter, and multiple parameters may be influenced a single input.

Interface 3: Static system with discontinuous mappings

Interface 3 is very similar to interface 2, but with the Duffing system removed as shown in

Figure 4.8: Lookup table that relates input dial 1 to γ in interface 2.

Figure 4.9, rendering the audio engine non-dynamical in that its behaviour no longer depends on prior states, only the current input. The discontinuous mapping is retained however. Although the system is in some ways similar to interface 2 and to a lesser extent interface 1 in terms of the processes involved, the range of possible sounds is very different, and the system is effectively an oscillator passed through a resonant filter.

Interface 4: Static system with continuous mapping based on audio recording of interface 1

Interface 4 attempts to preserve the sound world of the Duffing systems and is therefore based around a two minute audio file recorded from interface 1. The system is therefore not a nonlinear dynamical system, but retains a very similar sound world to interfaces 1 and 2. The inputs are mapped continuously to positions in the sample, playback rate and overall volume. Granular processes are used to separate the control of playback rate from the control of the pitch of the sample.

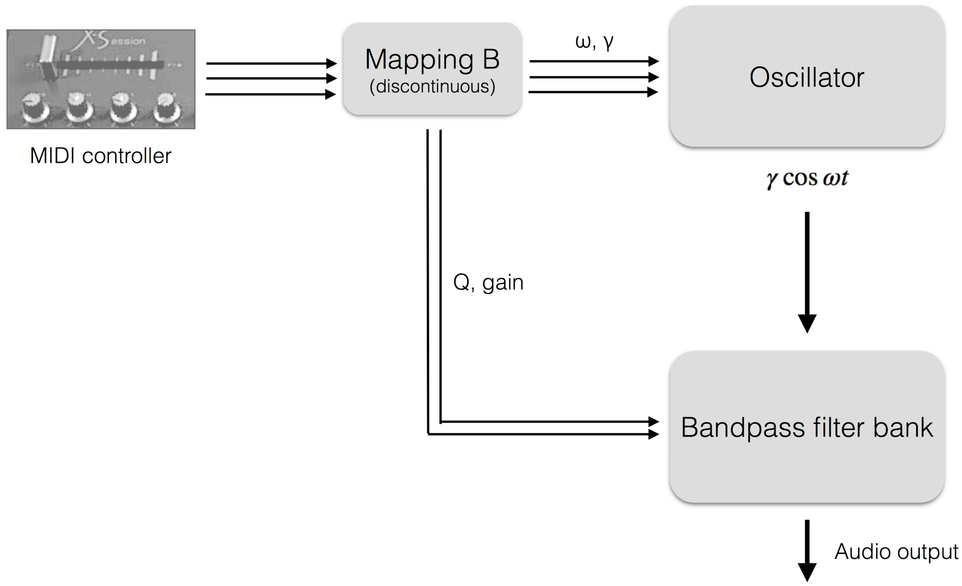

Figure 4.9: Interface 3. Duffing system and feedback are removed, leaving an oscillator and resonant filter bank. The discontinuous mapping is otherwise preserved from interface 2.

4.2.3.2 Data Collection Methods

As with the initial exploratory studies, four methods were used for data collection, mixing quantitative and qualitative information:

1. data logs from the controller inputs,
2. audio recordings of participant compositions,
3. Likert-scale questionnaires,
4. semi-structured interviews.

The mixture of collection methods attempts to provide some possibility for triangulation in the results. Ideas and narratives suggested by the quantitative data in the questionnaires can be compared with the study data logs, musical recordings and participant interviews. The latter in particular can provide useful context for the more quantitative aspects. Each collection method is explained in more detail below.

Input data logs

Input data recordings provide a method for analysing the specific behaviour of each participant in a quantitative manner. They provide insights into aspects such as: how much overall activity there was in each study, event frequency and duration, preferences for particular parameters, areas of interest for particular parameters, etc.

Audio recordings

Audio recordings can be useful in a number of ways. They could be immediately played back in the interviews that follow each study, allowing the user to talk about particular decisions at particular moments, and to refresh their memory of using each interface (rather than relying on 'think aloud' methods which can be problematic in musical activities (Kiefer et al., 2008)). The audio was also a useful motivation under certain circumstances, as the knowledge that the activity is being recorded helped to encourage participants to focus on creating something that they think is meaningful and that they would stand by creatively. Finally, they can help to support discussions that arise from the participant interviews.

Questionnaires

The questionnaire asked each participant to what extent they agreed or disagreed with the following six[3] questions for each interface (each on a five point Likert-scale):

1. "I felt in **control** of the sound"

2. "I found it straightforward to **recreate** particular sonic events"

3. "I was often **surprised** by the instrument's response"

4. "I feel that there are many areas that I could still **explore** and discover"

5. "I found a way of using the system that I felt fitted well with my own musical **practice**"

[3] The six questions presented here are as they were deployed in the main study. The questions used in the smaller trial run study discussed in the next section (Section 4.3) differ slightly and number only five. See Section 4.3.3 for specific details on the changes.

6. "I felt that my actions were **significant** in determining the final (recorded) result"

These questions will be referred to by the terms in bold text for the remainder of this chapter. Participants were also asked to rank the four interfaces in terms of which they found the most satisfying to use.

Finally, the questionnaire asked participants to list briefly their main musical tools and instruments, give a (brief) summary of their musical background, and to provide values between 0 and 10 in response to the following questions:

- How would you describe your overall level of musical experience? (0 = no experience, 10 = highly experienced)
- How significant is free improvisation to your musical practice? (0 = not engaged with free improvisation at all, 10 = it constitutes their entire practice)
- What level of experience do you have with electronic musical tools? (0 = no experience, 10 = highly experienced). This question was not included in the trial run study described in Section 4.3, but was added for the main study.

The responses to these demographic questions are detailed in Section 4.4.1 below.

Semi-structured interviews

As mentioned above, the interviews conducted at the end of the participant sessions help to provide context for the quantitative aspects. In particular, they explore the more nuanced aspects of the study-specific research questions posed in Section 4.1 regarding control, depth, surprise and exploration. The questions listed below were asked as a matter of course, but there was time in the interviews for follow up questions that varied based on the participants' responses. Some questions overlap with the questionnaire, but allow participants to provide richer answers and serve as starting points for wider discussions around the topic.

- If you found the systems unpredictable, was this a problem, a boon, or did it vary? How did this vary across the four interfaces?

- Do you enjoy unpredictable interactions in your own practice?
- Did you find that you could repeat sonic events on particular interfaces? Some kinds of events but not others?
- Was this a problem/boon/did it vary depending on the interface? (in the context of making something you were happy with)
- Could you explain the processes behind any of the interfaces? Does this affect your use of them? Is it important for you to understand a system to be able to use it in your practice?
- Were there elements in the interfaces that you felt would be interesting to explore over longer periods? Which specific elements of which interfaces? Does this matter to you with the tools you use in your practice?
- Did you feel that you picked up any specific techniques with each interface?

The questions also serve to establish links between the specifics of the study and the participants' own practices, relating questions of unpredictability, control, exploration, and long term use to the participants' interactions with their own musical tools.

4.3 Trial run study

This section presents the specifics of the trial run study conducted with four participants in order to test the methodology described in the preceding section. Participant demographics are detailed first in Section 4.3.1, followed by a breakdown of the results provided by the questionnaires, interviews and data logs. While the goal of this study is primarily to test the methodology and the numerical results cannot provide any statistically meaningful data, the results are nevertheless detailed here briefly for reference. Despite the limitations of the quantitative aspects, the interview data is still helpful to see how the participants understand the issues under consideration, and how the questionnaire responses can be potentially contextualised in terms of the interview data.

4.3.1 Specific trial run methodology

Four participants (A, B, C, D) were recruited, all of which have a significant background in music, but vary considerably according to how significant they feel that free improvisation is in their own practice (respectively, 1, 5, 7 and 8 on a scale where 0 corresponded to no engagement with free improvisation and 10 implied that free improvisation constituted the participant's entire practice). The variation in experience was deliberate and the participants recruited were known to the author prior to the study. This specific selection of candidates made it simple to select participants with a variety of backgrounds to test whether the study methods and data collection questions would be coherent to musicians from different domains (see Table 4.2).

The questionnaire and interview questions used in this trial study differ slightly from those used in the main study, as they were subsequently refined (see Section 4.3.3 the nature of these refinements). The five statements for which participants were asked to provide Likert-scale respond were:

- "After a short time with the interface I could **predict** the result of a particular action"
- "I could **recreate** particular sonic events or phrases with relative ease"
- "I felt that I **understood** the underlying system relating my actions to sounds"
- "I feel that there are many areas that I could still **explore and discover**"
- "I found a way of using the system that I felt fitted well with **my own musical practice**"

Participant	improv	instrument(s)	background
A	1	piano and guitar	musical analyst
B	5	laptop, mixer, FX pedals, guitars, percussion	composer and digital artist
C	7	piano, prepared piano, guitar, voice	jazz performer and songwriter
D	8	Clarinets, vocal, objects, lo-fi electronics	free improviser

Table 4.2: Study participant demographics

4.3.2 Trial run study results

As this is a preliminary study the potential refinements to the methodology are the central concern. As the sample size is small, the numerical data is not strong enough to produce concrete evidence of any particular hypothesis, but helps to provide broader pictures of user engagement when combined with questionnaire and interview responses.

The questionnaire data shown in Figure 4.10 suggests a link between scope for exploration and discovery and the inclusion of nonlinear dynamics. A Wilcoxon signed-rank test shows a statistically significant link between the inclusion of nonlinear dynamical processes and the agreement with the statement "I feel that there are many areas that I could still explore and discover" ($W = 5$, $p < 0.05$). The answers to the other questions did not appear to relate significantly to the changes in either independent variable.

Table 4.3 shows participant satisfaction with each interface alongside improvisation scores. This shows interface 1 being the most satisfying for participants engaged to some extent with free improvisation, although the correlation is not significant with such a small sample size (Spearman rank correlation, $\rho = 0.775$, not significant).

As the trial run study sample size is too small to ascertain anything concrete via quantitative methods, the interviews are helpful in drawing out specific case studies, and helping to explain the quantitative data. For example, the interviews provide a range of justifications for the participants with stronger engagement with free improvisation ranking interface 1 as the most satisfying:

- "[interface 1] was really fun [...] much more enjoyable [compared to interface 2]" (participant C)

- “I felt I could explore, the unpredictability was nice” (participant D)
- “I felt like it changed more, it was more variable” (participant B)

Participant D linked interfaces 1 and 2 closely however and referred to both as being open to exploration. Participants B and C differed in how unpredictable they found interface 1, with some rating interface 4 and interface 2 as equally or more difficult to predict. Participants B and D both felt that interface 1 fitted in best with their existing practice compared with the other interfaces. By contrast, participant A, who did not identify as an improviser (1/10) ranked interface 1 as the least satisfying of the set. Interfaces 1 and 2 were grouped together as being more unpredictable than interfaces 3 and 4, and despite describing the unpredictable elements as fun, preferred interface 3:

> “[...] it was easier to [...] get somewhere I had in my mind. The other ones were more noisy [...] so I couldn’t control [them] that much.” (participant A).

As the quantitative data suggests, interfaces 1 and 2 were generally linked to the potential for exploratory and discovery approach, whether participants saw this as something that suited their own practice or not. Participant A and participant C both seemed less inclined to explore freely and both expressed some frustration with trying to achieve ideas that they had in their head through the interfaces that they perceived as more unpredictable. This is illustrated in the quote from participant A given above. Participant C sees the unpredictability as a problem under particular circumstances (notably in interface 2):

> “when something has happened that might have been a bit unpredictable [...] there’s a certain couple of things that you can do that will get you to where you want to go [...] an overall idea that you have in mind, but obviously if it’s too unpredictable then you can’t even do that.” (participant C)

Participant D felt that unpredictability was a problem in certain situations but not others: “In the ones that I felt that I could still explore, then the unpredictability was a good thing”.

Participant	Improvisation	Most satisfying	...	...	Least satisfying
A	1	interface 3	interface 2	interface 4	interface 1
B	5	interface 1	interface 4	interface 2	interface 3
C	7	interface 1	interface 3	interface 4	interface 2
D	8	interface 1	interface 2	interface 4	interface 3

Key	Nonlinear dynamical	Mapping
interface 1	Yes	continuous
interface 2	Yes	discontinuous
interface 3	No	discontinuous
interface 4	No	continuous

Table 4.3: "Which interface did you find the most satisfying to use?" Table showing interface satisfaction preferences for the four trial run study participants and how this varied for their self-reported level of experience of free improvisation. See Section 4.2.3.1 for full details of the four interfaces.

Interfaces 3 and 4 were seen as frustrating to engage with in an exploratory manner and instead, were considered as something that might be more appropriate to use in a song based context. Participant C also made a distinction in the kinds of interaction they felt would be relevant for different areas of their practice: aspects that were too unpredictable were not seen as appropriate for song-based contexts.

4.3.3 Methodological refinements from the trial run

The trial run study demonstrated that the mixture of approaches to data collection can be mutually supportive, with the interviews being particularly helpful in providing context for the questionnaire responses. The various interfaces were different enough to spark divergent reactions from the participants with a variety of musical backgrounds, and participants were able to articulate the variation in their experiences through the semi-structured interviews.

Small adjustments were made for the subsequent study however. Firstly, the questionnaire questions were tweaked to be more comprehensible and less ambiguous. The question on how well participants understood the interfaces was removed completely as there was considerable inconsistency between how participants self-scored, and the level of understanding demonstrated in the interviews, and this element is only of minor relevance for the research questions. The question on whether a user could predict a particular outcome was deemed to

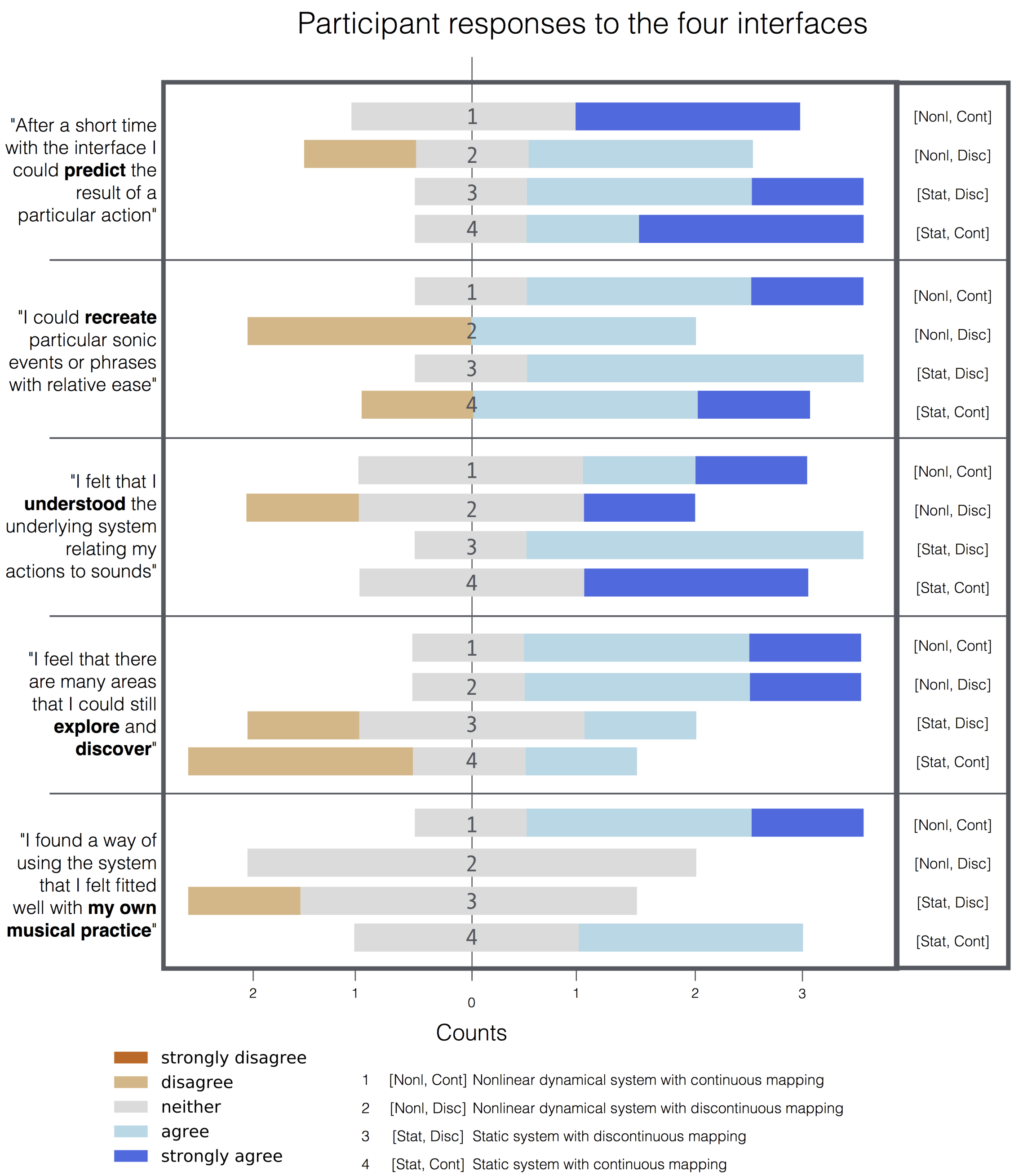

Figure 4.10: Trial run study results: four participants' agreement with five different statements as they apply to the four different musical interfaces.

be a little confusing, and was replaced with a simpler question that asked for agreement with the statement "I felt in control of the sound." The question of predictability was replaced with a question asking for the participant's level of agreement with the statement "I was often surprised by the instrument's response." The final question list for the main study was provided above in Section 4.2.3.2.

Secondly, the focus of the interview questions was changed slightly to include a range of questions pertaining to the participants' own practices. The questionnaire questions discussing unpredictability, control, surprise and exploration are followed up in the main study interviews with questions asking the participants whether it was a problem that they were or weren't surprised, or whether they did or did not feel in control, or whether this was a positive thing, or whether this depended upon the context. Similarly, on each topic, the participants were asked how they felt about the topic in relation to their own musical tools in their own musical practices.

4.4 Full Comparative Evaluation Study

This section details the main study as informed by the initial studies discussed earlier in Sections 4.2.1 and 4.3. The background to the study has been discussed in Section 4.1 and the specific methodology was laid out in Section 4.2.

The participant demographics are presented below, followed by the main results in Section 4.4.2 and discussion relating these results back to the research questions in Section 4.5.

4.4.1 Participants

28 participants were recruited for the main study, all of which had a musical background of some description. These participants were split into two groups of 14: those whose practice was predominantly experimental music or free improvisation as described in Section 2.2, and those with other musical practices such as pop, songwriting, jazz, classical performance, and other areas.

This division is intended to help explore differences in attitudes to the different interfaces for participants of different backgrounds as laid out in the initial research questions (Section 1.2). The categorisation was informed by a combination of the responses to the musical background questions described above in Section 4.2.3.2, and from the participant interviews. For example, in certain cases where the participant claimed to have a significant background in free improvisation, it was clear from their other responses that they understood the term in a very different context from the specific context discussed in Section 2.2.3. In other cases, the converse applied, although a participant may not have been actively involved in free improvisation, their engagement with experimental music (as defined in Section 2.2.2) was judged to be the significant aspect in terms of dividing the participants into groups due to the similar attitudes found in these domains.

Figure 4.11 presents the participant demographics in terms of this categorisation and their responses to the other questions relating to their musical background. The response

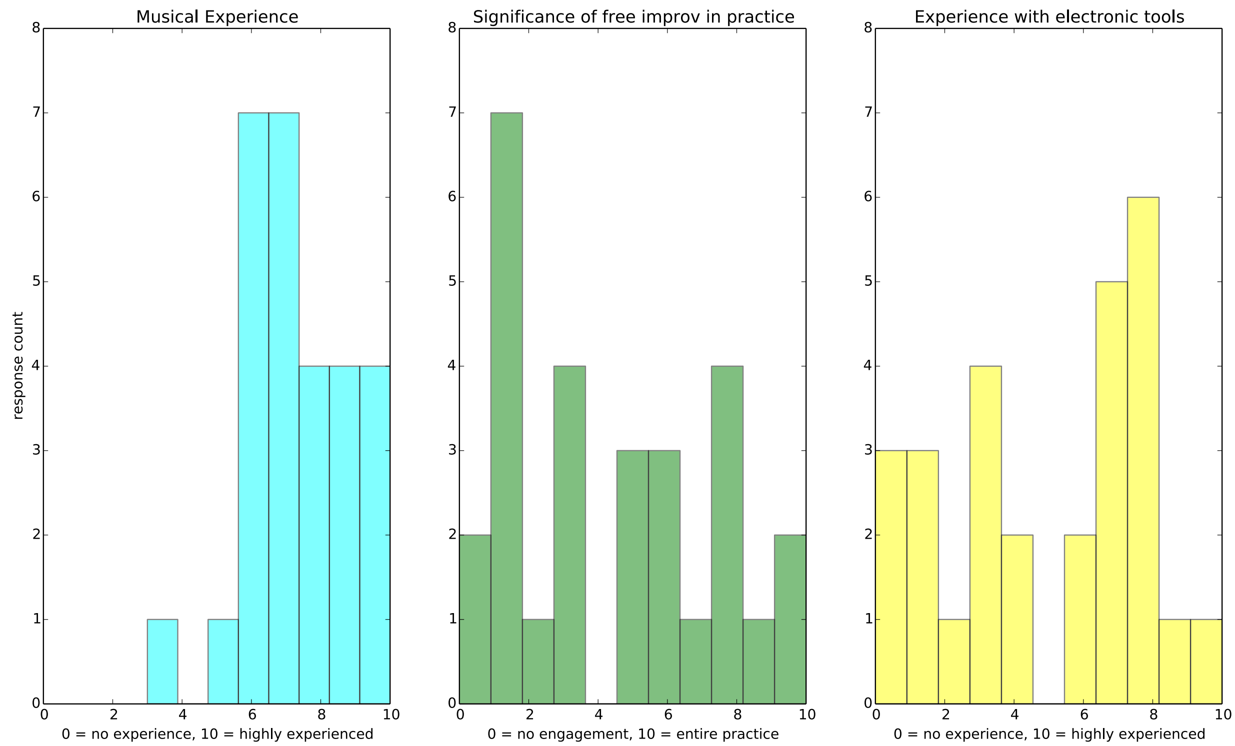

Figure 4.11: Responses from the 28 participants in relation to the demographic questions outlined in Section 4.2.3.2

counts for engagement with free improvisation and experience with electronic tools provide groups with more-or-less balanced numbers permitting comparisons between groups. There are 14 participants ranking free improvisation as having relatively little significance in their musical practice (scores ≤ 3), and 14 participants rating it as relatively significant (scores ≥ 5). Similarly, 13 participants claimed to be relatively inexperienced with electronic musical tools (scores ≤ 4) with 15 claiming to be more experienced (scores ≥ 6).

4.4.2 Results

This section presents the results from the main comparative evaluation study. Interpretations of the results are generally reserved for the following section (4.5), and relevant discussion subsections are signposted at relevant points as the results are presented. The wide range of data collection methods and the relatively open nature of the study research questions means that there are many ways of dissecting and presenting the results. This section begins with an examination of the quantitative data from participant responses to the Likert scale questionnaires, showing how these responses differ for the independent variables: the presence of nonlinear dynamical processes and the use of continuous or discontinuous mappings. Participant rankings for satisfaction with each interface are then presented and briefly discussed, and interrelations between the questionnaire responses are laid out. Section 4.4.2.3 highlights findings from the input data logs recorded from each participant's session. Finally, section 4.4.2.4 examines the data in terms of the experimental music and non-experimental music groupings discussed above in Section 4.4.1.

4.4.2.1 Questionnaire data

Figure 4.12 shows the participant responses to the six statements outlined in Section 4.2.3.2 for each of the four interfaces. Each interface is represented in the right column by the state of the two variables in that system, i.e. whether it uses nonlinear dynamical processes or not, and whether the mapping was continuous or discontinuous. Two significant results emerge when considering the questionnaire responses in terms of the independent variables:

- the inclusion of *nonlinear dynamics* in the interface was linked to feeling *surprised* and scope for *exploration and discovery* (agreement with questionnaire statements 3 and 4), as determined by Wilcoxon signed-ranks tests with $W = 77$, $p < 0.001$ and $W = 80$, $p < 0.001$ for surprise and explore/discover respectively,

- employing a *continuous* rather than a discontinuous mapping from the inputs to the sound engine was linked to feeling in *control* and being able to *recreate* particular sonic events (agreement with statements 1 and 2, $W = 104$, $p < 0.01$ and $W = 197$, $p < 0.01$ respectively).

Figure 4.14 highlights these results by grouping the responses around the independent variables rather than the results for individual interfaces: the inclusion or exclusion of nonlinear dynamics and the use of continuous or discontinuous mappings. This figure shows the above results slightly more clearly. Participant responses to questions relating to control and ability to recreate sounds differ significantly for the continuous/discontinuous distinction, whereas the differences for the presence or absence of nonlinear dynamical processes are slight. The converse is the case for questions relating to surprise and scope for exploration and discovery. The results therefore support the idea that the inclusion of nonlinear dynamics may support surprising, explorative interactions.

In certain respects this result might be expected: that the chaotic nature of nonlinear dynamics would be linked to surprise and discovery and that the abrupt changes in the discontinuous mappings would be deemed uncontrollable. The more interesting aspect is that the use of discontinuous mappings *doesn't* appear to influence the scope for surprise ($W = 149$, not significant) or exploration ($W = 227$, not significant), and — significantly for this research questions in this thesis — that the inclusion of nonlinear dynamical processes *doesn't* seem to affect perceptions of control ($W = 254$, not significant) or repeatability ($W = 365$, not significant).

This distinction seems to point towards the idea that the chaotic nature of the nonlinear dynamics can be helpful in supporting surprise and exploration without necessarily removing a sense of control and repeatability, and conversely that a discontinuous mapping can impair control and the ability to repeat events without significantly boosting the potential for surprise and exploration. This theme is explored further in the discussion section.

Further analysis of the participant responses shows strong correlations between the levels of agreement with the four statements relating to feeling in control, feeling able to recreate events, fit with personal musical practice, and significance of their actions in determining the resulting sound. Surprise was correlated with potential for exploration/discovery, and negatively correlated with control, ability to recreate, and significance of actions. These correlations are shown in Table 4.4 and discussed further in the next section 4.5.4.

	Control	Recreate	Surprise	Discover	Practice	Signif.
Control	---	0.56 ***	−0.30 **	0.09	0.51 ***	0.52 ***
Recreate	0.56 ***	---	−0.34 ***	−0.01	0.43 ***	0.42 ***
Surprise	−0.30 **	−0.34 ***	---	0.41 ***	−0.01	−0.23 *
Discover	0.09	−0.01	0.41 ***	---	0.24 *	0.21 *
Practice	0.51 ***	0.43 ***	−0.01	0.24 *	---	0.39 ***
Signif.	0.52 ***	0.42 ***	−0.23 *	0.21 *	0.39 ***	---

Table 4.4: Spearman rank correlation coefficients and significance values showing correlations between participant agreement with the six questionnaire statements. Control, recreate, practice and significance form a strongly linked group, whilst surprise and discover are quite separate and in some cases negatively correlated with statements from the control/recreate/practice/significance group. (*** for $p < 0.001$, ** for $p < 0.01$* for $p < 0.05$). Correlations of $p < 0.01$ are highlighted in blue (positive) and red (negative).

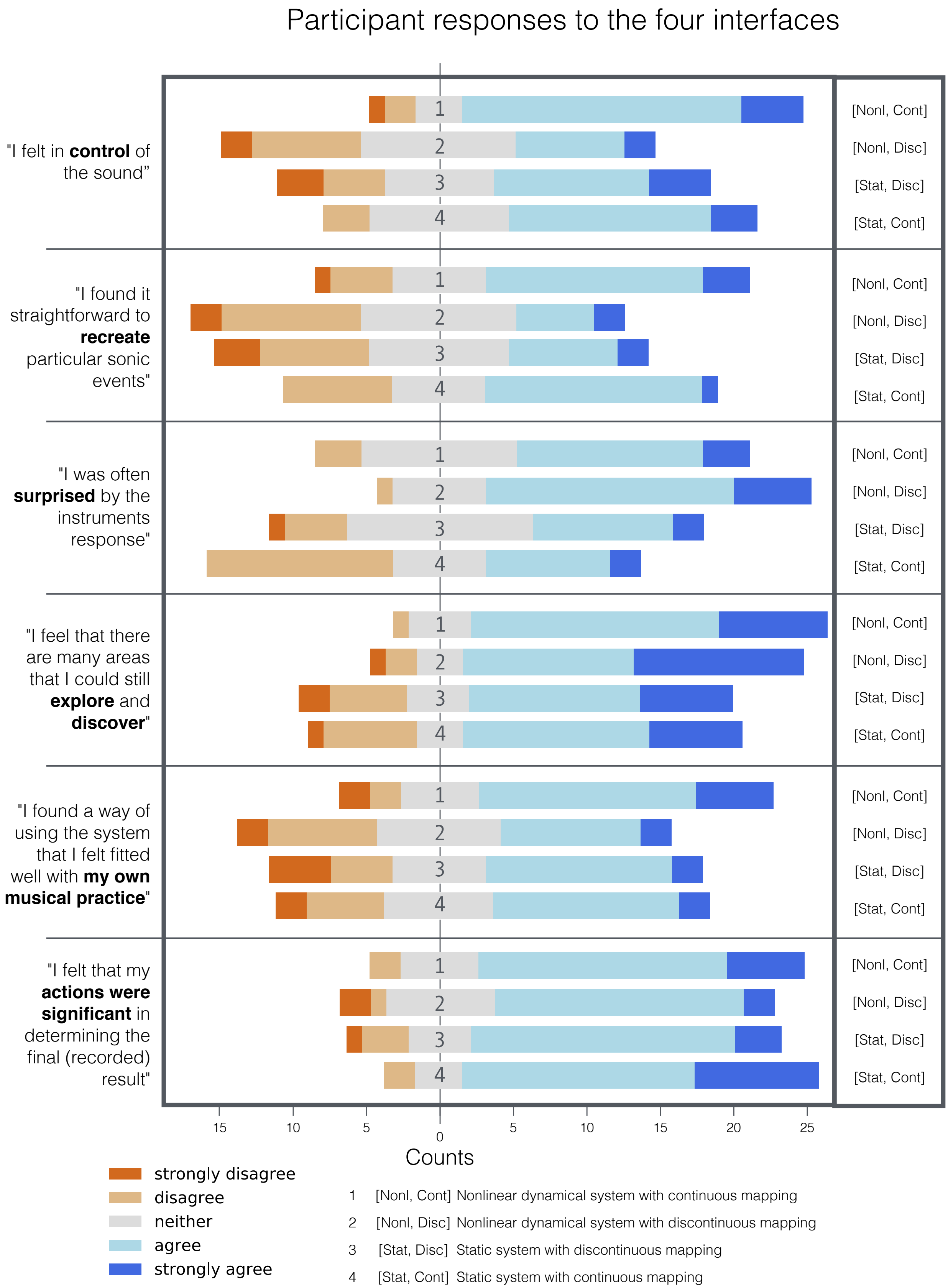

Figure 4.12: Participant agreement with six different statements as they apply to the four different musical interfaces.

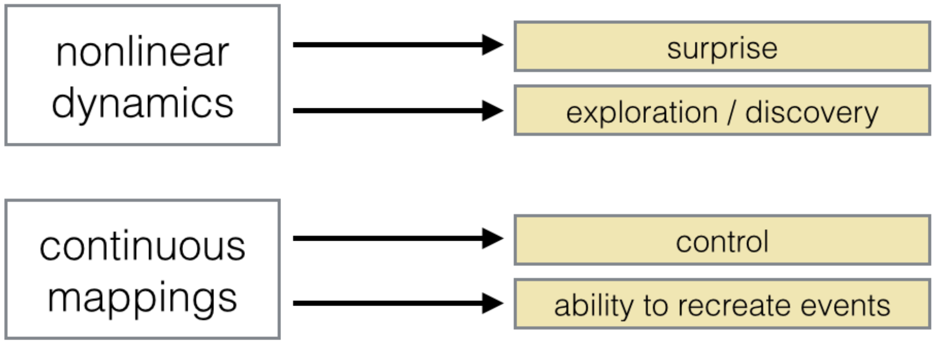

Figure 4.13: The key findings from the analyses of questionnaire data.

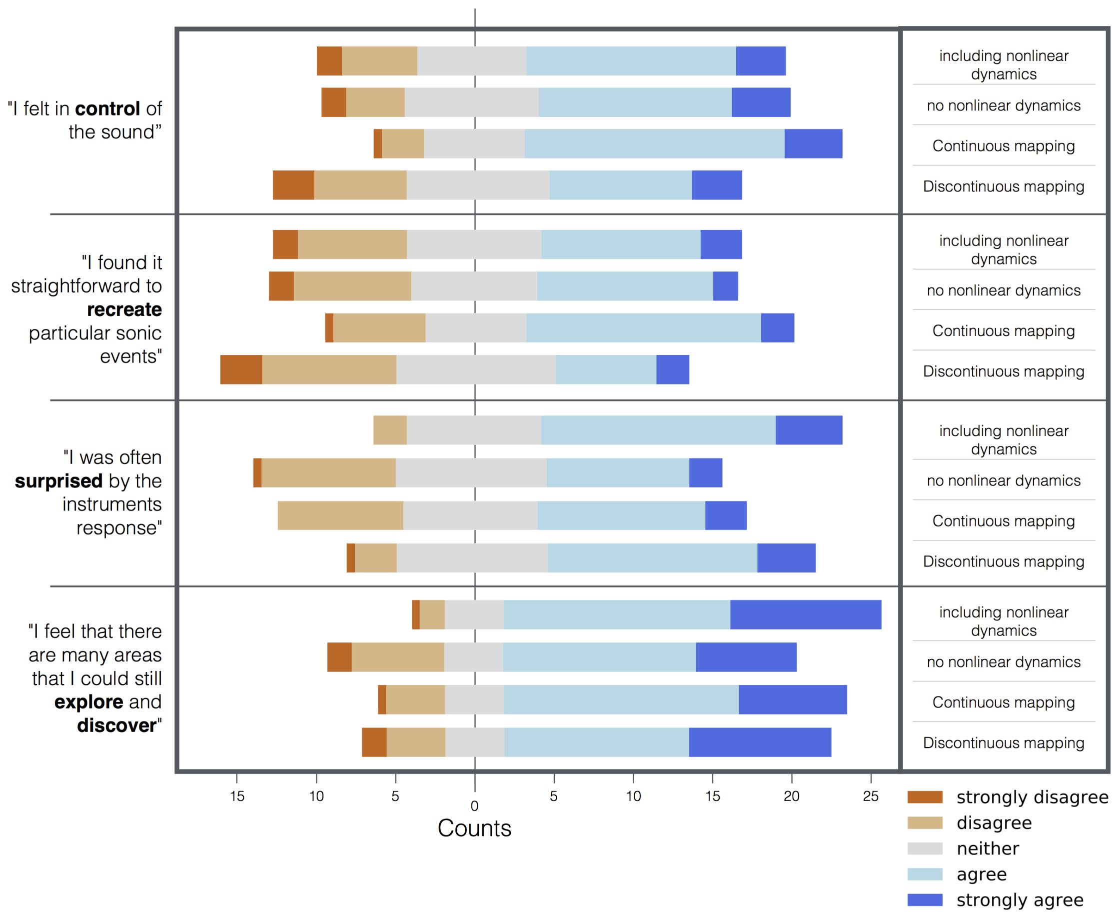

Figure 4.14: Participant agreement with four statements grouped according to whether they included nonlinear dynamics or not, and whether they used a continuous or discontinuous mapping. The key findings can be seen in the divergence between responses relating to *control* and *recreating* events for the alterations to the mapping, and the divergence between responses relating to *surprise* and *exploration* for the inclusion or removal of nonlinear dynamics.

4.4.2.2 Interface preferences

There were no significant links between the inclusion of nonlinear dynamics or the change in mapping on whether participants found a particular interface satisfying to use however, as Table 4.5 shows (in contrast to the initial findings of the trial run study presented in Section 4.3.2). This issue is discussed further in Section 4.5.6.

There was no correlation between the six questionnaire statements and preference for particular interfaces, with the exception of interface 1, where participants that ranked the interface highly in terms of satisfaction also claimed to feel in control, able to recreate particular sonic events and that their actions were significant in determining the sounding result (Spearman rank correlation coefficients of $r(26) = 0.383$, $p < 0.05$ for control, $r(26) = 0.378$, $p < 0.05$ for recreate and $r(26) = 0.479$, $p < 0.025$ for significance).

Interface	Rated Most Satisfying	Rated Least Satisfying	Overall score
1	10	7	2
2	5	7	-1
3	6	5	-1
4	7	9	0

Table 4.5: "Which interface did you find the most satisfying to use?" Columns 2 and 3 are counts. Overall score is calculated by awarding +2, +1, -1 and -2 for rankings of 1st, 2nd, 3rd and 4th respectively and summing

4.4.2.3 Data log results

Data logged from the MIDI controller input to the interfaces provides a quantitative method of examining engagement with the interfaces from the different participants, as discussed in Section 3. Some of the raw data is presented below in Sections 4.4.2.3.1, 4.4.2.3.2 and 4.4.2.3.3 to give specific portraits of certain participants. The data was analysed for the following:

- Session durations for both practice and recording sessions. Durations were left up to participants although advisory durations were given, and the lower limits were enforced by the software. The durations for both the practice sessions and recording sessions are shown in Figure 4.15.

- Overall level of **activity** for each participant on each interface. Given by the sum of the absolute distance covered on each input for a particular recording session divided by the length of time for that session. The overall activity levels are shown in Figure 4.16.

- Concentration of activity around discontinuous thresholds in the discontinuous interfaces — interfaces 2 and 3 — thereby creating percussive sounds. Given as a binary result, where participants either did or did not focus on these areas in their recording sessions. 19 (of the 28) participants focused on these areas with interface 2, and 24 participants with interface 3. The specific data logs demonstrate this activity shown below in Sections 4.4.2.3.1, 4.4.2.3.2 and 4.4.2.3.3.

Others metrics were considered but rejected as being overly simplistic, such as:

- Exploration metrics, such as a ratio representing the overall amount of the possible terrain that had been covered by a particular participant over a certain amount of time (attained by splitting each of the three dimensional space into 100 discrete zones, and counting the amount of zones that the participant had passed through in their engagement).

- A second exploration metric giving a ratio describing the proportion of time spent in the top 10 (of 100) zones, ‘‘top’’ meaning the ten zones most used by that participant on that interface. The higher the ratio, the more time the participant had spent in a relatively specific area. Lower ratios imply less focus in single areas and broader activity around the 3-dimensional space.

- Proportion of recording time spent in regions of the nonlinear dynamical interfaces that could be regarded as significantly less stable and more chaotic/unpredictable.

- Tendency to inactivity, given by the number of periods of time in recording session where the dials were left untouched for more than two seconds divided by the length of the session.

The raw data can give some useful examples of how different participants approached the study, and particular tendencies can be identified for certain interfaces. Logs for three participants are shown and briefly discussed below to provide short vignettes for each.

4.4.2.3.1 Participant vignette 1: participant 455667

The data logs for participant 455667’s recordings are notable as they contain the least overall activity for three of the four interfaces (0.01, 0.02, 0.11, 0.01 for interfaces 1-4 respectively, compared to respective medians of 0.23, 0.21, 0.32, 0.15). The inputs change very little over time (‘‘I don’t like to go crazy’’). Even with interface 3, where the discontinuous threshold is used to make percussive sounds, the movement is kept to the absolute minimum necessary to achieve these sounds (compare with the more pronounced movement across the threshold in the other two participant examples below). The participant described this as their approach to exploration:

> "Well, I think I just let my ear guide me and when I hear the sound I like, I try to explore with the dial and see where was the the best small parameter that I like and try to find it and try to see if I can replicate that by moving out and back in again"

4.4.2.3.2 Participant vignette 2: participant 381107

The data for participant 381107 contrasts sharply with the data for participant 455667 above. The heat-maps in particular show that the participant covered a much wider sonic terrain (although rarely used the volume/gain input). The contrast presents different possible interpretations of the term "exploration". Whilst participant 381107 seems to have explored many different areas of the interface, and found a range of different regions that are of some interest, participant 455667's approach presents a model of exploration that focuses on the minutiae of a very particular area, a deep exploration as opposed to a broad exploration. This discussion is taken up in Section 4.5.5.

Another notable aspect of the data logs for participant 381107 is the tendency to use the discontinuities of the mappings for interfaces 2 and 3 to produce percussive sounds, and to attempt to create rhythms out of these aspects. This tendency can be found in data logs from the recordings of 19 out of 28 participants for interface 2 (discontinuous, nonlinear dynamical) and in 24 out of 28 participants for interface 3 (discontinuous, not nonlinear dynamical). This can also be seen for participant 336074 in Figure 4.18 on both interfaces, and for participant 455667 in Figure 4.17 for interface 3. The repeated threshold crossings can be seen in the the data for inputs 1 and 2 where the path crosses backwards and forwards across particular points. Participant 381107 seems particularly interested in the regions around these thresholds:

> "I liked being able to come up with some kind of rhythm or kind of yeah, a kind of rhythm, or kind of triggering off a sound

4.4.2.3.3 Participant vignette 3: participant 336074

The data logs for Participant 336074 in Figure 4.18 show a very ordered approach that appears to impose a structure on the changes to the input dials: often sweeping rhythmically from one extreme to the other. The participant has a strong background in playing classical guitar, and little experience with either free improvisation (3/10) or electronic musical interfaces (2/10). The interfaces appeared to provide something relatively alien for the participant, meaning that there was really little to distinguish between them. The participant selected "neither agree nor disagree" for all interfaces in response to the statement on fit with their musical practice.

The participant reports using the rhythmic sweeping approach seen in the data as almost a last resort, perhaps due to feeling that the interfaces were very limited:

> "I was kind of reduced in a sense to thinking "well, right. I want some sort of pattern here, so I want something kind of rhythmic, some kind of motion kind of thing."

This can be contrasted with participant 455667 in Section 4.4.2.3.1 above who appeared to be much more comfortable with very small and occasional movements, suggesting they were potentially more comfortable with the actual sounds coming back from the interfaces.

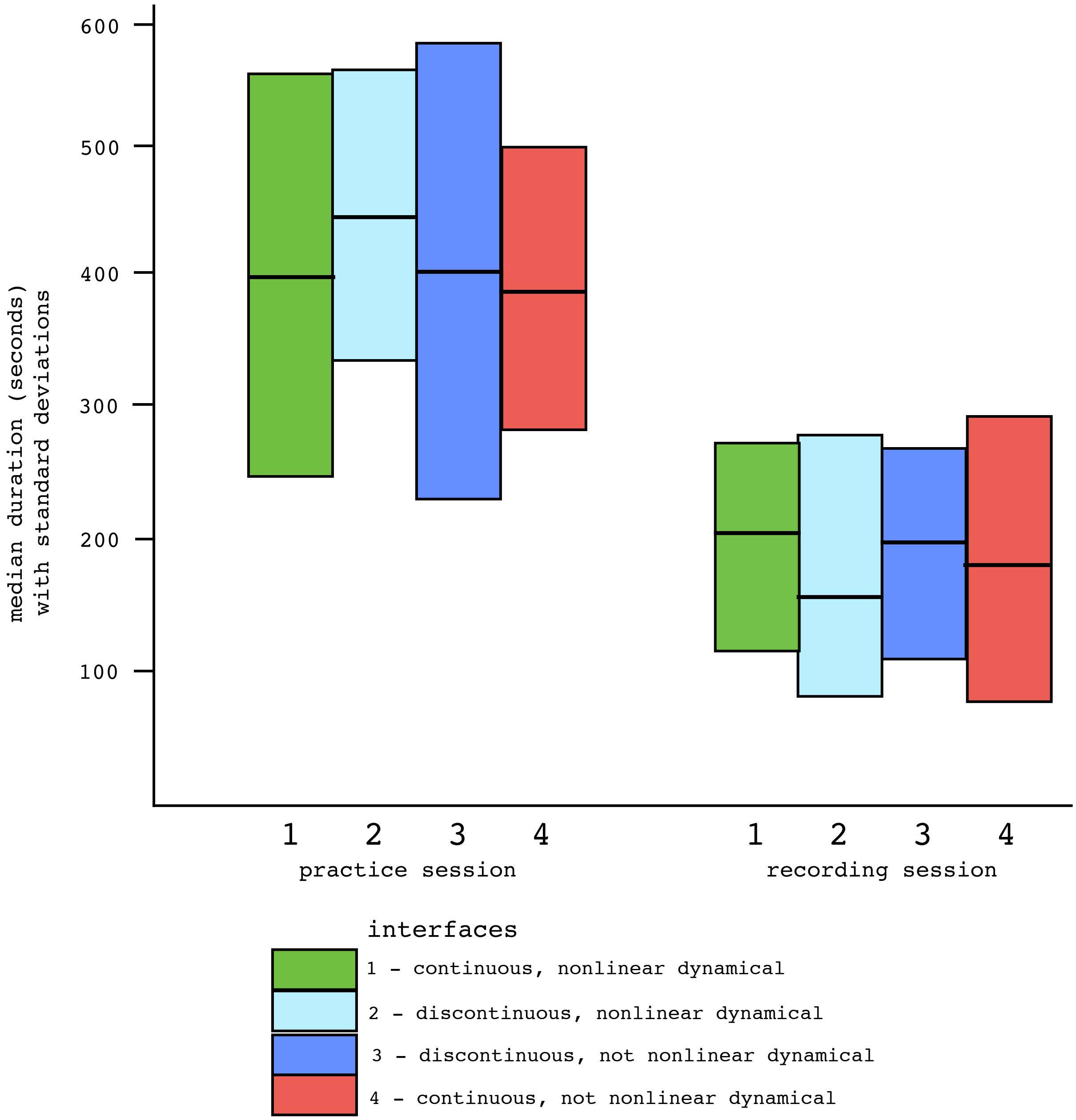

Figure 4.15: Median durations wth standard deviations for practise and recording sessions across the four interfaces.

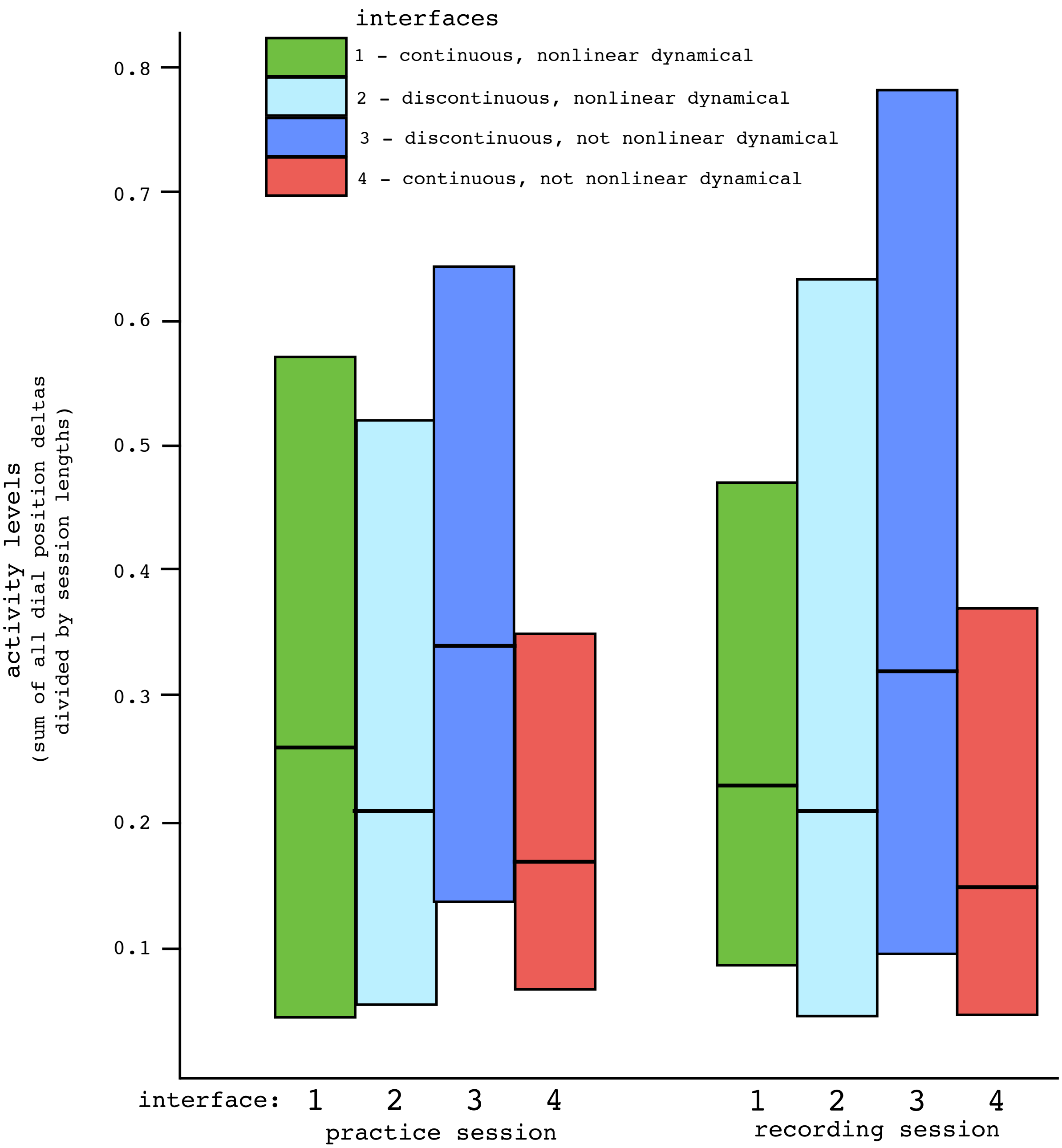

Figure 4.16: Median activity levels and standard deviations across the four interfaces. Activity level is determined by the sum of the distances covered on individual inputs divided by the duration of the session.

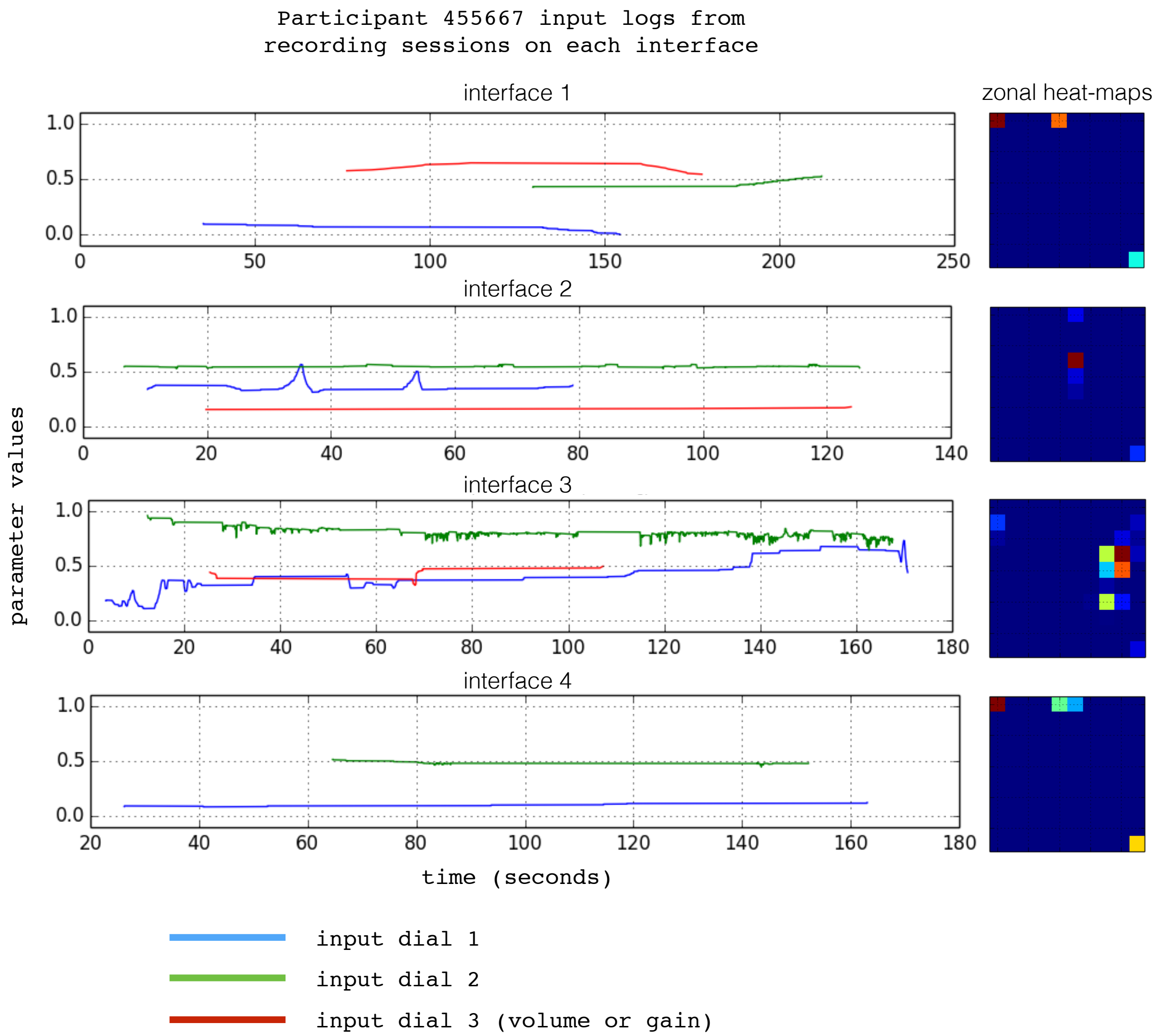

Figure 4.17: Visualisations of the data logs for participant 455667. Zonal heat-maps show the time spent in 100 discrete regions of the 2-dimensional space described by inputs 1 and 2. Inputs are normalised to the range 0-1.

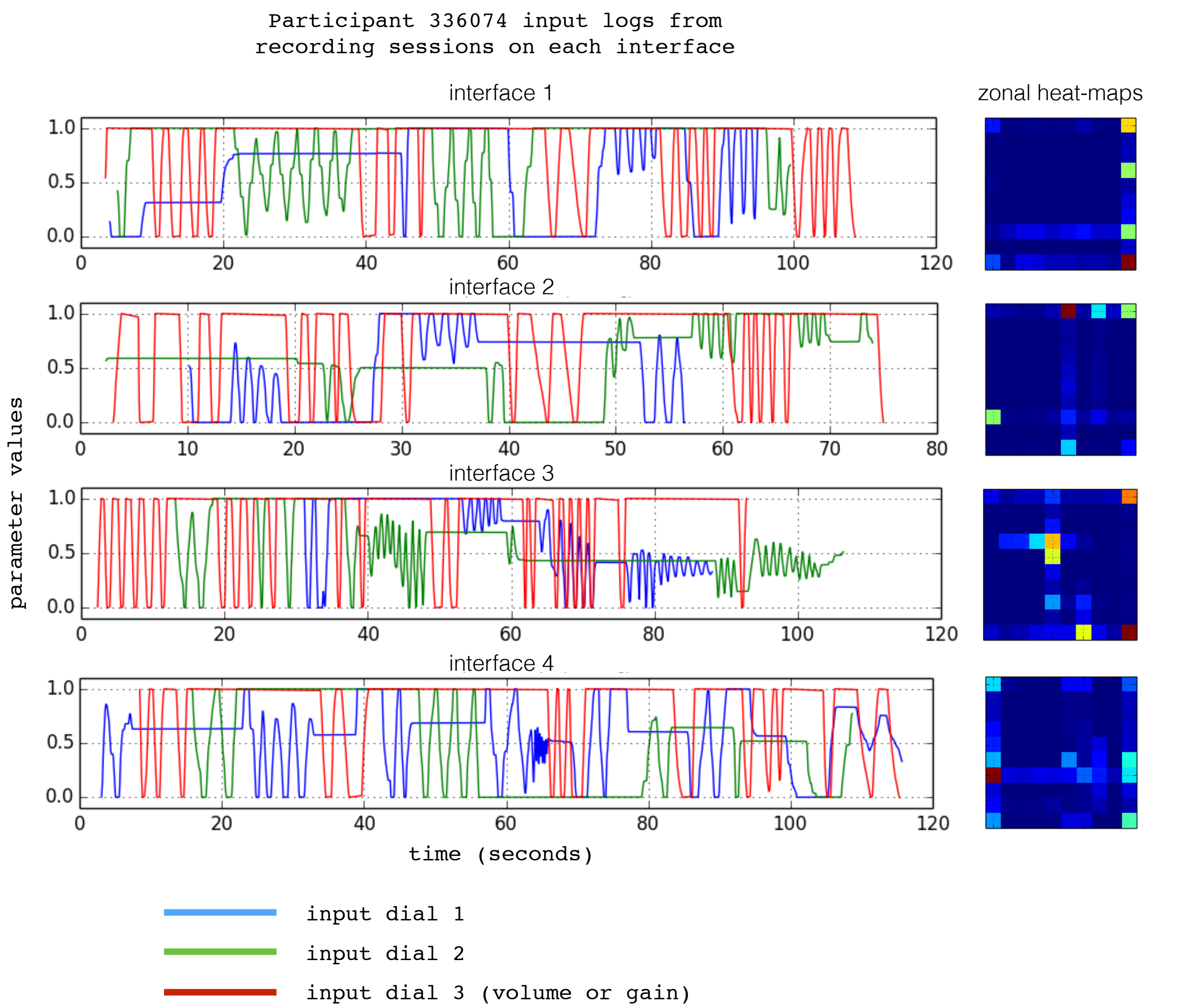

Figure 4.18: Two visualisations of the data logs for participant 381107. Zonal heat-maps show the time spent in 100 discrete regions of the 2-dimensional space described by inputs 1 and 2. Inputs are normalised to the range 0-1.

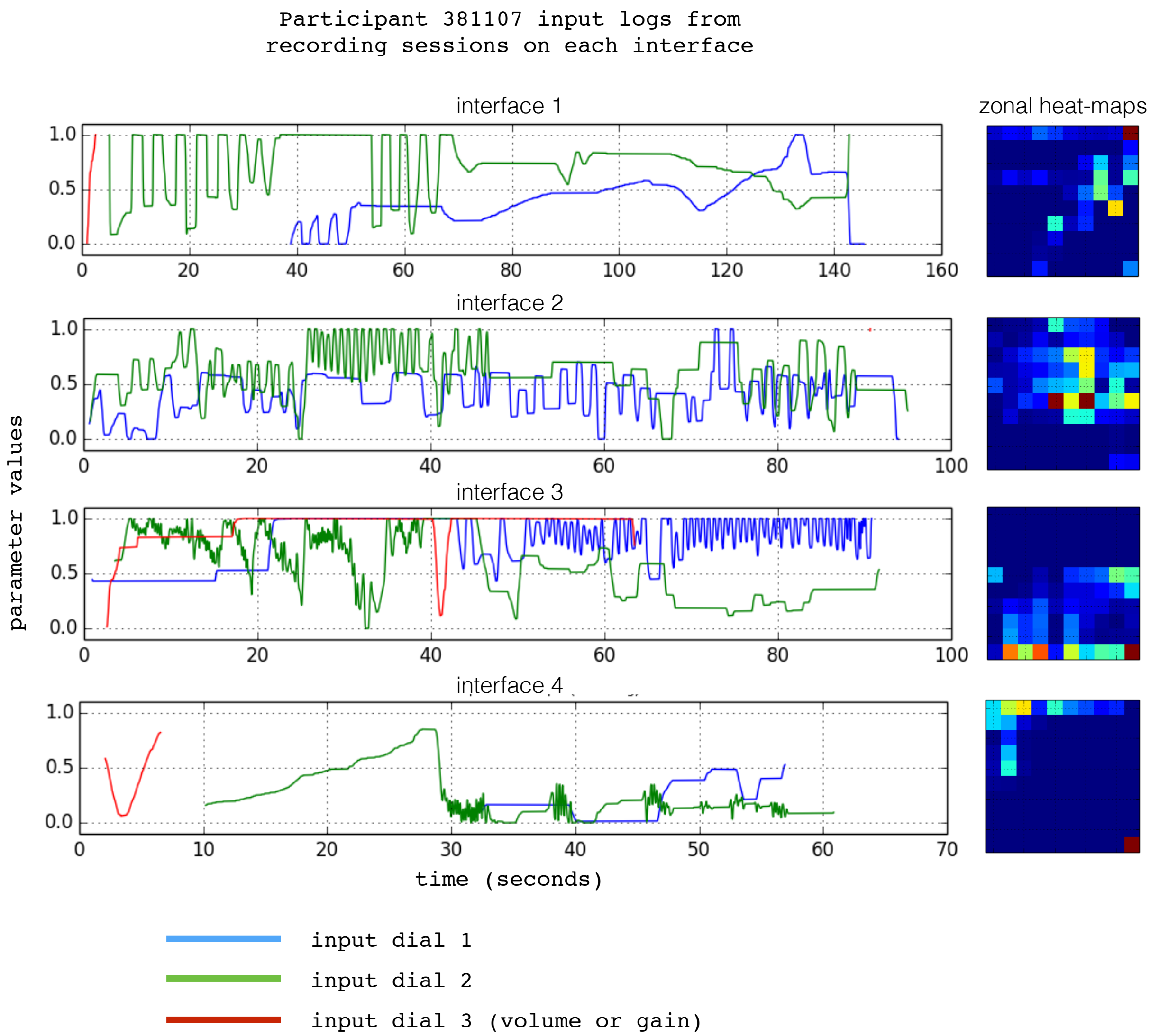

Figure 4.19: Two visualisations of the data logs for participant 336074. Zonal heat-maps show the time spent in 100 discrete regions of the 2-dimensional space described by inputs 1 and 2. Inputs are normalised to the range 0-1. The upper diagram shows very gradual subtle movements with long periods of little or no activity at all. The inputs are normalised to the range 0-1.

4.4.2.4 Differences between participant groups

The twenty eight participants can be grouped into many different categories based on the questionnaire and interview data (see Section 4.4.1), and can be compared across groupings where the groups are large enough to provide statistically meaningful data. A concern for this research is whether different groups experience the nonlinear dynamical components differently, and whether their approach or attitude varies according to the different kinds of interface. Grouping the participants by whether or not they have a background in experimental music — in the narrow sense defined in Section 2.2.2 — highlights a number of differences in participant engagement. Figures 4.20 and 4.21 show how the responses to different questions varied according to whether a participant was considered to be in this group or not, with the two groups being comprised of 14 participants each.

A notable result is that neither of the two points presented above in Section 4.4.2 are significant for the experimental music group alone, whilst they remain significant for the non-experimental group (see Table 4.7). This may relate to the fact that the experimental music group generally gave less varied responses for the four interfaces across all six Likert-scale questions. Figure 4.22 shows a comparison of response variation across the two groups, and Table 4.6 shows the significance of these distinctions. The degree of variation for a given participant is taken as the minimum score given for a particular likert-scale question (0 - 4) across all interfaces subtracted from the maximum score for that same question. For example, a variation of four would imply that the entire range of the likert-scale was used for a particular question, and that there was considerable variation in the participant's responses for different interfaces. A variation of zero would imply that the participant responded the same way for a given question across all four interfaces. The difference in variation between the two groups in relation to questions on feeling surprised and ability to recreate particular events was particularly pronounced, with mean respective variations of 1.93 and 2.07 for the non-experimental music group and only 1.07 and 1.36 for the experimental music group (Mann-Whitney U tests giving $U = 52$, $p < 0.025$ for the variation in control, and $U = 54$,

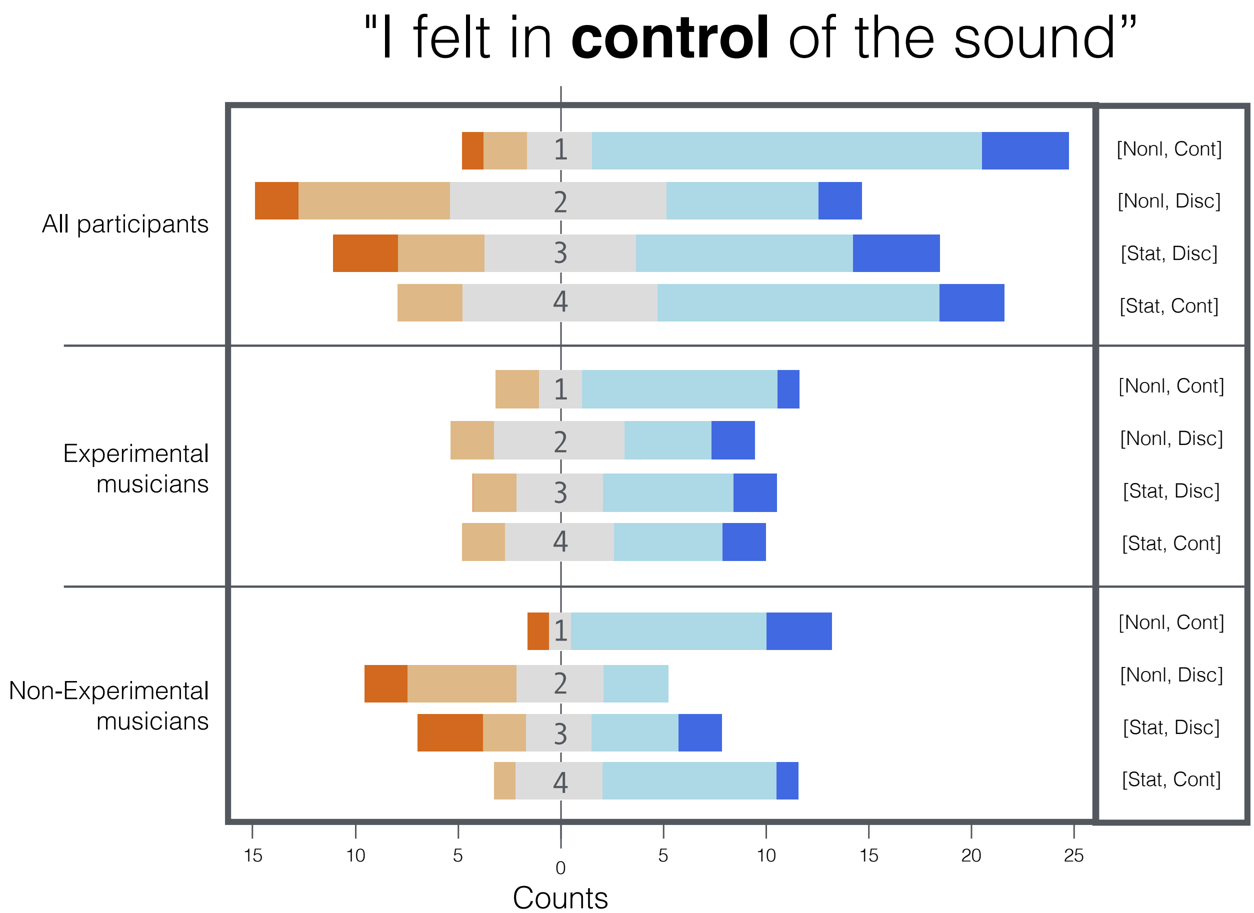

Figure 4.20: Comparison of response counts from musicians with and without experimental music backgrounds. The correlation between sense of control and the use of a continuous mapping (interfaces 1 and 4) is only significant for the non-experimental music group.

$p < 0.025$ for the variation in surprise).

Table 4.8 shows the preferences for each interface for the two groups. The interfaces are still difficult to distinguish on this basis however. Interface 1 appears to be more polarising for the experimental music group; despite six out of fourteen of the experimental music group finding interface 1 the most satisfying, four out of fourteen found it the least satisfying, and the overall score comes to only -1 indicating that overall there was no clear preference for the interface amongst this group.

The result observed in Section 4.4.2.2 — that satisfaction with interface 1 was correlated with whether participants found their actions to be repeatable, and that their actions were significant — also disappears for the experimental music group, but becomes more pronounced

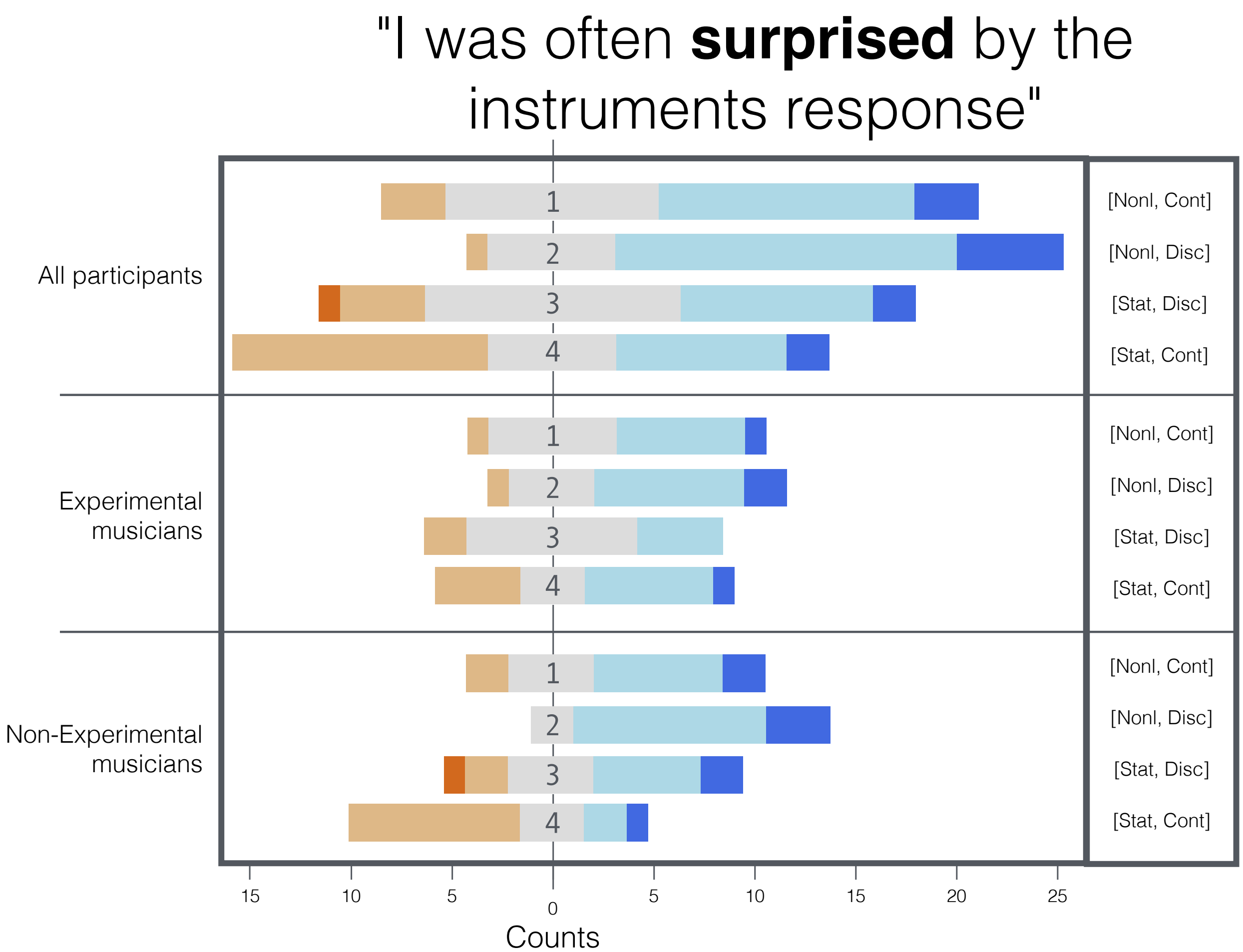

Figure 4.21: Comparison of response counts from musicians with and without experimental music backgrounds. The correlation between surprise and the inclusion of a nonlinear dynamics (interfaces 1 and 2) is only significant for the non-experimental group.

for the non-experimental music group as shown in Table 4.9. (Spearman rank correlation coefficients of $r(12) = 0.378$, $p < 0.05$ for recreate and $r(12) = 0.479$, $p < 0.025$ for significance). These results are discussed further in Section 4.5.6. A range of more minor results associated with the experimental music group are detailed below.

4.4.2.4.1 Comparison of activity levels

Activity levels were relatively consistent across the two groups in terms of how they approached their recorded pieces (median activity across all interfaces is 0.23 for both groups). The non-experimental music group were considerably more active in the practice sessions however (0.24 compared to 0.19 for the experimental group).

Question	U-val	p value	Mean variations experimental music	non-experimental music
Control	69	n.s.	1.36	1.86
Recreate	52	0.01	1.36	2.07
Surprise	53	0.02	1.07	1.93
Discover	69	n.s.	1.14	1.50
Practice	68	n.s.	1.29	1.79
Significance	77.5	n.s.	0.86	1.64

Table 4.6: Mann-Whitney U tests showing the significance of the differences in variation between experimental music and non-experimental music groups in their questionnaire responses (as shown in Figure 4.22). n.s. stands for 'not significant'. Response variation is defined as the minimum likert-score (0-4) for a given question across all interfaces subtracted from the maximum.

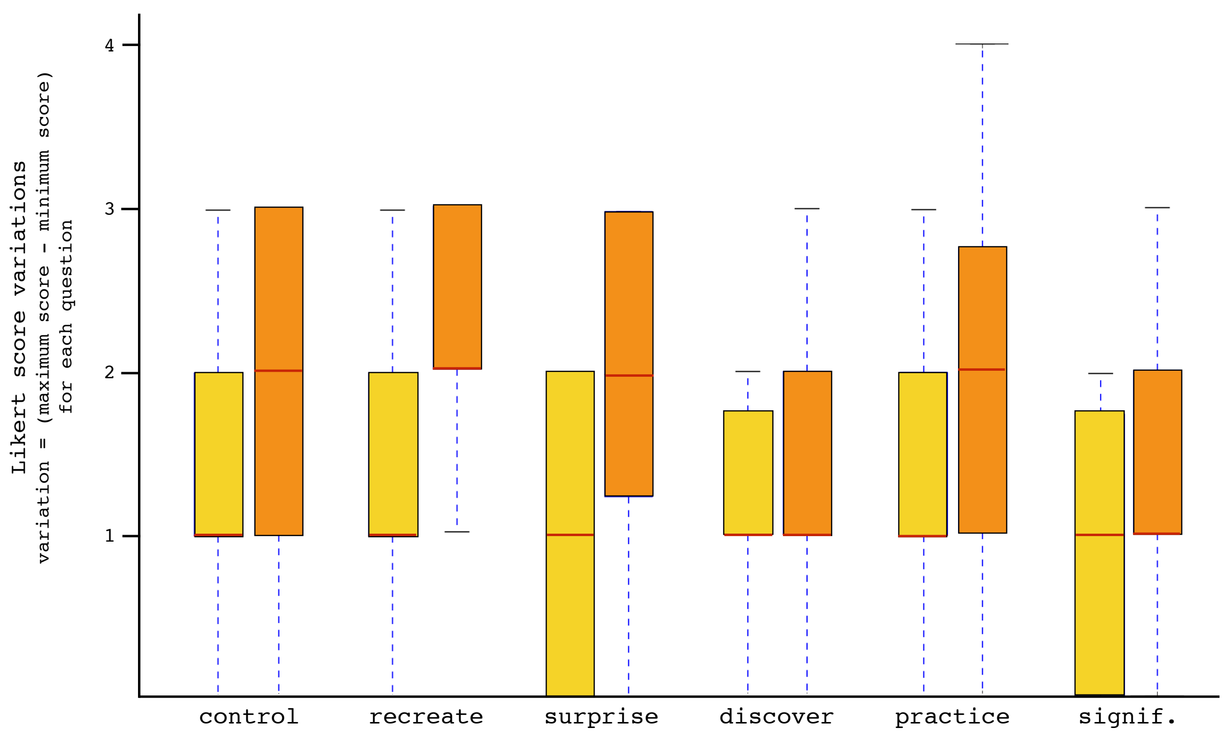

Figure 4.22: Variations in responses for the experimental music (yellow) and non-experimental music (orange) groups. Table 4.6 shows the significance of these results.

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Experimental music group			
Variable	Question	W	p value
mapping	control	49.5	*n.s.*
mapping	recreate	62.5	*n.s.*
NL dynamics	surprise	18.5	*n.s.*
NL dynamics	discover	32.5	*n.s.*
Non-experimental music group			
Variable	Question	W	p value
mapping	control	9	< 0.01
mapping	recreate	39	< 0.01
NL dynamics	surprise	22.5	< 0.01
NL dynamics	discover	12	< 0.01

Table 4.7: Wilcoxon signed-rank tests examining how the impact of the mapping decisions and the inclusion of nonlinear dynamical processes on responses to questions on *control*, *recreate*, *surprise*, and *exploration* differed when considering the experimental music group and the non-experimental group separately. n.s. stands for 'not significant'

4.4.2.4.2 Comparison of session durations

Across all four interfaces, the experimental musicians spent longer in the recording sessions, but spent considerably less time in the practice sessions (shown in Table 4.10). This is perhaps due to the fact that the sonic possibilities afforded by the four interfaces may be more familiar to the experimental musicians and hence that they need to prepare for less time and have a higher tolerance for such sounds in the recordings. It may also reflect a familiarity with free improvisation common to many of the experimental musicians, and hence a stronger tendency to record with less preparation.

4.4.2.4.3 Comparison of questionnaire correlations

Table 4.4 presented interrelations between different responses to the questionnaire ques-

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All participants

Interface	Rated Most Satisfying	Rated Least Satisfying	Overall score
1	10	7	2
2	5	7	-1
3	6	5	-1
4	7	9	0

Experimental group

Interface	Rated Most Satisfying	Rated Least Satisfying	Overall score
1	6	4	-1
2	2	2	1
3	2	3	-1
4	4	5	1

Non-Experimental group

Interface	Rated Most Satisfying	Rated Least Satisfying	Overall score
1	4	3	3
2	3	5	-2
3	4	2	0
4	3	4	-1

Table 4.8: "Which interface did you find the most satisfying to use?" Columns 2 and 3 are counts. Overall score is calculated by awarding +2, +1, -1 and -2 for rankings of 1st, 2nd, 3rd and 4th respectively

tions, showing close correlations between attitudes to control, ability to recreate actions, fit with practice and significance of actions on the one hand, surprise, and scope for exploration/discovery on the other, and negative correlations between control and surprise, and recreation and surprise. Table 4.11 shows these sets of correlations for the results separated into experimental and non-experimental musicians. There are several differences between the participant groups.

1. Firstly, for the experimental music group there is no longer a significant negative correlation between the sense of surprise felt for a given interface, and the feeling of

Interface 1	experimental musicians		non-experimental musicians	
	r	p	r	p
control	0.27	0.36	0.50	0.07
recreate	0.25	0.39	0.56	0.03
surprise	-0.09	0.76	-0.27	0.35
discover	0.14	0.63	0.31	0.28
practice	-0.06	0.85	0.35	0.22
significance	0.26	0.37	0.74	0.002

Table 4.9: Spearman correlations between questionnaire responses and satisfaction with interface 1 for experimental music group and the non-experimental music group.

	practice durations		recording durations	
Interface	Experimental	Non-Experimental	Experimental	Non-Experimental
1	346	358	237	142
2	366	412	193	137
3	363	433	227	114
4	346	380	220	139

Table 4.10: Comparison of median practice and recording session durations for experimental and non-experimental music groupings across the four interfaces. The experimental music group consistently spend less time in the practise session and more in the recording session. All times are in seconds.

control and ability to recreate particular sonic events, whereas this correlation becomes stronger for the non-experimental music group - particularly the link between surprise and ability to recreate.

2. Secondly, surprise and the potential for exploration and discovery in an interface are strongly linked for the experimental music group, but the link is much less strong and significant for the non-experimental music group.

3. Thirdly, the matrix of interconnections between control, recreate, fit with practice and perceived significance of actions is diminished for the experimental music group. Although it is still present, the correlations are not as strong or as significant.

Experimental Musicians						
	Control	Recreate	Surprise	Discover	Practice	Signif.
Control	---	0.41 **	−0.18	−0.07	0.41 **	0.33 *
Recreate	0.41 **	---	−0.1	−0.02	0.29 *	0.37 **
Surprise	−0.18	−0.1	---	0.6 ***	0.16	−0.11
Discover	−0.07	−0.02	0.6 ***	---	0.28 *	0.15
Practice	0.41 **	0.29 *	0.16	0.28 *	---	0.39 **
Signif.	0.33 *	0.37 **	−0.11	0.15	0.39 **	---
Non-Experimental Musicians						
	Control	Recreate	Surprise	Discover	Practice	Signif.
Control	---	0.67 ***	−0.38 **	0.21	0.59 ***	0.68 ***
Recreate	0.67 ***	---	−0.53 ***	0.03	0.51 ***	0.49 ***
Surprise	−0.38 **	−0.53 ***	---	0.28 *	−0.14	−0.33 *
Discover	0.21	0.03	0.28 *	---	0.23	0.26
Practice	0.59 ***	0.51 ***	−0.14	0.23	---	0.38 **
Signif.	0.68 ***	0.49 ***	−0.33 *	0.26	0.38 ***	---

Table 4.11: Spearman rank correlation coefficients and significance values showing correlations between participant agreement with the six questionnaire statements laid out in Section 4.2.3.2. (*** for $p < 0.001$, ** for $p < 0.01$* for $p < 0.05$). Correlations of $p < 0.01$ are highlighted in blue (positive) and red (negative).

4.5 Discussion

This section explores a range of issues that emerge from the results of the previous section and discusses them in terms of the study research questions laid out in Section 4.1.

4.5.1 Headline results

The central result highlighted in Figure 4.14 — that the inclusion of nonlinear dynamics in the interfaces was linked to both feeling surprised and feeling that there was more to explore and discover — may be a useful result for designers wishing to support such aspects in their own instruments. The interviews suggest that some users enjoy engaging with the kinds of affordances that the nonlinear dynamics appear to engender, whilst others see them as difficult and limiting.

As noted in Section 4.4.2.1, the links between nonlinear dynamics and surprise/exploration may not be particularly surprising given that the nonlinear dynamical processes can lead to chaotic interactions that complicate the relationship between participant input and sonic output. What seems more notable is the fact that there was *not* a link between these nonlinear dynamical interfaces and a lack of control, or between these interfaces and the inability to repeat particular sonic events. Conversely, while the discontinuous interfaces were correlated with a lack of control and lack of repeatability, they did *not* correlate with a sense of surprise, or with perceived scope for exploration and discovery. This suggests that although nonlinear dynamical processes can be complex and chaotic, they are not inherently uncontrollable and can be learned and abilities may be developed. This result seems highly significant for thinking about musical actions, and for thinking about the nature of surprise in creative interactions. Different conceptions of surprise and unpredictability that emerge from this study are traced in the following two subsections.

4.5.2 Different conceptions of surprise

The term 'surprise' and questions around unpredictability in the musical interfaces were important concerns in this study (see questions 3, 4 and 5 in Section 4.1). This section uses the participant interviews to expand on the headline results stated above, outlining a more nuanced assessment of what is meant by 'surprise', and showing in particular how different kinds of surprises can affect engagement in different ways. Many participants found surprises that were arbitrary and abrupt to be frustrating and limiting. A useful distinction was made by a participant who contrasted these kinds of arbitrary events with surprises that lead to new possibilities:

> "What I want is a surprise that leads somewhere, rather than a surprise that's a dead end." (participant 637565)

This may help to explain the fact that the discontinuous mappings were not seen as significantly more surprising or explorable than the continuous mappings: the abrupt changes in the output at given points in the input may be initially surprising, but since they are exactly the same each time, they do not promote exploration, they merely limit the bounds of different areas. Several participants explicitly reported that the abrupt changes inhibited their musical exploration:

- "when I got to a certain point when I felt like I was attuned to searching and playing with the sounds one tiny movement of the hand would sort of kill it or disrupt it." (participant 459256),
- "it was in a sense not satisfactory either because during the recording I made I fell onto a thing that [...] was really not very nice, I was very surprised about, so I was a bit disappointed because I was just happy exploring something nice and it completely fell off!" (participant 735182),
- "each one of the gestures seemed to have a limited range, whereas the other ones, micro movements could create some very interesting relationships" (participant 941414).

A potentially important aspect of nonlinear dynamical processes that might relate to the idea of surprises that lead somewhere is the fact that they may exhibit *hysteresis* (see Section 2.1.1.3.2). Since the output is not dependent solely on the current input, but also on the previous states, the system can have different 'modes' where it behaves differently, and responds differently to the inputs. Once in these modes, it may even be difficult to return to a previous mode, requiring a fairly extreme change of parameters to force the system back to a prior mode. These modes therefore provide discoverable areas that importantly, can't be reached simply by setting the inputs to particular values, but that also require a particular history of inputs. From an interaction point of view, this can provide considerable scope for long-term exploration, as there are discoverable modes, behaviours and sounds that may not be found even though trying out every input, and every combination of every input. The particular input histories and therefore the *timing* of the inputs can open up new areas for exploration.

A limitation of the approach taken in this study to comparing the kinds of boundaries found in nonlinear dynamical processes with hard, abrupt discontinuities is that the MIDI input controller had a very limited resolution. This point was highlighted by participant

788295: ‘‘in a sense a knob is a sort of analog device, but it controls something digitally. And so that’s very noticeable’’. A system that is fully analog — not quantized — might provide a better comparison, as in such a system the participants could truly have explored the very fine detail around the boundaries in nonlinear dynamical processes. A method such as no-input mixing board discussed by Kuivilla (2004) and Sanfilippo and Valle (2012) (feeding an analog mixing desk back on itself) provides one such example, where the minutest of changes to the dials can have a very wide variety of results. However, this kind of interaction was reported to an extent in conjunction with interface 1 (nonlinear dynamical with continuous mappings):

- ‘‘the idea that small incremental changes, tiny incremental changes, the control of your finger basically, can create really interesting changes’’ (participant 941414)
- ‘‘it felt really quite comfortable, and then there was this very very fine movement of the fader that really changed the sound quality and so there was really fine movement of the fader and maybe quick and sensitive at the same time, movements of the knobs.’’ (participant 79220)

Although, not everyone enjoyed this kind of interaction:

> ‘‘I would make one incremental change on the dial and something [...] sometimes it would be something that was incorporating some weird equation into the generation of it [...] it was frustrating [...] [couldn’t] fathom what was going on.’’ (participant 295392).

There were definite links between surprise and exploration (see also the discussion on quantitative correlations in Section 4.5.4 below), but the nature of the link appears to be very personal, with different kinds of surprises suiting different kinds of exploration (see also the following Section 4.5.3 on deterministic and stochastic surprises, and Section 4.5.5 on broad vs deep exploration).

A potentially interesting approach to future work might be to deliberately attempt to create an interface that *is* seen as surprising, but yet is *not* linked to the potential for exploration and discovery.

4.5.3 Deterministic surprises

The distinction outlined above between arbitrary surprises and surprises that lead somewhere also serves to highlight potential differences between stochastic and deterministic surprises. An obvious approach to encouraging surprises in interactions might be to incorporate randomness. Indeed many artists have explored such processes, notably John Cage and subsequent experimental music composers. Many musical systems exist that do include stochastic processes (from Xenakis' dynamic stochastic synthesis, through to 'randomise' buttons in VST plugins and shuffle functions on MP3 players) and the area provides many interesting possibilities for artists. From an interaction perspective however, there appear to be important distinctions between chance processes and the chaotic-but-deterministic nature of nonlinear dynamics. Crucially, the deterministic nature of nonlinear dynamics means that although they are unpredictable and allow for exploration, they still allow for actions to be repeated, and as Keep (2009) puts it "to re-access fruitful results." In David Borgo's account of improvisatory practice, randomness is described as not producing "a sense of surprise, but rather confusion, dismay, or disinterest" (Borgo, 2007, p 1). This theme is returned to in the subsequent ethnographically-informed study detailed in Chapter 5, with contrasting approaches to surprise with and without random processes laid out in Table 5.3.

In the context of reflective design and reflective practice (see Section 2.3.1), Sengers et al. (2005) link surprise to "puzzling out what to do next or why the status quo has been disrupted." Although stochastic surprises may help to take the instrumental interaction beyond direct control, the contingent nature of such surprises may be very different in kind to deterministic surprises. In the case of arbitrary discontinuities or stochastic surprises, although reflection may provide insights into the nature of the system, it will not necessarily inform the user's interaction, as the events cannot be developed or elaborated. By contrast, surprises due to the nonlinear dynamical processes may be reflected upon, explored, investigated and harnessed as a resource.

4.5.4 Control, surprise, exploration and discovery

The study results allow for further examination of the potentially complex relationships that may exist between control, surprise and scope for exploration and discovery highlighted in the literature review (Sections 2.3 and 2.2.3). This research is not attempting to establish a definitive relationship between these elements, but seeks to look at different possible relationships, and how these connect to musical practice and to the musical tools being employed. Table 4.4 shows significant correlations between different participant responses to the six Likert scale questions. These correlations present a potentially useful method of gaining insights into such interrelations. Figure 4.23 visualises these connections. There is a strong network of interconnections linking four of the elements: perceived level of **control**, ability to **recreate** events, **significance** of actions in determining the sounding result, and — perhaps more surprisingly — how well each interface seemed to fit each participant's own musical **practice**. Participant scores to these Likert scale questions correlated strongly: if a participant agreed that a particular interface was controllable, they were also likely to say that it allowed them to repeat events, fitted well with their practice, and that their actions were significant. Three of these four elements (excluding fit with practice) correlate negatively with surprise. This also seems like a natural connection: interfaces that are uncontrollable will likely be surprising. Surprise itself correlates with scope for exploration and discovery, which in turn has slightly weaker but still significant connections back to fit with practice and significance of actions. This somewhat contradictory network may be an anomaly in the results, but it may also point to ambiguous attitudes to control in musical interactions. Control and the ability to recreate actions appear to be positive elements in that they fit in with musicians' practices, but absolute control may preclude the possibility of surprise.

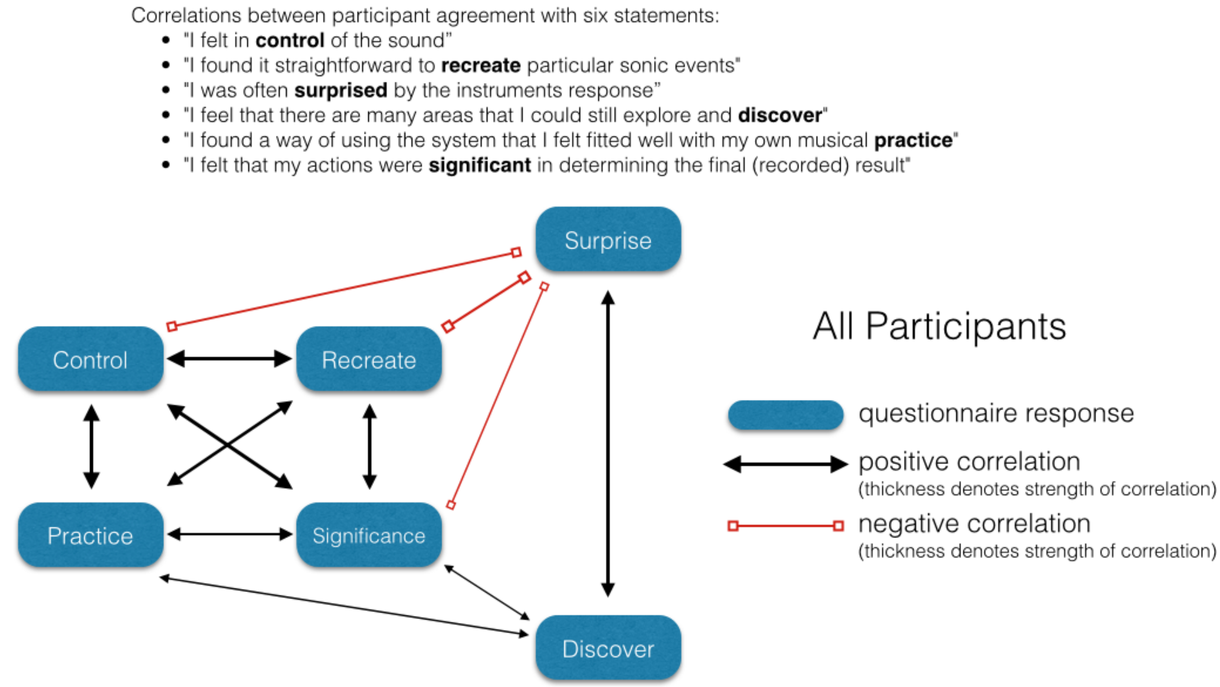

Figure 4.23: Visualisation of Spearman rank correlations coefficients for significant correlations between participant responses to Likert scale questionnaire questions (based on the data in Table 4.4). Thicker lines are stronger correlations and red lines represent negative correlations.

This in turn may limit the scope for exploration and discovery which is also valuable in the practices of musicians.

Table 4.11 shows these correlations in the responses from the experimental music group and the non-experimental music group. These are visualised in Figure 4.24. The left hand image showing the relationships between responses from participants in the experimental music group shows generally weaker correlations, which may relate to the significant reduction in variation of responses compared with the non-experimental music group (reported in Section 4.4.2.4). The only correlation that is stronger for the experimental music group than for the set of participants as a whole is between surprise and scope for exploration and discovery. This connection fits well with the discussion of contemporary musical practices detailed in Section 2.2. The negative correlations disappear completely (contrasting with stronger negative correlations from the non-experimental music group) suggesting that there may be different conceptions of control and surprise in the two groups. The prevalence of

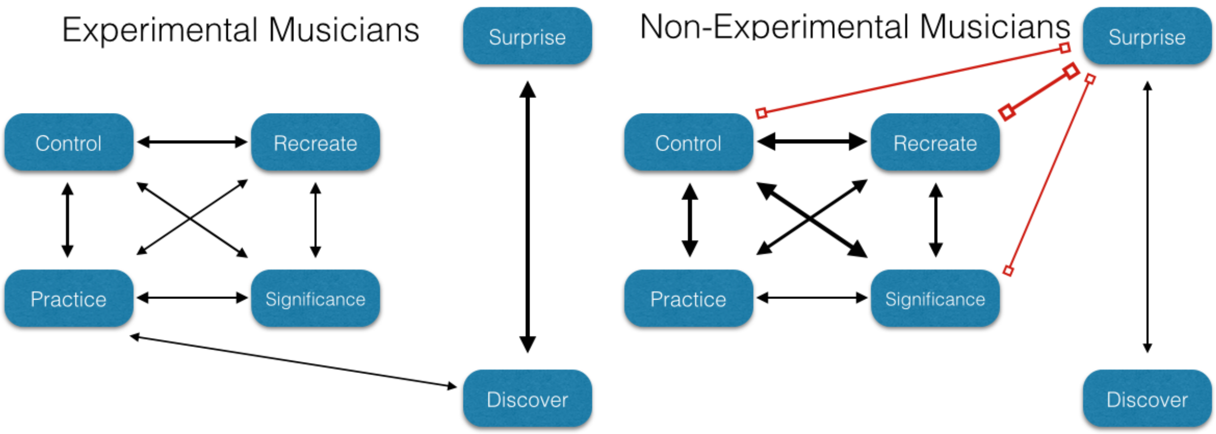

Figure 4.24: Visualisation of Spearman rank correlations coefficients for significant correlations between participant responses to Likert scale questionnaire questions, grouped according to the participant's experience with experimental musical practices (based on the data in Table 4.11). Thicker lines are stronger correlations and red lines represent negative correlations. No arrow between two elements means that there was no statistically significant correlation.

interactions in which the instrument is as an active participant in the musical process traced in Section 2.2.3 fits in with this result: since the instrument is expected to contribute its own — potentially surprising — behaviours, being in control may have a slightly different meaning. The musician can be in control of a situation in which surprising things may occur. In the post-study interview, participant 569940 summed this up well by simultaneously highlighting the importance of control ("I like to know what I'm doing instead of blindly flailing and hoping something will come out") whilst not necessarily being in complete control ("I might not know where it's going to go, but at least I know that it's going to affect this particular aspect of the sound and it'll probably go this certain way").

4.5.5 Broad exploration vs Deep exploration

The study highlighted that there can be different ideas of what 'exploration' may mean in an interaction context. One view might involve covering as much territory as possible until the entire space of possibilities has been scanned. A contrasting view however may consider exploring only one small part of one small area, exploring the subtleties and nuances of particular sounds and behaviours. The vignette presented in Section 4.4.2.3 for participant

455667 shows a particularly minimal approach to working with the interfaces, with very low levels of activity on all inputs for all interfaces, and consequently only very small areas of the whole space of possibilities utilised. The fact that the participant did not cover much terrain does not mean that these logs do not represent explorations however. This kind of *deep* exploration is an important consideration in instrument design. It seems to be something that many acoustic instruments can do very well: there are endless nuances in how a single note or sound may be played (consider the emphasis placed on a saxophone or trumpet player's 'tone' or 'sound' in jazz for example (Miller, 1995; Liebman, 2006)). Participant 637565 provides an idea of how these micro variations in the interaction play a part in musical explorations:

> "What I'm interested in often is in taking a sound and manipulating it in a way that's interesting, so I'll find a sound and then [...] with a bow [...] I'll twist the bow a little bit and see what happens to the sound and what doesn't happen to the sound."

The implication seems to be that something unexpected may (or may not) occur around this very small adjustment, which may then lead the musician in their playing. This matches the participant quotes highlighted above in Section 4.5.2 and the preference for surprises that lead somewhere. In particular, the idea of deep exploration seems to suit the kind of interaction afforded by the hysteretic nature of nonlinear dynamical systems, as pointed out above in Section 4.5.2: since the history of the input is relevant and the interaction is time-dependent, a very small set of input values can yield a vast array of possibilities.

4.5.6 Little variation in satisfaction across the four interfaces

In order to focus on aspects of interaction, the four interfaces were designed to be comparable, and therefore to all be of potentially equal interest (see Section 4.2.3.1). The fact that there was no clear preference for a particular interface or group of interfaces (e.g. the level of satisfaction was similar across the independent variables, see Table 4.5) is useful in the context of this study, as all four interfaces were designed to be of more-or-less equal interest. The lack of a clear preference for a particular interface suggests that the interfaces were broadly comparable for the purposes of this research, and the other results can be considered without the findings being ascribed to a particular interface or independent variable being seen as "better" than any other.

4.5.7 Distinctions between participant groups

Section 4.4.2.4 presented a range of differences between two groups of participants, split based on their experience of experimental music as defined in Section 2.2.2. This is helpful in unpicking how musicians of differing backgrounds may think and engage with different musical interfaces in different ways. This section examines these results to provide a broader range of perspectives on surprise and exploration as they pertain to HCI in general, and to highlight interesting musicological insights pertaining to experimental musical practices.

As noted in Section 4.4.2.4, the links between a) the presence of nonlinear dynamical processes and scope for surprise and exploration, and b) the presence of discontinuous interfaces and a lack of control and ability to recreate events, is *not* significant when considering only the results for the experimental music group (as shown clearly in Figures 4.21 and 4.20). This suggests a significant difference in engagement and attitude. One possible explanation is that the experimental music group were more accepting of the specifics of each interface (in line with a material-oriented approach as outlined in Section 2.2.1), and were less inclined to try to realise pre-formed musical ideas. To give a more specific example, having a sense of control, or being surprised by a particular tool may relate to one's expectations: if unpredictable interactions are familiar, then one may feel in control despite the unpredictable nature of the interface. Similarly if one is comfortable with surprises from an instrument, then the instrument may not seem so surprising. This explanation is supported by a further result: that there was significantly less *variation* in the Likert questionnaire responses from the experimental music group. Variation for a given participant is taken as the minimum score given for a particular Likert-scale question (0 – 4) across all interfaces subtracted from the maximum score for that same question, as discussed in Section 4.4.2.4 and shown in Table 4.6 and Figure 4.22 (see also Figures 4.20 and 4.21).

As mentioned in Section 4.4.2.4.2, the notably shorter durations of the practise sessions and the longer durations of recordings for the experimental music group across all four interfaces (Table 4.10) may suggest a general openness to the kinds of sounds afforded by the particular interfaces used in this study, whereas the non-experimental music group may have struggled to find sounds and behaviours that they enjoyed sufficiently to make recordings they were interested in. It may also reflect a familiarity with free improvisation common to many of the experimental musicians, and hence a stronger tendency to record with less preparation, and to actively explore during the recording process itself.

Finally, the correlations between different Likert scale results also suggest slightly different relationships between control, surprise and discovery for the two groups (Table 4.11). For the experimental music group, there is *not* a statistically significant negative correlation between surprise on the one hand, and the interconnected set of control, recreate and significance on the other. The relative independence of surprise from questions of control may reflect the fact that, as noted above, musicians engaged in more experimental practices are used to encountering and actively encouraging surprising interactions, and may feel that they are "in control" of situations that are somewhat unpredictable. This is supported by the fact that the only relationship that becomes stronger for the experimental music group is the link between surprise and scope for exploration and discovery (Spearman rank correlation coefficient of 0.6, $p < 0.001$ for the experimental music group, but 0.28 with $p < 0.05$ for the non-experimental music group - see Table 4.11). As with the other results reported in this section, this fits in well with the characterisations given in Section 2.2 of experimental musical practices being more open to surprising aspects, and actively embedding these elements in their practices. Participant 079920 — placed in the experimental music group — exemplified these attitudes in their interview, highlighting the importance of exploration and discovery, and the role that unpredictability can play:

> "the highest one I ranked [interface 1] was actually the most unpredictable one because it was really satisfying because there's so much more to explore. [...] the tool has to be complicated enough so I can really get lost in it and forget my knowledge, and I can find new sounds. [...] There always has to be something coming from a different place, so there has to be a balance and control and possibility of experimentation and surprise"

Despite this however, some members of this group did express dissatisfaction with elements that were seen as overly surprising and disruptive to the process of exploration. The quote given above in Section 4.5.2 expressing annoyance at surprises that shut down exploration came from a participant classified as experimental.

> "it was in a sense not satisfactory either because during the recording I made I fell onto a thing that [...] was really not very nice, I was very surprised about, so I was a bit disappointed because I was just happy exploring something nice and it completely fell off!" (participant 735182, placed in the experimental music group)

4.5.8 Limitations of the methodology

Although the study has drawn conclusions, made useful distinctions, and raised issues for further research, there are significant limits on what can be claimed. It is important to note that the headline results of this study described above in Section 4.5.1, and the conclusions drawn from them, cannot be easily generalised. The design of a musical interface requires many design decisions, and the design elements under consideration cannot easily be isolated and tested independently of the other elements. Oversimplifying a musical device risks rendering it "unmusical" (Stowell and McLean, 2013) and therefore not appropriate for research into musical interactions. The interfaces used in this study represent only one possible implementation of the nonlinear dynamical components, and these components are a single factor amongst many in influencing the nature of the interaction.

A future approach to examining nonlinear dynamical processes might be to attempt a categorisation of the different possible implementations, and to draw careful distinctions between these categories. A candidate distinction has been touched on already: whether the nonlinear dynamical process is implemented as part of the sample-rate audio process or whether it is in the control mapping to a separate audio engine (explored briefly in the exploratory studies: see Section 4.2.2). There are also important considerations in terms of the nonlinear dynamical processes themselves which may affect participant behaviour and the experience of interacting with such processes: e.g. the number of dimensions in the system, autonomous vs nonautonomous systems (see Section 2.1.1), and the qualitative nature of possible bifurcations (see Section 2.1.1.3.1 and Lakshmanan and Rajasekar, 2003, p. 75, for an outline of the possibilities).

Similarly, other factors could be contrasted with nonlinear dynamics, other than the simple discontinuous mappings used in this study. For example, a similar future study that explored differences between stochastic processes and nonlinear dynamical processes as discussed above in Section 4.5.3 might help to further draw out what is particular about the latter processes, and support the discussion regarding more nuanced conceptions of surprise and exploration.

The influence of the particular sounds and musical behaviours afforded by the interfaces has been noted above in Section 4.2.3.1. Although in this study, care was taken to keep the interfaces within a relatively consistent sound world, this overall sound world was selected relatively arbitrarily, and the study could be re-run with very different kinds of musical affordances. At the heart of this problem is the fact that music can be many different things to different people, and there is no simple way of designing an interface that does not emphasise or prioritise certain musical approaches over others.

A related point is the that of confining musical experiments and tasks to a lab-based context which may differ considerably both from the social nature of a concert or group rehearsal on the one hand, and the intimacy of practicing, rehearsing or recording alone on the other.

A useful direction for future studies would be to examine how views change when using the tools for prolonged periods. Participants were asked to judge the scope for exploration and discovery in a particular interface after only five to twelve minutes of use. It would therefore be beneficial to examine how attitudes towards these elements differ over longer periods of time (see Gelineck and Serafin, 2012, on this point, and the discussion in Section 2.3.3.4). It would also be very useful to see how perception of surprise develops over longer periods, to see whether the nonlinear dynamical processes can still produce unexpected results after several days, weeks or months.

4.5.9 Summary

The relatively open-ended nature of this set of comparative evaluation studies has provided a broad range of issues to consider. A very specific conclusion is reached, that the particular nonlinear dynamical processes implemented did seem to engender a sense of exploration and discovery, and allow for surprising outcomes, without being seen as uncontrollable. The study also raises a very useful set of questions in relation to the wider issues under consideration: the role of surprise in creative interactions, different possible definitions of surprise in this context, different ideas of what is meant by the term 'exploration', and how this pertains to the instruments and tools being engaged with and the approaches taken by the musicians engaging with them.

The distinction between surprises that lead somewhere, and surprises that are a dead end may be particularly helpful in thinking about design issues in relation to exploration. Although to some extent whether a surprise can be said to lead somewhere is dependent on the musician's attitude, it also appears to be a function of an instrument's design.

The limitations of the methodology employed in this chapter discussed in the previous section — such as the difficulty of inferring generalisations about nonlinear dynamical processes beyond the specific systems implemented, and the marked separation between these lab based studies and musicians' actual practices — suggest that although the methodology has some merit, it may be useful to approach the subject from a different direction.

The following chapter presents an ethnographically-informed study into the practices of free improvisers. As explained in Chapter 3, this provides a secondary perspective on the subject. The results of the comparative evaluation studies presented in this chapter are examined along with the results of the ethnographically-informed study in Chapter 6, and related back to wider questions in the literature surrounding music and HCI highlighted in Chapter 2.

Chapter 5

Ethnographically-informed study

The studies presented in the previous chapter provide a range of insights into the role of nonlinear dynamical processes in musical interactions, and help to explore different relationships between control, surprise and exploration. The quantitative aspects of these studies establish concrete differences in engagement between the specific systems under consideration. However, the limitations to this methodology discussed in Section 4.5.8 highlight the difficulties in making any generalised claims regarding nonlinear dynamical processes in musical interfaces. The interviews conducted at the end of each study suggest a complicated picture of how different musicians view their own creative interactions with their tools. The terms ‘exploration’ and ‘surprise’ can be understood to mean a variety of different things, the subtleties of which are difficult to address in lab-based studies.

This chapter presents an ethnographically-informed study designed to approach these questions from a different perspective. The mixture of research methods is intended to help triangulate towards a more complete understanding of interactions with nonlinear dynamics, and the wider questions regarding attitudes to surprise and exploration in musical interactions. The two studies are therefore mutually supportive, with each providing useful context for the other as discussed in Chapter 3.

The ethnographically-informed study limits itself to examining the practices of musicians engaged in improvisatory practices, particularly free improvisation. As noted in the literature review, improvisation provides a fertile area for examination for this thesis, due to the wide variety of approaches to engaging with musical instruments, the explicit focus on exploration, and the apparant tendency to draw on the nonlinear dynamical properties of musical instruments. Free improvised musical practices provide a site where the roles played by exploration and unpredictability in instrumental interactions are foregrounded and exaggerated (see Section 2.2.3), allowing them to be studied more closely. The rich examples of creative interaction found in this domain provide nuanced insights pertinent to broader questions around musical interaction, the design of musical tools, and ideas about creative interaction more generally.

5.1 Overview and research questions

A set of semi-structured interviews were conducted with 24 musicians whose practices incorporate free improvisation in some way. These musicians appear to engage (knowingly or otherwise) with nonlinear dynamical processes as part of their practices. Thematic analysis is used to code and analyse the interview data, and themes are developed and discussed with reference to case studies of particular participants.

As discussed above, it is clear from the first study that terms such as 'exploration', 'surprise' and 'control' are complex and may be understood and valued differently by different musicians. The term 'surprise' in particular was seen as ambiguous by many participants, and yielded a mixture of responses, suggesting different potential categories of surprises. For example, when performing an action such as bowing a string, the participant may not be able to predict the exact timbral nuance of the sound produced, but as long as the result fits within a certain area of expectation the result is not regarded as a surprise. These nuances surfaced in the interview sections of the first study, but were not easily discerned in the quantitative aspects. The ethnographically-informed study presented in this section therefore attempts to zoom in on these important details and distinctions. In doing so, the focus shifts away from directly attempting to evaluate the role of nonlinear dynamical processes in musical interactions. The problems highlighted at the end of the first study — particularly the myriad ways in which nonlinear dynamics may feature in musical interactions and the internalisation of such processes in advanced musicians — suggest that a less direct approach may be more productive, both in terms of examining the roles that such processes may play in existing practices, and considering more general questions around exploration, surprise and control in creative interactions. Although the structured interview questions do not therefore explicitly address nonlinear dynamical aspects, these elements are a tacit concern. As participants are selected based on the fact that their practice appears to embrace nonlinear dynamical processes in some way, these issues are very much embedded in the discussions. The focus on broader concerns such as the nature of musical exploration, surprise and control also serves to generalise the results, and to contribute to wider discussions around these issues in interaction design, HCI and beyond as discussed in the literature review (Section 2.3.4).

5.1.1 Primary research goals for the ethnographically-informed study

The primary goals of this study are therefore as follows:

1. gain a clearer understanding of the role(s) of surprise in instrumental interaction,
2. examine different categories of surprise in musical tool interactions,
3. attempt to clarify and unpack exploration in improvised musical performance practices,
4. examine the role that the nonlinear dynamical properties of certain tools may or may not play in relation to exploration and unpredictability,
5. gain an understanding of how the nature of musical tools may help to facilitate (or hinder) long term exploration.

The specific methodology for this study is laid out in the following section, detailing the specific structure for the participant interviews (Section 5.2.1), providing more information on participant recruitment and demographics (Section 5.2.3), and the specific approach taken to using thematic analysis (Section 5.2.2). The data is then presented through descriptions and examples of the data codings, subcodings and themes in Section 5.3 and discussed in more detail in Section 5.4.

5.2 Methodology

To gain a rich, qualitative insight into attitudes to surprise, exploration and control in musical performance, 24 participants were interviewed about their practice and their relationships with their tools. Thematic analysis was employed to code and analyse the interview data (see Section 5.2.2).

In order to devise interview questions for this study, an initial categorisation of surprise was proposed. These categories were then put to the participants to see whether they recognised them in their own practices. The initial categories were as follows:

1. Genuinely or effectively random aspects. This could include randomised functions on hardware or software devices, but also interactions that were effectively random such as radios, autonomous motorised movements (e,g. vibrators moving around by themselves), dipping into recorded media at unknown points (as described by Wessel and Wright, 2002) or other chance-based methods.

2. Situations that are deterministic but impossible to control accurately. This might include situations where tiny, almost imperceptible movements lead to varying output, or where musicians are pushing against their physical limitations of strength, endurance and accuracy.

3. Unstable interactions that may change abruptly at unknown thresholds. Feedback provides an example: a performer may slowly increase the gain of an amplifier knowing

that at some threshold it may abruptly feedback, but not knowing at exactly what point.

4. Changing situations that result in surprises, such as playing in a different acoustic space or using new tools and/or new combinations of tools.

These categories are based on the practices described by participants in the first study interviews. They are not mutually exclusive, and some examples may fit multiple categories. For example, dipping arbitrarily into recorded media (e.g. a record or an audio file) at various points is technically deterministic, but is limited by accuracy and memory of what is where in the recording. They nevertheless provide a useful starting point for discussing the nature of surprises with the participants.

5.2.1 Semi-structured interviews

Semi-structured interviews were conducted with each participant individually, focusing chiefly on the participants' individual performance practices. The structured questions detailed below allowed the research questions to be addressed relatively directly. The loose interview structure also allowed participants to deviate significantly for periods of time, leaving room for themes to emerge more organically in the analysis processes, and for potentially unexpected areas of discussion.

Interviews were conducted in person, or via remote video connection. Audio from the sessions was recorded and transcribed for subsequent analysis. The pre-prepared questions are listed below along with the rationale behind each.

1. **What tools and instruments do you use in your practice?** This sets up the framing for the interview: interactions with musical tools. It also provides functional information about the participant's tools, and depending on the detail in the participants response, may include interesting descriptions of fairly complicated apparatuses.

2. **Could you describe the role of exploration in your performance?** This is a very general starting point, but it allows the participants to interpret the term 'exploration' on their own terms. Follow up questions help to clarify what exactly they understand by the term, and how it relates to improvisation and the tools that they use.

3. **Are you often surprised by your instrument/tools (as appropriate)?** For participants that answered yes, the follow up question asked them to give a specific example. Further follow up questions also probed the participants attitudes to different kinds of surprise based on the categories listed above in Section 5.2: if a participant's example belongs to one category, the other categories could also be asked about.

4. **What is the motivation for employing or actively searching for unpredictable elements?** This question helped move from specific examples to more general aesthetic concerns, and helped to get closer to their ideas about exploration and interaction. (phrased as appropriate for the participants responses up to this point. If the participant has not expressed a desire for surprise, the question can be inverted to ask why they are *not* interested in surprising situations).

5. [**Question regarding hypothetical random button**] This question involved asking the participant about how they would feel if their tools were replaced with a single button that when pressed would play a sound completely at random. The sound could be potentially anything, and the participant would have no control over the development of the sound. This extreme example was proposed in order to force participants into spelling out things that they might otherwise have thought were too obvious to mention regarding control, surprise and exploration (particularly as the author and interviewer is known by most participants to have a degree of familiarity with improvised music). It is particularly useful for establishing what is important about surprise in interaction, and how the participants would ideally like this to be manifested in relation to their

instruments and practice.

6. **Is there anything that has been in your mind during this interview that has not been said, or anything that you wish to add?** This gave the participants an opportunity to say anything that hadn't been directly asked about in the questions thus far.

Where possible, a video or audio recording of the participant performing was found in advance, and certain sections identified where it seemed likely that the participant was dealing with material that was in some way surprising, or otherwise seemed to be exploring some kind of unknown territory. This provided a very concrete situation for the participant to talk about, and even if the musical sections selected proved not to be surprising situations, they could still provide significant insights into the participant's thought process when playing.

5.2.2 Thematic analysis

Thematic analysis constitutes a broad set of practices (Braun and Clarke, 2006). This section lays out the specific approach to coding, subcoding and developing themes from participant interviews taken in this study. As discussed in Section 5.2.4, the researcher's background has doubtless influenced both the formulation of the questions and the interpretation of the answers. It is hoped that these biases help to provide a useful starting point, and have led to useful research questions, rather than a blinkered view that prevents broader aspects from being seen. With that in mind, the approach to coding and analysing is explained in detail below to attempt to make the process as transparent as possible.

The analysis is primarily deductive: to an extent, there is a preexisting starting point that influenced the approach to coding and development of themes. As the interview questions are directly related to specific research questions, many themes and codes are developed based on these questions rather than from a more grounded approach. There are inductive aspects however; the semi-structured nature of the interviews leaves room for participants to discuss broader issues, and to potentially introduce themes that were not initially anticipated. This openness is necessary in attempting to investigate such relatively new terrain where specific hypotheses are not clearly formulated in advance.

The approach taken here is based on the structure laid out by Braun and Clarke (2006, p 87), incorporating the following six steps:

1. gaining familiarity with the data,
2. generating initial codes,
3. searching for themes,
4. reviewing themes,
5. defining and naming themes,
6. reporting the themes.

Despite the focus on deductive analysis, the initial coding was relatively open (in the sense described by Strauss and Corbin, 1998): informed by the research questions, but not limited to data extracts with immediate relevance to the research questions. Themes that might not have been seen as immediately relevant could therefore be considered more fully before being either retained and incorporated, or sidelined as being outside the scope of the current project.

In general, the fact that the questions put to the participants relate closely to the concerns of the study — particularly in relation to surprise and exploration — means that the participants' responses directly relate to the themes, and can be coded based on their explicit content. However, certain issues relating to the research questions are not easy to pose directly. Ideas around nonlinear dynamics, emergence, and acoustics were difficult to tackle head-on with participants, so codes, subcodes and themes on these topics often rely on the latent content of the data extracts. For an example of this, see the case study of participant 4821 discussed in Section 5.3.2.1, where the participant discusses bowing a violin string with a spring attached. The complexities of the resonances and the bowed interaction are evident to the participant, who considers the situation to be fertile for exploration, but it can be difficult to conduct fluid discussions with musicians in the language of acoustics or nonlinear dynamics, despite the tacit presence of such issues. The final coding is presented in Section 5.3.1 with full descriptions of the derived codes, subcodes and themes.

5.2.3 Participants

This study focuses on musicians engaged in what can broadly be referred to as experimental musical practices (see Section 2.2), and in particular, free improvisation. This tightens the scope of the study, and provides a very rich set of practices from an interaction design perspective. As discussed in Section 2.2.3, free improvisation provides an interesting perspective on the relationships between musicians and tools. 24 participants with different instrumental practices were recruited. The vast majority of these were London-based musicians (22 out of 24). This was in part a practical consideration, but London contains a very diverse range of experimental and freely improvised musical practices. The community is far from homogenous in the approaches taken towards instrumental interactions, and interacting with other improvisers.

The participants were recruited individually, selected to cover a broad range of different tools and instruments. Table 5.1 shows a breakdown of the different instruments played by the participants in three categories: participants using primarily acoustic instruments, participants using primarily electronic instruments, and participants regularly using a mixture of the two.

5.2.4 Researcher bias

It should be noted at the outset that the author has connections to free improvisation, including occasionally attending Eddie Prévost's improvisation workshop (see Section 2.2.3), putting on concerts involving some of the study participants, and performing and socialising with some of the participants. This is to some extent inevitable in a specific community of

Participant	**Acoustic Instruments**
No. 7474	Objects
No. 1747	Piano / objects
No. 2999	Cello
No. 3284	Trombone
No. 5559	Saxophone
No. 4821	Violin
No. 5173	Double bass
No. 5619	Double bass
No. 7855	Viola
	Electronic Instruments
No. 1883	Laptop / samples
No. 4692	Electronics / theremin / radios
No. 1948	Laptop / samples / electronic objects
No. 7864	Modular synthesiser
No. 8745	Modular synthesiser / laptop
No. 9924	Sine tones (laptop)
No. 8133	Digital feedback networks
	Mixed Electronic and Acoustic
No. 1684	Flute / electronics
No. 8684	Objects / voice / effect pedals
No. 4652	Saxophone / objects / electronics
No. 3598	Piano / samples / objects / effect pedals
No. 2418	Wine glasses / objects / effect pedals
No. 5592	Objects / laptop sampling
No. 7321	Violin / drums / laptop sampling
No. 8854	Electric guitar / feedback / objects

Table 5.1: List of tools used by the ethnographically-informed study participants, categorised as acoustic, electronic or mixed for each participant (identified by their participant numbers)

interest, but precludes approaching a fully objective, external standpoint. Nevertheless, the experience of having spent time embedded in the community attending relevant workshops and concerts helps to provide insight that can be beneficial in navigating interviews with improvisers and interpreting the data.

5.3 Results

A description of the iterative process of coding the data is given below. The final data codings are then presented, with short descriptions of each code, example data extracts that demonstrate each code, and subcodes representing further breakdowns of each code. A full transcript of a single interview is provided in Appendix A for reference. Finally, the themes are presented, discussed and evidenced with explanatory case studies from the data corpus.

5.3.1 Interview Coding

As discussed in Section 5.2.2, codes and themes were developed iteratively, guided by the research questions and the content of the data corpus itself. Figure 5.1 shows the initial coding, initial themes, and the relations between the two. As these codes were iterated, some were modified or merged, for example the initial theme "after surprise: what happens next" has been incorporated into the more general theme "expanded ideas of surprise" as the former doesn't relate to many codes not already covered by the latter. Some themes have also been considered out of scope for the present study (e.g. "social aspects of improvisation," "engaging with the history of the instrument"). Figure 5.2 shows the final codings that are described individually below.

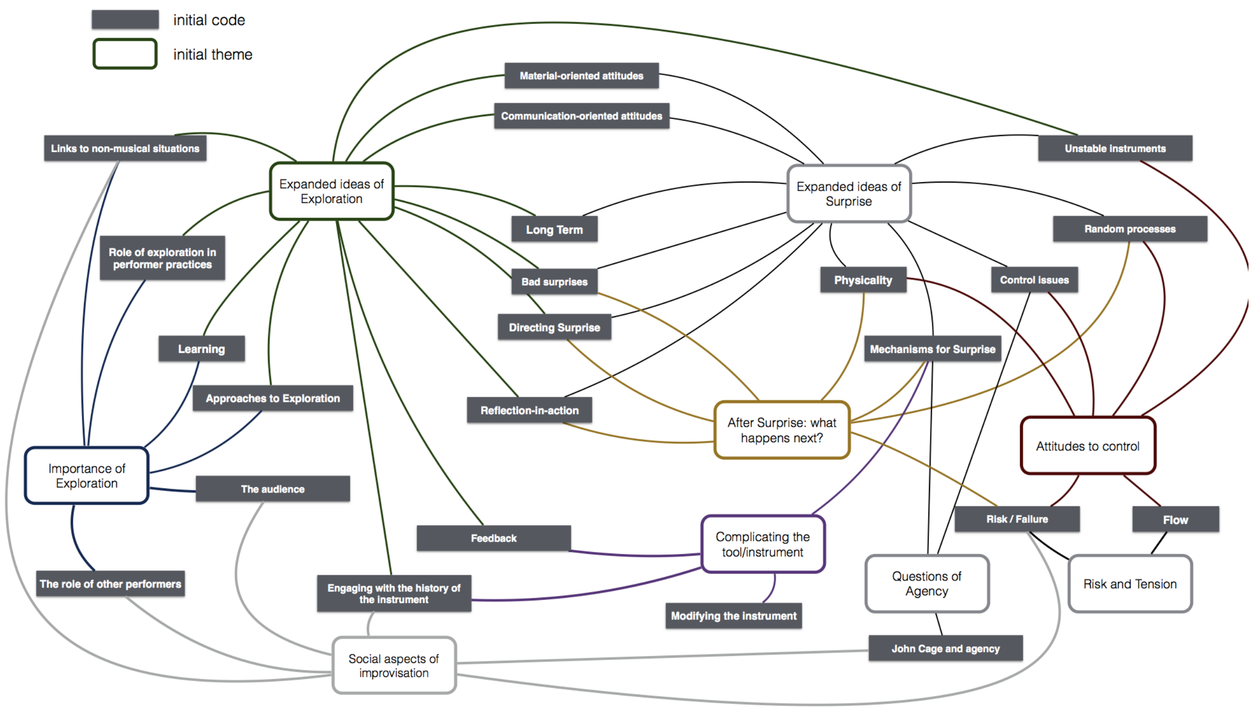

Figure 5.1: Initial coding map showing initial codes and themes.

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
1) Role of Exploration in participant practices I) importance in improvisation II) definitions and descriptions III) discovery and new sounds IV) dialog with the instrument	✓	✓	✓	✓	✓	✓
2) Role of Surprise in participant practices I) surprise in improvisation II) dialog/relinquishing agency III) instability IV) after surprise	✓	✓	✓	✓	✓	✓
3) Practical approaches to eliciting surprise I) feedback / nonlinear dynamics II) physical or mental limitations III) random processes			✓	✓	✓	✓
4) Attitudes to Control I) lack of control II) total control III) importance of control			✓	✓	✓	✓
5) Learning	✓	✓	✓	✓		
6) Risk and Tension I) risk for the performer II) risk for the audience III) risk and unstable tools	✓		✓	✓		✓
7) Long term - changes over time	✓	✓	✓	✓	✓	
8) Complexity I) feedback II) complexity and surprise III) combinations / assemblages IV) complexity as a resource		✓	✓	✓	✓	✓
9) Physicality			✓	✓		✓

Figure 5.2: Final codings, sub-codings and themes. The check marks indicate that a particular code connects with a particular theme.

5.3.1.1 Coding 1: Role of Exploration in participant practices

	Themes					
Codes and subcodes	**The importance of Exploration**	**Expanded ideas of exploration**	**Expanded ideas of Surprise**	**Attitudes to Control**	**Complicating the instrument**	**Risk and Tension**
1) Role of Exploration in participant practices I) importance in improvisation II) definitions and descriptions III) discovery and new sounds IV) dialog with the instrument	✓	✓	✓	✓	✓	✓

This code categorises data extracts where participants describe exploration in relation to their practice. Participants were asked about this directly as part of the structured interviews via the question, "could you describe the role of exploration in relation to your practice?" (see Section 5.2.1). The issue was also discussed at other points in the interviews. References to 'searching', 'seeking' and 'finding new things' are similarly relevant for this code. A selection of example data extracts are provided below to give a clearer picture of the coding.

Coding 1 Examples:

- "exploration and discovery is the playing actually, it's very very important"
- "it's funny because I've got a slight — not a problem with the word "exploration," and I certainly enjoy the term, particularly as a lecturer, I think trying to get people to explore things — but then I don't know if in my own practice that would be the term I would use."
- "it's massive, it's very important. It's [...] the purpose of what I'm doing"
- "a constant dialog or search between you and your materials"
- "I would hope that exploration was the core idea, the main thing that I was trying to do, although, again I think it's a grey area..."
- "So the solo playing is basically exploration of the sound of the instrument."

Coding 1 Subcodes:

Subcodes are provided for the individual codes where relevant. Subcodes are helpful for grouping data extracts within specific codings for further discrimination. Four specific subcodes of coding 1 are detailed below.

1. **The importance (or not) of exploration in improvisation**

   Data relating to the significance of exploration in the participant's practice

2. **Definitions and descriptions of exploration**

   Data that provides clarification on precisely what participants understand by the term "exploration" or related terms such as "investigation" and "searching"

3. **Discovery, new sounds, newness**

   Participant views in relation to discovery and finding new things.

4. **Dialogic or conversational engagement with tools and instruments**

   Data relating to the tool's role in improvising, exploring and creating new sounds, where the participant ascribes either agency to the tool, or uses language discussing the interaction as "two-way", as "dialog", as a "conversation", etc.

5.3.1.2 Coding 2: The role of surprise in participant practices

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
2) Role of Surprise in participant practices I) surprise in improvisation II) dialog/relinquishing agency III) instability IV) after surprise	✓	✓	✓	✓	✓	✓

This code is similar to (1) but addresses surprise and unpredictability in relation to improvisation. It is distinguished from (3) and (4) below by focusing more strongly on the reasons why unpredictability might be sought, and how it is integrated into different perspectives on improvisation. It is closely linked to interview question 3 ("Are you often surprised by your instrument/tools?''), and particularly question 4 (''What is the motivation for employing or actively searching for unpredictable elements?'').

Coding 2 Examples:

- ''For me the holy grail is when it does unpredictable stuff that you have not made yourself''
- ''I'm trying to find some way of developing what I see as being a new idea or discover a new idea, and then unpredictability and the unexpected and investigation is then the key I think for attempting that.''
- ''For me it's about discovery. My entire process is about discovery.''
- ''It's almost a tautology to say you're looking for unpredictable things to happen when you improvise''
- ''it's interesting for me to have a system which is not entirely under my control [...] it feels more like a dialog, because you're dealing with a set of materials that will throw things back at you, and that's become quite important''
- ''I mean I don't look for something new, but I expect my system to surprise me.''
- ''Of course feedback is always unpredictable, that's what's exciting about it.''

Coding 2 Subcodes:

There are some points of overlap between the subcodes for this theme, and the subcodes for theme (1) above, as many of the data extracts pertaining to surprise also contain points about exploration, and vice versa.

1. **General attitudes towards surprise in improvisation**

   Data relating to how the participants view surprise in relation to their practice.

2. **Dialog with the instrument, relinquishing agency**

   Participant views relating to the tools and instruments producing their own results, or the responsibility for the musical results and progression being shared in some way or at least beyond the mere whim of the participant.

3. **Instability**

   Surprise in relation to unstable and chaotic tools, instruments and situations.

4. **After surprise**

   Considerations of how participants react to surprises, how things develop subsequently.

5.3.1.3 Coding 3: Practical approaches to eliciting surprises

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
3) Practical approaches to eliciting surprise I) feedback / nonlinear dynamics II) physical or mental limitations III) random processes			✓	✓	✓	✓

In contrast to code (2) which focuses on participant attitudes to surprise, this code comprises of data extracts relating to the specific mechanisms by which surprises are generated. The data extracts may relate to certain physical playing techniques, modifications to instruments and tools, or potentially or the deliberate use of chance processes or blind selection. The surprising nature of these situations may be deliberately sought, or the unpredictable nature may be incidental.

Coding 3 Examples:

- "I can actually get to a situation where I yeah, as you say use the XY thing, it allows for a lot of unpredictability, you simply cannot in any way be sure exactly what it is, even a small movement in which the granular thing is so tiny can have some seriously profound effects on the sound."

- "I've discovered this one area of overtones where they came out and really surprised me, I'd never heard anything like it."
- "Because sometimes I'll get a certain kind of split note through it, which is where almost two tones come, multiphonics, which are unexpected and uncontrollable as well"
- "the intensity of it is completely unpredictable, particularly because I've got two single pickups and then a double pickup."
- "generally becomes quite an unpredictable setup, because it's fresh, and maybe I've injected a few different things and sort of plugged it up a different way or something simple like that"

Coding 3 Subcodes:
As this code brings together a variety of mechanisms for surprise from the participants' practices, subcodes can help to differentiate particular groupings. The groupings may not be mutually exclusive, and certain mechanisms may fit multiple subcodes.

1. **Feedback / Nonlinear dynamics**

   Unpredictability connected to the nonlinear dynamical nature of the system. This could be due to electronic feedback processes or the nature of acoustic instruments such as bowed strings, reed instruments and so on (see Section 2.1.4.3).

2. **Physical or mental limitations**

   Unpredictability due to physical limits, e.g. tools, instruments or other setups that are very sensitive to minute variation, and/or players pushing at the limits of strength and endurance. The unpredictability could also be due to mental limitations, e.g. using systems that are very complicated to understand, or rendering something deliberately unknown. There may be overlap between this category and the other two subcodes.

3. **Random processes**

   Processes or approaches that incorporate actual randomness, or processes that are effectively random from the performer's perspective.

5.3.1.4 Coding 4: Attitudes to control

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
4) Attitudes to Control I) lack of control II) total control III) importance of control			✓	✓	✓	✓

This code is comprised of data extracts relating to considerations of control, whether participants felt it is an important aspect in their practice, or whether it is relinquished at certain points.

Coding 4 Examples:

- "you have to have some kind of control. But there's this line between the two I think, that is really about when music is most exciting"
- "Participant: Yeah, because you can't really control it, but you can sort of... Interviewer: Ride it? Participant: Yeah, that's it, that's exactly right."
- "I think they make a great noise, but you can be fairly sure that they couldn't do it again if you asked them to. Interviewer: So to be able to replicate it is important? Participant: Yeah completely because it means that you know what you're doing, and even if you've never done it before, but having the concentration and the intention to say, ok, this is interesting, let's stay here and reflect on this a bit."
- "you end up in that state where you can't really see what's going on, and you're trying to control it as well, but you're not necessarily controlling it but you can control it."

Coding 4 Subcodes:

1. **Situations not entirely under control**

   Data relating to situations where the participant is not in complete control.

2. **Total control**

   Attitudes towards having complete control.

3. **The importance of control**

   Attitudes towards the importance, or not, of control in the participants' practices.

5.3.1.5 Coding 5: Learning

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
5) Learning	✓	✓	✓	✓		

This code collects together participant comments relating to the role of learning and understanding in their practices. This is considered in a very broad sense and may encompass learning about the specific workings of their tools, how to deal with specific situations, other players, audiences, social situations, themselves, and so on.

Coding 5 Examples:

- "it's also how you learn, how you keep learning"
- "I think it has to do with learning. I feel like if I'm avoiding unpredictable, unstable outcomes, I'm not going to learn anything."
- "in general, of course, you explore something you try to understand something, you try to transcend something"

- "I think I am trying to make sense, I'm sort of gathering information of what that spring is doing, but I'm then trying to make a piece out of it - I am actually trying to make a piece out of it"

- "As I say I explore to learn really, and just to expand my own potentials in music"

- "Surprise is a byproduct of learning. Unexpected results are part of this."

5.3.1.6 Coding 6: Risk and Tension

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
6) Risk and Tension I) risk for the performer II) risk for the audience III) risk and unstable tools	✓		✓	✓		✓

Code (6) comprises of data extracts relating to considerations of risk and tension in improvisation. This may include risk from the performers point of view, or as perceived by the audience and other players, and may be seen in a positive, negative or neutral light.

Coding 6 Examples:

- "it might fall out underneath you but then you can get out there, and it's like how far can you pull this invisible rubber band before it snaps."

- "So I love that panic and I'd like to think that the panic adds to the creativity"

- "it's a bit like being a jockey riding a crazy horse, because the potential of it, it's a very powerful tool, so you have to be very careful"

- "they could fall at any point, because then that creates a tension"

- "putting yourself in the position of a free improviser who'll perform in front of an audience is a type of risk, one you put yourself under, which should reflect - hopefully - the type of risks that you might be prepared to take in real life."

Coding 6 Subcodes:

1. **For the performer**

   Attitudes towards risk, tension and failure from the performers perspective.

2. **For the audience**

   Risk, tension and failure as they are perceived by others (audience, other players).

3. **Risk and unstable tools or areas of tools**

   Data connecting risk and tension with unstable systems.

5.3.1.7 Coding 7: Long term engagement - changes over time

	Themes					
Codes and subcodes	**The importance of Exploration**	**Expanded ideas of exploration**	**Expanded ideas of Surprise**	**Attitudes to Control**	**Complicating the instrument**	**Risk and Tension**
7) Long term - changes over time	✓	✓	✓	✓	✓	

This code collects data extracts pertaining to the ways in which interactions with tools develop over time, and how surprise and exploration are seen over time. This may involve discussion on how a particular tool does or does not manage to remain surprising and engaging over long periods, and how participants view these changes and (potentially) adapt. The time scales may vary from day-to-day changes, to developments over years or decades. This also includes comments relating to the long-term potential of different tools.

Coding 7 Examples:

- "I've played the instrument for so long, it's harder to surprise myself."

- "the process slows down over time. Initially, when I first opened the gate on this world of potentials, everything was surprising"
- "[surprise] becomes rarer and rarer I would say, but the joy of it moves somewhere else into this forensic detail"
- "explore the sonic properties of that physical object. If you think about it like that, then there's an infinite number of possibilities for how you're going to make something"
- "there are these tiny moments where you're really, when I'm completely amazed, and I've had it for 6, 7, 8 years now, so I'm quite surprised that for what it does,"

5.3.1.8 Coding 8: Complexity

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
8) Complexity I) feedback II) complexity and surprise III) combinations / assemblages IV) complexity as a resource		✓	✓	✓	✓	✓

This code incorporates attitudes to complexity or the lack of complexity in interactions with musical tools, and how this relates to improvisation, surprise or exploration. This may include very general points, or very specific examples. Candidate examples may include existing complexity or simplicity as found in instruments, or situations that have been deliberately rendered complex or simplistic. Note that this coding is focused on complexity of interactions, rather than necessarily the complexity of the objects themselves or sounds produced, although these may often be related.

Coding 8 Examples:

- "I think with the physical instrument and the electronics, you have a number of different ways of creating instability. So on the flute specifically you have different fingerings, so you might use a broken column fingering like a multiphonic-type fingering which can produce some instability, and with the microphone that produces another level of complexity or you've got proximity to the speaker and microphone, so there are a number of combinations of factors which produce this result and that you can explore, and in doing so you're making use of a technique which is well hard-wired in your body which somehow feels satisfying for an instrumentalist."

- "it's just a quality of radio that it gets easily interfered with, and it's not just picking up the radio, it's also being influenced by the whole network of stuff. So that was important."
- "They'd be using all of it, or not all of it. So in that case, yeah, I don't see why not, because it's such a vast complex structure"
- "I can then change for example, just change frequency or one oscillator which might control another oscillator and through sub, and be controlling LFO or might be controlling something in the delay, so it has this kind of delayed influence ... delayed replies? You turn something, you're hearing, but then there is a sudden delay and something else responds to that and you're kind of holding that whatever it is."

Coding 8 Subcodes:

1. **Feedback**

   Complexity discussed in relation to feedback (whether acoustic or as part of a digital system).

2. **Complexity and Surprise**

   The role of complexity in creating surprise.

3. **Complexity through combinations/assemblages (including both simple combinations and actual interconnected parts)**

   Complexity as a result of combining multiple simple elements.

4. **Complexity as a resource**

   Complexity discussed as something that can be deliberately drawn on, or explored, or that leads to something new.

5.3.1.9 Coding 9: Physicality

	Themes					
Codes and subcodes	The importance of Exploration	Expanded ideas of exploration	Expanded ideas of Surprise	Attitudes to Control	Complicating the instrument	Risk and Tension
9) Physicality		✓	✓	✓		✓

Finally, coding 9 brings together discussions of physicality and the role of the body in interacting with the instrument as it relates to improvisation, surprise and exploration.

Coding 9 Examples:

- “I'm not sure that I could unpick those things, because it's psychosomatic, so it's extremely visceral, but it's also cerebral, so there are things that you can find that are interesting, but they're also simultaneously very physical, and as soon as you get into that repetition thing, it is physically interesting. It's really different often.”
- “I think that's a fair word to use - the topography of it - is something that — definitely more than exploring it in terms of sound — it tends to be a very physical exploration.”
- “One of the things I like about the process of performing with a physical instrument is that it engages the whole body”
- “the slight changes that occur out of the imperfections of your technique and the slurring that starts when you start doing something physically over an amount of time that becomes imperfect, and I suppose out of that you get these nice imperfections”
- “that might be as good an example of trying to push a physical action, push yourself so much that the physical action is out of your control.”

5.3.2 Themes Extracted from the Data Coding

The themes outlined below are the result of an iterated process as described in Section 5.2.2. As such they are developed both in relation to the research questions and through an inductive approach to analysing the data corpus. Each theme is described briefly and related to the concerns of this specific study as outlined at the start of this chapter. Where appropriate, case studies of individual participants have been included to help highlight how the theme is represented in the data, and how the data item can be related to the research questions. Broader discussions are reserved for Section 5.4, where links between themes are examined, and wider ramifications are considered. Although the themes are presented as discrete units, they have many points of overlap, as shown in Figure 5.2.

5.3.2.1 Theme 1: The importance of exploration in improvised performance

	Theme 1
Codes and subcodes	**The importance of Exploration**
1) Role of Exploration in participant practices	✓
2) Role of Surprise in participant practices	✓
3) Practical approaches to eliciting surprise	
4) Attitudes to Control	
5) Learning	✓
6) Risk and Tension	✓
7) Long term - changes over time	✓
8) Complexity	
9) Physicality	

The question was explicitly posed towards the start of each interview: ‘‘what role does exploration play in your practice?’’ Examining data extracts for coding (1) -- the role of exploration -- shows that the majority of participants (15 of 24) were very clear that exploration was a central element in what they do, whether practising or performing. A further four agreed in general, but had caveats about whether one could genuinely set out to explore and find new things, or that this was instead a consequence of following a different train of thought rather than a direct intention at the outset. For two participants the question did not seem to fit, or their answers didn’t provide a clear position on exploration. Finally, three participants deliberately distanced themselves and their practice from the term, all of whom detailed a more compositional approach to performance and improvisation (e.g. participant 7321 described performance as a ‘‘crystallisation of previous exploration’’).

The importance attached to exploration by the participants is not particularly surprising given the emphasis placed on *searching* by established improvisers such as Eddie Prévost and Cornelius Cardew, both of whom appear to have influenced many of the participants (see Section 2.2.3). It is useful to establish this at the outset however, as this helps to build a clearer picture of the participants' motivations, providing context for their attitudes to other elements.

Table 5.2 shows how the participants responded according to the instruments that they play. It is notable that all blown instrument players (flute, trombone, and two saxophones) are in the top category (exploration plays an important part in their performance practice), along with five out of six of the bowed instrumentalists (cello, viola, violin, two double basses). Eight out of nine (89%) of the participants who had reservations about the term 'exploration' used electronics in some way, compared to only six out of the fifteen who placed exploration at the centre of their practice (40%).

The meaning of these links between attitudes to exploration and choice of instrument are not clear however. A tempting conclusion for this research would be that there is a link between the nonlinear dynamical properties of bowed and blown instruments identified in Section 2.1.4.3 and an inherent explorability, but this is a big leap from the given data, and there are a wide range of other social and cultural factors that may contribute to this result. Similarly, the reservations for the term 'exploration' held by many participants employing electronics may stem from a variety of factors.

Two case studies are therefore presented below that examine the attitudes of participants in the more extreme groups. Firstly, participant 4821, a violinist who expressed enthusiasm for the term, and secondly, participant 5592, a composer who improvises with a wide range of objects which are sampled and manipulated digitally with a laptop, who had certain issues with the term.

Exploration is important		
Part. No.	Instruments and Tools	Category
2999	Cello	Acoustic
3284	Trombone	Acoustic
4652	Saxophone	Acoustic
4821	Violin	Acoustic
5173	Double bass	Acoustic
5559	Saxophone	Acoustic
5619	Double bass	Acoustic
7855	Viola	Acoustic
8854	Electric guitar, feedback and objects	Mixed
3598	Piano, samples, objects and pedals	Mixed
1684	Flute and electronics	Mixed
1883	Laptop, samples and objects	Mixed
8133	Digital feedback networks	Electronic
1948	Laptop and samples	Electronic
9924	Sine tones	Electronic
Exploration is important with some caveats		
Part. No.	Instruments and Tools	Category
1747	Piano and objects	Acoustic
4692	Electronics, theremin and radios	Electronic
7864	Modular synthesiser	Electronic
8745	Modular synthesiser and laptop	Electronic
The importance of exploration is unclear		
Part. No.	Instruments and Tools	Category
7474	Objects	Acoustic
8684	Objects, voice and pedals	Mixed
Distanced themselves from the term		
Part. No.	Instruments and Tools	Category
7321	Violin and laptop sampling	Mixed
2418	Wine glasses, objects and pedals	Mixed
5592	Electronic objects and laptop sampling	Electronic

Table 5.2: The importance of exploration for participants using different tools, broken into four categories

Theme 1 case study (a): participant 4821

The participant is a violinist with extensive experience of improvising solo and with others, and playing composed contemporary compositions. When questioned on the role of exploration in their practice, the participant responded:

> "I would say the beginning of my use of preparations was all based on exploration and it really informed the way that I was playing that I would be seeking or looking where the sound would take me, I was completely led by the sound. And I would also be trying to create something out of something where I had no idea what sound qualities it would yield."

The participant describes using a range of preparations with the violin — such as springs, paperclips and pegs — and using each as the basis of an investigative process: "the intention to really go into minute detail of [...] all the possibilities of that." These investigations were recorded and released as a solo album with each track being a particular investigation. Nevertheless, the participant confesses — somewhat guiltily — that despite this intention, the results of these investigations are shaped to an extent, as they are played with a compositional mindset: "I started off thinking that I'm just going to document it and see what it does, but I can't help myself from shaping what comes out."

Several other participants expressed similar ideas: the intention to be purely investigative whilst maintaining — often with some guilt attached — some overall direction and compositional structuring (e.g. participants 7855, 1747, 8854). This investigative mode of performing seems to encapsulate a pure idea of exploration-based improvisation to which many participants aspire, but often deviate from. There may be a variety of sources for this ideal, but the idea of investigation and letting the sounds lead the performer are woven throughout many strands of contemporary music, e.g. John Cage and the New York School (see Section 2.2.2), Cardew/Prévost and AMM (see Section

2.2.3).

Theme 1 case study (b): participant 5592

Participant 5592 is engaged in a range of activities, but considers themself foremost a composer, drawing this distinction keenly in relation to improvised performances as part of an established duo: "we're not real improvisers, we're two composers on stage improvising together." The participant performs with a diverse range of objects, many of which are children's toys that produce sound — often very simple sounds — recording these into a microphone connected to a laptop running MaxMSP. The software records the sound and plays it back using granular synthesis processes. These processes are sometimes controlled directly and sometimes left to their own devices. When questioned directly about the role of exploration in their improvised performance, the participant responded:

> "I've got a slight — not a problem with the word 'exploration' — and I certainly enjoy the term, particularly as a lecturer, I think trying to get people to explore things -- but then I don't know if in my own practice that would be the term I would use. I would rather use, I'm 'performing' the object, but I have explored it in practice. [...] I tend to not think of it as an exploration, and that's why I think the first thing that I always say, so as I perform with object number one, I'm already thinking about objects two and three."

The participant demonstrates an awareness of other approaches to improvising — characterised in the previous case study — that involve a more explicitly exploratory approach, and consciously differentiates their own work:

> "if there is exploration, it will be more of the type: stopping, stepping back, listening to what's already happening, to make sure that the decision

> that I've made whilst performing it was right and is it the right moment to introduce that new sound, rather than finely working with that object until I get a full image of that object''

This compositional approach outlined by participant 5592 can be related more closely to the distinction made in relation to Donald Schön's notion of reflection-in-action in Section 2.3.1: the participant is engaged in a conversation with the situation in the manner Schön elaborates upon. Sounds are created and heard, but they don't inform the specific interaction that generated the sound. The reflection is not on the interaction itself, but on the wider emerging situation. This is clearly distinct from the more in-the-moment dialog being described by participant 4821. The latter can still be considered as engaging in reflection-in-action, but this engagement is very much *in the interaction itself*. This issue is significant for this thesis, and is discussed further Sections 5.4.2 and 6.1.1.

The choice of instruments is also a notable contrast between the two case studies: the often simple objects used by participant 5592 may not permit the kind of intense investigative exploration afforded by the violin, the bow, and the simple-yet-complex additions of paperclips, springs and pegs (or at least they may not be as rewarding in this regard).

5.3.2.2 Theme 2: Expanded ideas of exploration

Continuing closely from theme 1, the range of responses to the question regarding the role of exploration in improvisation (and other questions) serves to provide an expanded idea of both exploration and surprise, and importantly, how the two relate to each other. A range of related concerns are discussed by the participants, and although there is considerable overlap, each concern may be emphasised differently. For instance, many participants declared an interest in ``finding new things'' in performance or in rehearsal, seeming to place this as an aim, or a goal to reach. Several participants questioned this as a motive however (or even the possibility of attaining such a goal), stating that it was not a goal, but a side effect or a fringe benefit of playing with a particular mindset.

	Theme 2
Codes and subcodes	**Expanded ideas of exploration**
1) Role of Exploration in participant practices	✓
2) Role of Surprise in participant practices	✓
3) Practical approaches to eliciting surprise	
4) Attitudes to Control	
5) Learning	✓
6) Risk and Tension	
7) Long term - changes over time	✓
8) Complexity	✓
9) Physicality	

A way of talking about exploration that is employed by several participants (5173, 1747, 3284, 8854) is as a "questioning." Participants 1747 and 8854 see the questioning as more of a process of investigating the objects that they are performing with, and being open to those objects leading them somewhere ("The questioning is just 'oh interesting, what is this?"' - participant 1747). This attitude appears to link closely to the importance placed on *learning* by several participants (discussed further in Section 5.4.4), and an approach to performing that focuses on the present moment (discussed further in the case study below).

It is also instructive to see how the three participants identified in the first theme — who do *not* consider exploration to be part of their performance practice — view exploration, and how they can improvise without necessarily exploring. All three take a more compositional view of their performance practice, and appear to see the performance as a negotiation through material that they have already explored elsewhere: the sonic results are already known, and all that remains is to present these results. Although there may be an exploratory aspect to the presentation of these results (e.g. structuring, timing, fitting them with other performers), it is possible that they are deliberately distancing themselves from the more specific idea of exploration described above in relation to Prévost and Cardew, with whom all three artists are familiar. These questions are explored in a specific case study of participant 8854 below.

Theme 2 case study: participant 8854

Participant 8854's views on exploration are considered here in more detail to help provide a more focused examination of the subject. This participant is a longstanding attendee at Eddie Prévost's improvisation workshop, and acknowledges the influence that this has had on their thinking and improvisatory guitar playing[a]. The participant is also a language teacher and is studying for a postgraduate qualification in linguistics, which perhaps contributes to an emphasis on linguistic comparisons throughout the interview. They acknowledge the importance of improvisation in their practice:

> "I see it as exploring, what I'm doing when I'm playing is exploring or enquiring into the nature of what I get back, the sort of response I can elicit from something, so it's exploratory in the sense that a conversation is I suppose [...] You initiate something and you get a response, you follow up on that response and you try and build — I hesitate to use the word language — but you build some sort of meaning that spreads out across this sort of constant cycle of exchange."

This back-and-forth "cycle of exchange" process came out frequently in participant interviews (see Section 5.4.2), and is closely linked to the exploratory approach to improvisation laid out by Cardew and Prévost in Section 2.2.3. Participant 8854 discussed this both in group and solo playing, pointing out that it was difficult to achieve this enquiring approach in the latter. The participant saw the extensions that they add to the guitar — such as metal objects like allen keys and spanners between the strings — as being helpful in this regard. The participant talked frequently of wanting to be in a situation where there was an "incomplete grammar," where the guitar as it stands is seen as being almost completely mapped out already:

> "I think that's where my first encounter with objects came from, the idea to create something that's incomplete, that's incomplete grammar to the guitar that's more relative to the moment and the interaction and the situation that you're in when you're playing as opposed to the pre-mapped

> out geography of the guitar, this system, this grammar, this lexicon of the guitar that we draw from and play certain styles in"

The participant also initially states "I think what interests me is the process of finding new material within the moment of doing something." As has been noted, this is a relatively common comment in this study, but the participant makes an important clarification to this a few minutes later in the interview:

> "When I feel like an improvisation is going well it's when you've established this balance between not trying to find new things, because that in itself is a meaningless activity, it's about creating a situation of openness to the potential of the things that you've got and you're working with at the time, and if you're playing with something and you're thinking, oh I've done this before and I have to change it"

The "situation of openness" is returned to again and the participant is concerned to distinguish this attitude from an approach that is concerned with finding "the new" more directly (the latter is described as "ceasing to be productive"), and uses the word "nowness" as a satisfactory replacement for "newness". A focus on being present in the moment is notable in many participant responses (e.g. 1747, 2999, 5173) from musicians engaged in Prévost's workshop, and is notably absent from the three participants who see their performance practice as less focused on exploration as discussed in theme 1 above (e.g. 5592 explicitly states that they are thinking ahead rather than thinking about the present - see case study in Section 5.3.2.1).

This more nuanced description of the relationship between exploration, finding new things, and an engagement with sound-making tools that emphasises an engagement with the emerging moment-to-moment situation is illuminating. Despite the enthusiasm for exploration, actually finding things is not, in fact, the goal; the occurrence of sounds or events that are seen as new are regarded as "fringe benefits" (this can be closely linked to participant 5173 — another longstanding attendee at Prévost's improvisation workshop — who describes new, surprising things as "byproducts" of the exploration process).

Being focused on the present state of the instrument and the present sounds that are occurring can be linked with the dialogic nature of the engagement: a question and answer approach would seem to necessitate waiting for the response and being open to it, rather than participant 5592's more compositional attitude: "essentially it's the idea of having a collection of objects and thinking 'what comes next?' So as I'm performing with one object I'm already thinking about the next rather than 'oh, what is the computer doing with it at the moment?'"

[a] the participant also cites Ben Watson's biography of Derek Bailey (Watson, 2004)

5.3.2.3 Theme 3: Expanded ideas of surprise

	Theme 3
Codes and subcodes	**Expanded ideas of Surprise**
1) Role of Exploration in participant practices	✓
2) Role of Surprise in participant practices	✓
3) Practical approaches to eliciting surprise	✓
4) Attitudes to Control	✓
5) Learning	✓
6) Risk and Tension	✓
7) Long term - changes over time	✓
8) Complexity	✓
9) Physicality	✓

As with exploration, many participants reported some enthusiasm for being surprised not only in practice or rehearsal situations, but also in performance. However, the term surprise was sometimes seen as ambiguous, and participants would generally have to unpack what it meant before agreeing that it played a part in what they do. The word 'unpredictable' often proved a better fit for situations where the participant would have a relatively clear idea of what might emerge from a particular action or process, but some aspect or small detail might not be determined. An example brought up by participants engaged with bowed interactions (e.g. 7855, 1747, 5173) shows this well: when starting to bow a string or another object, even relatively experienced participants confessed that they may not know exactly how the string will initially react, which harmonics will be prominent, how noisy or how clean the note will be, and so on. But it is perhaps too strong to term the result a surprise, despite the somewhat unpredictable outcome. Once the interaction has begun, the participants could then work with whichever specific sounds and behaviours emerged, and could begin to guide the sound in a much more focused way. This kind of interaction can be linked to other attitudes expressed by the participants, particularly a view of the interaction as a 'dialog' or 'conversation', which fits in closely with the idea of exploration as a kind of questioning as discussed above in Section 5.3.2.2.

Each participant was asked to give an example of being surprised by their tools and instruments. Most of these surprises are seen in a positive light and are situations that have been deliberately engineered as rich areas for exploration. They are shown below in Tables 5.3, 5.4 and 5.5 and are grouped into three categories: surprise as a result of the nonlinear dynamical properties of the instrument, surprise due to a lack of physical control or due to an inability to understand the complexity of a tool being used, and surprise due to actual or effectively random processes. These categories are not mutually exclusive and some examples are in more than one category. These categories have been developed from those outlined in Section 5.2 that were devised following the comparative evaluation studies, but have been adapted here to fit the specific examples provided by the participants. The categorisation is not meant to be a definitive taxonomy, but serves as a useful starting point for wider discussions on different kinds of surprise and unpredictability in musical interactions that are developed below in Section 5.4 and Chapter 6.

The categorisation is therefore intended to illuminate commonalities and contrasts between the categories. Of particular interest is how control is manifested, how there may be different attitudes to surprises that involve nonlinear dynamics compared to the other categories, and how nonlinear dynamics and physical limits are integrated in many acoustic instruments. These issues are explored below in a case study of participant 3598 who embraces a range of approaches to surprise. Different notions of surprise are discussed in more depth in Section

6.1.

Theme 3 case study: participant 3598

Participant 3598 has a long history in free improvisation and in many other musical areas. The participant is often identified as a ‘‘second generation’’ free improviser (see Piekut, 2014), active from the 1970s onwards. The participant’s improvised practice can incorporate a wide range of different tools and instruments: often the piano, but also a range of objects, toys, effect pedals, samplers, feedback, contact microphones, ukulele, and so on. The diversity of tools enabled the discussion and comparison of a range of different kinds of surprises. Some examples of surprising interactions mentioned by the participant are listed below.

1. Cheap toy insects that contain a small motor and move about by themselves: ‘‘Well the insects are obviously deliberately quite unpredictable’’

2. The sampler is a source of surprise: the participant describes having made a list of which sample is located where, subsequently losing the list, but preferring not to know which trigger is which sound. ‘‘I mean I can easily do it again obviously, but I’d sooner not know’’

3. The sampler scrub function that ‘‘isolates a very small portion of that sound and you don’t know what it’s going to be, so that’s definitely not predictable.’’

4. Feeding back a toy voice modulator: ‘‘voice changing thing which is just a toy from Toy’s ’R’ Us, but it does amazing feedback things that I never predict, it’s a bit like doing the Wolfman by Robert Ashley which I saw years ago and was really excited.’’

5. Other feedback methods, such as with contact microphones: ‘‘Of course feedback is always unpredictable, that’s what’s exciting about it.’’

6. Surprises from the idiosyncrasies of pianos in different venues. The participant

(1) Surprise through nonlinear dynamical processes	
Participant	Mechanism for surprise
1684	Adding feedback to extend the flute - adds a behaviour that develops "almost independent of your action thereafter"
1948	Cross modal feedback between a sound-making light sensor, and a light-making sound sensor
2999	Bowing the cello very close to the bridge, and playing very high harmonics across multiple strings - it "just lifts off"
4821	"Wolfe note" on the cello - a note that may or may not sound or is harder to get to sound cleanly
3284	Twisting the embouchure to produce unpredictable multiphonics on the trombone that are "unexpected and uncontrollable" and that just "come and go"
3598	Feedback with a toy voice modulator
4652	Pushing at extremes of the saxophone: exploring very loud or very quiet areas where it is difficult to control accurately.
4692	No-input feedback setup with a button that needs to be held to get the sound: muting and unmuting is part of a feedback network, so does more than merely mute and unmute a sound as the feedback takes time to develop. Finds the threshold with it where it does interesting things.
4821	Adding a spring or a paperclip between violin strings and bowing it producing unpredictable harmonics. They will also fall off the string at some unpredictable point.
5173	Bowing a double bass right on top of the bridge whilst rapidly moving a single finger which is lightly touching the string.
5559	Working with high frequency, high intensity sounds on the saxophone where the harmonics are all very close together and "fizz about". Then attempts to add other layers in, e.g. adding voice, or "bending through" the harmonics: "interferences and dynamics and distortion"
5592	Throwing two magnets in the air (separately), for the sound of them connecting in the air (or not)
7321	Deliberately using too little rosin on the violin bow to create less stable higher harmonics
7855	Uncertainty about bowing a string for the first time: can get different harmonics, a pure tone, a gravely noise
7864	Balancing a network of interlinked LFOs to create unpredictable fluctuations that are hard to control directly
8133	feedback networks where the parameters for the processes found at each node respond to the audio being generated.
8854	Electric guitar feedback.

Table 5.3: Mechanisms for surprise that involve nonlinear dynamical processes

(2) Surprise through physical and mental limitations	
Participant	Mechanism for surprise
2999	Uncertainty due to fatigue: contrasting genuinely stumbling rhythms with faked stumbling rhythms.
4652	Pushing at extremes of the saxophone: exploring very loud or very quiet areas where it is difficult to control accurately.
5559	Working with high frequency, high intensity sounds on the saxophone where the harmonics are all very close together and ‘‘fizz about’’. Then attempts to add other layers in, e.g. adding voice, or ”bending through” the harmonics: ”interferences and dynamics and distortion”.
8684	Vocal repetition of a single word or phrase until it necessarily starts to change from exhaustion.
9924	Unpredictability from the imprecision of the sine tone interface.
1948	CDJs - physical uncertainty in the movement of the CDJ turntable interface that are incredibly sensitive.
8745	Refreshing the modular setup regularly: repatching, adding new modules, removing modules and getting back to a point where the whole thing isn’t known too well - a regular cycle.
7321	Detuning the violin before performance to explore the microtonal elements - the harmony therefore can’t be easily known beforehand.
1883	Limited understanding of particular granular synthesis processes - they are not understood and may do unexpected things (e.g. combinations of grain rate, grain size, traversal rate, envelope settings and so on).
1948, 1883, 3598	Dipping into samples and not knowing what will be there.
1948	Huge amount of long samples available in performance (although they are categorised as much as possible).
8684	Dipping into records - looking for a particular loop, but with the knowledge that something completely different may come out.

Table 5.4: Mechanisms for surprise that rely on physical or mental limitations

(3) Surprise through (effectively) chance/random processes	
Participant	Mechanism for surprise
1948	Actual randomisation of sounds (Ableton Live follow actions).
1948, 4692	Radios - which are also interfered with by other devices.
1948, 1883, 3598	Dipping into samples and not knowing what will be there.
1948	Huge amount of long samples available in performance (although they are categorised as much as possible).
5592	Fizzing tablets in water: participant can never be sure how intense they will be or how long they will fizz for.
3598, 5592	Motorised objects moving by themselves.
7321	Performing with recorded excerpts of earlier work on shuffle on a CD (not done by the actual participant, despite them being sympathetic to this approach).
8684	Dipping into records - looking for a particular loop, but with the knowledge that something completely different may come out.
8745	Stochastic synthesis process (using an implementation of Xenakis' Gendyn algorithm) for fluctuating LFO signals.
4692	Overloading a drum machine arpeggiator algorithm ("if you start to press buttons too quickly it would get lost").

Table 5.5: Mechanisms for surprise that involve chance elements

describes deliberately not playing the piano much at sound check so that it can be explored during performance.

7. The participant describes Charlemagne Palestine performing his piece 'Strumming Music' that evokes all sorts of unpredictable resonances from the piano through extreme, repetitive, tremolo playing: "Extraordinary and completely unpredictable resonances. You start thinking "that sounds like a bunch of French horns, what the hell is going on? How does he do it?" I mean he doesn't do it, the piano does it."

This list of surprises provides examples of all of the categories of surprise laid out in Tables 5.3, 5.4 and 5.5: randomness or effective randomness (the sampler, the movement of the insects), mental constraints, and the complex nonlinear dynamical properties of the tools (repeatedly struck piano strings resonating, Larson feedback).

A distinction between these kinds of surprise was put to the participant: ‘‘Interviewer: there appears to be a difference in kind between the kind of surprise involved with playing samples at random, or jumping to unknown points in the sample, and the kind of surprises that you get with microphone feedback where you can push towards and through thresholds into different territory’’. The participant expressed an understanding of that distinction ‘‘Participant: Oh yeah I’m very conscious of that.’’

The feedback approach was linked to the kinds of exploration encountered by reed players such as John Butcher and Evan Parker. The participant expresses enthusiasm for ‘‘jumps in tessitura’’ in the simple reed instruments played by improviser Terry Day and in Hans Reichel’s bowed wood Daxophone instruments[a].

The participant also expressed enthusiasm at the idea of the completely random button (see Section 5.2.1) and claimed that that would be interesting to explore in performance. When asked as to the motivation for employing surprises, the participant gave the following answer:

> ‘‘It’s a bit of a cliché but I’d always say that I panic when all the equipment is working. Especially if it’s a solo and it seems to me that it’s almost like, the analogy that comes to mind is the fantastic Morecambe and Wise sketch where Eric Morecambe has an enormous ventriloquists dummy. It’s a fantastic sketch. He’s struggling with this - the whole narrative is him struggling with a ridiculously large ventriloquists dummy. So I think if nothing is going wrong with my stuff... well I panic either way actually. I’d panic if something went wrong with it, because if it’s a duo or something you can let them play a solo while you figure it out. So I love that panic and I’d like to think that the panic adds to the creativity but perhaps it takes away. Perhaps this is just total self indulgence on my part that I like putting myself in this situation where I have to rescue something from the

embers of a dead sampler."

Although the term is not employed directly, this is consistent with the dialogic approach elaborated previously: if nothing unexpected happens the performance may be felt to be a little flat (particularly if the performance is solo, just the participant and their tools). A significant part of the practice is dealing with what comes back. This particular participant appeared to acknowledge different categories of surprise, but did not seem to have a preference for any particular category. This is reflected in the vast range of different tools and instruments that the participant uses and the openness to different approaches to improvisation.

[a] A range of wooden instruments that can be bowed or struck, similar in many to ways flicking or bowing a ruler placed protruding over the edge of a table. See `http://www.oddmusic.com/gallery/om08800.html` for more information.

5.3.2.4 Theme 4: Attitudes to control

Codes and subcodes	Theme 4 Attitudes to Control
1) Role of Exploration in participant practices	✓
2) Role of Surprise in participant practices	✓
3) Practical approaches to eliciting surprise	✓
4) Attitudes to Control	✓
5) Learning	✓
6) Risk and Tension	✓
7) Long term - changes over time	✓
8) Complexity	✓
9) Physicality	✓

While some participants described deliberately finding or creating situations in which they would undermine their own control (e.g. 3598, 8133, 5173, 1684), others saw the lack of control as something to work against, endeavouring to gain more control of initially uncontrollable situations (e.g. 1747, 1883, 7864). Methods for relinquishing control are documented somewhat in the previous theme in relation to the mechanisms for surprise (see Tables 5.3, 5.4 and 5.5). Several participants provided useful analogies to describe situations between control and uncontrol that they found particularly fruitful or enjoyable:

- Participant 4692 - riding a horse: "it's a bit like being a jockey riding a crazy horse, because the potential of it, it's a very powerful tool, so you have to be very careful [...]

It's more like going into such a state and, yeah, riding the horse and going to search a place with this horse.''

- Participant 1948 - surfing: ''it's more like a feedback thing where you're surfing with it and you're playing with the edges, and it might fall out underneath you but then you can get out there [...] you have to be always moving through the piece, but your goal is to sort of try to keep it - so you're surfing, but it's shifting - you're like surfing something that's going down rapids. So it's moving, but you have to stay afloat''

- Participant 1948 - elastic band: ''it's like how far can you pull this invisible rubber band before it snaps. And you can almost feel the tension.''

- Participant 7864 - kneading dough: ''but it's like dough, when you're doing bread, so you're kneading, you kind of create some kind of conversation with the instrument, with however it's patched, and then with your body which is almost like another module, or like a complex of modules where you're kind of interacting''

- Participant 7864 - channeling water: ''it's like with [a] current of water: I kind of like controlling that current and it can spill out sometimes, and maybe if it was a current of colour it might spill onto the canvas and do something [...] I somehow feel more comfortable, or I feel better in that territory.''

- Participant 3598 - confrontation/boxing match: ''yes, what we look forward to is the - I was going to say boxing match but that's ridiculous - but certainly confrontation or a negotiation or something between you and the piano is the narrative of the piece''

- Participant 3598 - managing an oversize ventriloquists dummy (repeated from the case study in the preceding section): ''It's a bit of a cliché but I'd always say that I panic when all the equipment is working. Especially if it's a solo and it seems to me that it's almost like, the analogy that comes to mind is the fantastic Morecambe and Wise sketch where Eric Morecambe has an enormous ventriloquists dummy. It's a fantastic sketch. He's struggling with this - the whole narrative is him struggling with a ridiculously large ventriloquists dummy."

- Participants 8745 - fighting: "there's a vague internal logic to it, but you're kind of fighting it"

- Participants 5559, 4821, 7864 and 1684 - pushing:

  - "that's what I've been doing really, just playing with the saxophone set up properly, but not playing it properly, and just pushing it in different ways" (participant 5559)

  - "I think the control is as important, and the tension of it, that it might just all collapse, but you're still managing to push something through that's actually quite difficult to keep it all going." (participant 4821).

  - "I would have for example another envelope plugged into feedback. And that would be pushing into self-oscillation which could go really crazy, but you kind of try to retain it within, so it doesn't spill out of the... like if you have water so it doesn't spill outside of that scope." (participant 7864).

  - "I suppose an element of technique and a sort of challenge which becomes important where your aesthetic ideas are being disrupted but you can actually kind of, the harder you try and push for something, and then a third thing emerges, then it starts to be challenging in a sort of sense in which it follows your intention and then disrupts it and you develop a new intention and it disrupts it again and you develop these towers of intentionality." (participant 1684)

The common ground in these analogies seems to be shared agency with the tools: the performers can attempt things, shape things and influence things, but the tools can shift and slip and elude control: the horse bolts, the wave breaks, the opponent lands punches, the oversize dummy wobbles precariously, and so on.

With the latter point, whilst "pushing" might seem like a very general musical concern (e.g. artists talking about pushing boundaries, pushing themselves), the term as it is used here seems to imply that they are pushing the tools, and that this pushing may produce unexpected outcomes or reveal new territories to be explored. Pushing, in this situation, therefore seems closely related to the descriptions of riding, surfing and fighting discussed above.

Similar situations are described by other participants that rely less on the use of metaphors or similes:

- Participant 4821: "I think there is a strand running through my kind of surprise. It's not that much of a surprise. It's working with the instability, but the music doesn't completely change"

- Participant 4692: "sometimes I try other things, but I seem to come back to this because this is how it works for me, I put this on this edge and this creates a way, a road to somewhere, and then I just go to this road."

- Participant 8133: "And in the end, what's really important for me is to create that situation where you are at the edge of chaos"

- Participant 3284: "Interviewer: Because you're in a more unstable area? Participant: Because it's a more unstable area, yeah. Interviewer: But that's ok when that stuff happens, that's part of the fun of being in that area? Participant: Yeah. It may be a bit uncomfortable or a bit awkward or a bit difficult, but it's more rewarding in the end, as a player at least anyway.", "I would like to think that I'm trying to push it into areas where things are a bit unbalanced and a bit unstable."

Such descriptions flesh out the idea of a dialogic, conversational relationship with the instrument. These kinds of descriptions and analogies can be linked at many points to the nonlinear dynamical category of surprise outlined in the previous theme. Surfing, riding, fighting and pushing all seem like appropriate terms for engaging with the complexities of bow and reed dynamics, feedback, and some of the more elaborate systems created by the participants discussed in Table 5.3. By contrast, the kinds of surprises that employ random processes in Table 5.5 don't seem to fit in with this kind of language. A case study of participant 1684 is provided below who provides a useful insight into attitudes to control in relation to the nonlinear dynamical category of surprises. The list of analogies given above is returned to later as a key foundation for the discussions of unstable interactions in Sections 5.4.1 and 6.2.

Case study: participant 1684

Participant 1684 plays a wide range of different flutes, but often uses a bass flute with a small microphone inside that is used for deliberate feedback. This allows the keys of the flute to be used to vary the characteristics of the feedback. Often the end of the flute is deliberately blocked, effectively doubling the length of the bore: "it makes it slightly less controllable in some ways, but also produces some interesting things." A lack of control is cited as a productive aspect, and is again linked to a dialogic interaction with the instrument:

> "I do occasionally do solo sets but not that often and so one of the reasons why it's interesting for me to have a system which is not entirely under my control is that it feels more like a dialog, because you're dealing with a set of materials that will throw things back at you, and that has become quite important, in the way that the development of that type of performance feels good to me. In other words it's not just a monologue, there's some sort of disruption going on."

This is related to both group playing and solo playing:

> "I think any kind of surprise or any unexpected or uncontrolled input into that system of the group can be productive or unproductive, but I think I

> notice it especially when I'm doing something on my own. It certainly feels more like a conversation than a monologue''

The participant explicitly links this lack of complete control to a move away from the notion of primary creativity:

> ''I think the one aspect of the surprise thing that I haven't mentioned is that it feels slightly different because one feels as if you're not taking total responsibility for the outcome and that is interesting and productive psychologically I think because it circumvents some of these notions of primary creativity and the genius ideas and all of those things which are so present in music still I think. It takes it into the zone of emergence and dialog which I actually thing is a really fundamental reason for making any type of music, and you look at different traditions around the world, the kind of exploring together thing is often a really important motivation to make music, whereas the kind of Paganini model is a totally culturally specific thing.''

The importance of emergence is mentioned frequently throughout the interview. Interestingly, the participant sees the flute as slightly limited in relation to creating a dialogic relationship, and that the feedback system ''enables this dialogic improvising approach.'' One aspect of this noted by the participant is the site-specific nature of feedback: the system will behave differently in different spaces, so even with extensive rehearsal, the system will respond in somewhat unpredictable ways in the concert. This point was made by other participants employing feedback (5559, 1948, 8854, 8133, 8684), and by others who saw the variability in acoustics as a resource for exploration (2999, 7474, 7855, 9924). The only participant who saw the variability in acoustics as a problem was participant 2418 who described undesirable feedback as being a problem in certain spaces, and expressed the desire to bring this under closer control. Notably, this was one of the participants identified in theme (1) as distancing themselves from exploration in their performance practice.

Participant 1684 gives a useful account of controlling feedback in a dialogic manner:

> "So when something starts to develop then you might follow it for a while or keep it stable for a bit, and it feels a bit like, it's got an element of just ... balance about it, and there's always a question of "what if I do this, what if I do that?" So that exploratory component drives the next thing that you do."

This account fits closely the approach to exploration described by participant 4821 in Section 5.3.2.1 given above, and neatly outlines the question-answer approach described by others. The participant also highlights a dimension that is underrepresented in the present study: the importance of the cultural history of the instrument, and how this influences approaches to playing. As well as helping to setup a dialogic relationship with the instrument, the inclusion of the electronics is also "part of an exploration to denature the history of 19th century classical flute tradition that I grew up with." This places the performer into another kind of dialog with the history and traditions of the instrument. This comes out in other interviews with participants performing with instruments with long histories (5559, 2999, 3284, 1747 and particularly 5619 and 7855); this kind of a dialog is seen as almost unavoidable. This point is difficult to connect with the research questions posed in this thesis and is somewhat beyond the present scope, but it remains a very influential factor in how many of the participants think about their engagement with their instruments.[a]

[a]See Haworth (2015) for a useful account of the impact of the cultural weight of different musical software and how a musician's choice of tool deliberately engages particular histories.

5.3.2.5 Theme 5: Deliberate Complication

	Theme 5
Codes and subcodes	**Complicating the instrument**
1) Role of Exploration in participant practices	✓
2) Role of Surprise in participant practices	✓
3) Practical approaches to eliciting surprise	✓
4) Attitudes to Control	✓
5) Learning	
6) Risk and Tension	
7) Long term - changes over time	✓
8) Complexity	✓
9) Physicality	

The case studies presented above in Section 5.3.2.4 in relation to control (participant 1684) and in Section 5.3.2.1 in relation to exploration (participant 4821) also demonstrate a tendency found in many of the participants: rendering a situation more complex through additions or modifications. Participant 1684 did this by adding a microphone to a bass flute to mix feedback tones with the sound of the flute. The result was a complex interrelation of the two: changes to the flute altered the nature of the feedback, and changes in the feedback influenced the behaviour of the flute:

> "I think with the physical instrument and the electronics, you have a number of different ways of creating instability. So on the flute specifically you have different fingerings, so you might use a broken column fingering like a multiphonic-type fingering which can produce some instability, and with the microphone that produces another level of complexity or you've got proximity to the speaker and microphone, so there are a number of combinations of factors which produce this result and that you can explore [...]"

Participant 4821 incorporated preparations such as springs onto the violin strings, adding an extra resonating body to the acoustic system creating complicated interactions between the spring resonances, the string resonances and the behaviour of the bow. Both cases seem to be an attempt to complicate situations that have become too understandable, predictable, or otherwise limited, allowing them to be explored afresh. Many more examples can be found in the participant interviews. Brief summaries of some of these are provided below.

1. Participant 5559 adds feedback to the saxophone with a microphone: "so then it's also acoustic sound, amplified acoustic sound and feedback and sometimes there's [...] this

kind of unstable fulcrum or nexus between those things. Then you start to get some quite interesting and weird stuff."

2. Participant 7864 describes setting up a modular synthesiser in complicated ways so that the results of a single action may have complex, unpredictable results: "so there's for me an ideal situation that I can be there, create these pulses, this pulsating, I can then change for example, just change frequency or one oscillator which might control another oscillator and through sub, and be controlling LFO or might be controlling something in the delay, so it has this kind of delayed influence ... delayed replies? You turn something, you're hearing, but then there is a sudden delay and something else responds to that and you're kind of holding that whatever it is [...] I don't want to predict those repercussions. But somehow I like to predict, the terrain, yeah."

3. Participant 1948 describes the radios being interesting tools to explore because they are influenced by the other electronic tools used by the participants: "it gets easily interfered with, and it's not just picking up the radio, it's also being influenced by the whole network of stuff. So that was important."

4. Participant 1948 also describes creating interrelated networks of objects that mutually influence each other, leading to complicated chains of causes and effects.

5. Participant 1747 describes improvising with the keys of a piano as being harmonically very rich and complex: "what I enjoy the most is when it becomes too complex for me to even anticipate. This is when my ear is delighted."

6. Participant 5619 describes adding a second bridge to the double bass: "It's just a way of opening up a new area. It's like prepared piano. Expanding the potential of the instrument."

7. Participant 8813 describes the creation of complex digital feedback networks with a range of different effects present at each network node.

Some of the participants also acknowledge the complexity of their existing instruments as a resource, such as participant 7321's violin:

> "The violin is capable of producing a massive range of long uninterrupted sounds, very percussive sounds, it has an extremely rich harmonic sounds [and this] lays in the fact that there's a depth of information that comes out of every corner of that instrument, any instrument really that has materials like metal, resonating bodies that are connected with various mechanisms, a violin is a very very advanced music technology."

Or participant 5559's saxophone:

> "Well, it's an endless, open, complex system, and it's something that I spend a huge amount of my time doing, and it connects with a whole set of memory and potential that I'm interested in"
> (again, as discussed in the preceding section, the cultural and historical aspects of the instrument play an important role in the participant's approach, and in this case, the personal relationship with the instrument is also embedded deeply in the complexity of the interaction).

A counter example is provided to an extent by participant 3284 who describes being attracted to the trombone as a child because "Every other instrument was a bit more complicated and that just looked dead simple so I thought "that's the one for me"." The participant still maintained the view that it was essentially a very simple instrument, and quite limited: "it's basically a single tube and you just play simple harmonics based in that single tube and then you make the tube longer or shorter to change the tones" [1]. The participant also describes feeling locked off from the physical processes that generate the sound, comparing

[1] This idea of simplicity seems to relate more to the construction rather than the interaction, similar to the distinction made in Chapter 1: acoustic instruments are very simple in some senses, but are rarely simple in terms of the relation between input action and output sound. See for Harrison et al. (2015) for an overview of the complexity of the trombone.

the relatively inaccessible air column inside the trombone with a string on a violin or piano that is available to tamper with. The participant nevertheless describes approaches that produce complexity and allow for exploration, through a twisting of the mouth on the mouthpiece: "sometimes I'll get a certain kind of split note through it, which is where almost two tones come, multiphonics, which are unexpected and uncontrollable." The participant also expresses concern about the instrument becoming too known and predictable: "So yeah, it is a fine thing and things can change and become unexpected. And perhaps my worry is that I get too used to all those fine adjustments and everything becomes routine. And I know what happens if I move the mouthpiece by exactly this amount."

The example of complexity highlighted by participant 1747 in the list above is different in kind from the others in that it highlights a complexity that is not in the interaction, but is instead in the results. The piano keys as a percussion instrument can be seen as relatively simple (notwithstanding the subtle complexities discussed by participant 3598 in relation to Charlemagne Palestine's approach to the piano in Section 5.3.2.3), but the resulting harmonies can be immensely complex, meaning that although the interaction was known — certain keys were depressed deliberately — the way the various tones and overtones combine can still be surprising. In playing two notes, A and B, both individual notes are present, but there is also A+B which is a third element that may not be known or possible to intuit in advance despite A and B being known interactions individually. This is different from how two inputs may combine in an instrument such as a clarinet, for example, holding a certain fingering on a clarinet (action A) and playing with a certain embouchure (action B) may combine in a way that produces something very different from the results of the actions separately. Although the distinction may not be so clear cut in all cases (even in the piano example, the resonances of the separate strings may be mutually influential to some degree), the theoretical distinction between combinatorial unpredictability and the more holistic, interactional complexity found in nonlinear dynamical processes is important in tracing more nuanced understandings of surprise in interaction. This distinction is returned to in Section 6.1.1.

In general however there appear to be many links between the complexity of musical tools and instruments, and surprise and exploration in improvisation. In terms of the categories of surprise laid out in Tables 5.3, 5.4 and 5.5, the list above can be linked to both an inability to completely know the results of an action due to the complexity of the situation being engaged with, and the complexities of the nonlinear dynamical behaviours of the instruments. Some participants approach this through additions to the instrument, some through networks of objects or instruments, some through exploring complex areas of existing instruments.

5.3.2.6 Theme 6: Risk, Tension and Failure

	Theme 6
Codes and subcodes	**Risk and Tension**
1) Role of Exploration in participant practices	✓
2) Role of Surprise in participant practices	✓
3) Practical approaches to eliciting surprise	✓
4) Attitudes to Control	✓
5) Learning	
6) Risk and Tension	✓
7) Long term - changes over time	
8) Complexity	✓
9) Physicality	✓

Despite not being explicitly asked about in the interview questions, risk, tension and failure were frequently brought up by participants in conjunction with attitudes to surprise and exploration. A link between unpredictable interactions and risk/tension seems likely, as the latter seem to imply some element of uncertainty. The language used to describe such elements is important, as to term the situation 'risky' or 'tense' implies that there are undesirable outcomes that are being narrowly avoided. This contrasts somewhat with the openness to possibilities described by many participants.

Several situations described in the previous themes have already alluded to risk, tension and potential for failure as a positive aspect in improvised performance. Participant 4821's addition of springs and other objects to their violin strings creates an unpredictable situation where at some point the instrumental setup will fall apart:

> "that sort of has interested me as well, just the unpredictability of them, that they could fall at any point, because then that creates a tension, and also it's not predictable where the sound is going to go, not even to me, I can't plan it.

> [...] I think the control is as important, and the tension of it, that it might just all collapse, but you're still managing to push something through that's actually quite difficult to keep it all going."

Participant 3598's account of both panicking if something goes wrong and panicking if nothing is going wrong is also relevant. The comments from the two participants suggest both an acceptance of failure, and an enjoyment in courting it. The spring inevitably does fall off the string, and although the exact timing of the event is an uncertainty, the outcome is not. Other participants also presented this potential for failure in a positive light:

- Participant 1883: "I want to be getting some pleasure out of this improvisation, even if it's quite risky, I just find that much more interesting, and much more worthwhile doing."
- Participant 7321: "putting yourself in the position of a free improviser who'll perform in front of an audience is a type of risk, one you put yourself under, which should reflect - hopefully - the type of risks that you might be prepared to take in real life."
- Participant 7864: "It's funny, but in those very far territories you then kind of patch something and you get completely unpredictable results, especially through this [...] sub-oscillator where you're taking out those sub-oscillators, you get really interesting results which kind of surprised me, it's risky, it's a complete instrument, you can't remove modules."
- 8684: "It is more something about, they were written in an unstable environment, and again, not to do with purism that I want to replicate them, but there was a sense of intimacy and intensity that was captured in that uncertain environment that would feel wrong to just have on a sampler live. I don't think I could recapture the intensity of the performance if I had it on a sampler, if I had it on a sampled loop as opposed to a live loop"

These four participants — along with participant 3598 — all employ electronic tools, and as alluded to by participant 8684, could all achieve similar sonic results with much simpler means. However, they all seem to enjoy adding an element of risk or difficulty into their performance. Although participant 8684 feels that using a sampler would make things less "intimate and intense," participants 1883, 3598 and 7321 all employ samples in a somewhat risky way: either by triggering samples without knowing exactly which sound will be triggered, or without knowing exactly what sound is where within a sample.

Discussions of risk and tension are blended with broader discussions of unpredictability in the following sections, particularly in Section 5.4.1.

5.3.2.7 Themes and codes beyond the scope of this study

As has already been noted, there are a wide range of topics that came up during the participant interviews that are being bracketed out of the discussions in this thesis. Issues such as the wider social, cultural and political aspects are out of scope for the sections that follow. The focus is primarily on the performer and their tools, however partial this view might be. Considerations of the audience and interactions with other improvisers are therefore also put to one side for the purposes of this analysis.

5.4 Discussion

The thematic analysis conducted in the previous section is examined here and linked to the study-specific research questions outlined in Section 5.1. Three broader issues are reserved for Chapter 6: wider reflection on the implications for HCI, relationships with the literature discussed in Chapter 2, and triangulation with the comparative studies discussed in Chapter 4. The subsections below explore characterisations of surprise and exploration that emerge from the thematic analysis, making links between ideas of surprise and exploration, and the nature of the tools being considered. Section 5.4.1 discusses *edge-like* interactions that deliberately explore unstable areas of the instrument. Section 5.4.2 looks further at the idea of a *dialog* between the participant and their musical tools. Section 5.4.3 distinguishes between participants using ‘‘essentially nonlinear’’ instruments and participants using ‘‘incidentally nonlinear’’ instruments, examining how this is linked to attitudes to exploration. Finally, in Section 5.4.4, the role of *learning* is considered, in relation to instrumental interactions in free improvisation. The role of nonlinear dynamics is considered in relation to the characterisations traced in all four sections.

5.4.1 ‘Edge-like’ interactions

Section 5.3.2.4 highlighted a particular set of attitudes to control that are brought together here under the title ‘‘edge-like interactions’’. This was a relatively consistent motif across the data set, and was often evoked through a range of metaphors and analogies such as surfing, riding a wild horse, stretching an elastic band, fighting, kneading, pushing, and so on. Participants expressed a keen interest in driving their tools and instruments to states where control was still possible, but where the tools exhibit a range of semi-unpredictable and possibly emergent behaviours, and have the potential for relatively abrupt changes or even failure. The topic also connects several of the main themes from the previous section: specific attitudes to exploration and surprise, a specific view of control, and incorporation of elements of risk and tension. The participants provide a range of motivations for working in such states:

- finding new sounds, behaviours, and territory for exploration,
- establishing a dialog with the tool,
- learning (discussed further in Section 5.4.4),
- reducing their own agency,
- tension and risk.

To develop a clearer picture of edge-like interactions, a case study is presented below of participant 4692, the participant who made articulate comparisons with riding a wild horse, and who, from the start of the interview, invoked the term 'the edge' to describe their approach. The participant describes the links between this kind of tool interaction and their own creative process. Although the participant is keen to stress that others may not work in the same way, the process appears to be a good fit for many of the other descriptions of participants finding a balance point between control and unpredictability. This mode of interaction seems highly significant for this thesis and is therefore also discussed in more general terms in Section 6.2 in relation to nonlinear dynamical processes and existing HCI theories.

Edge-like interaction case study: participant 4692

Participant 4692 has used a variety of tools, primarily electronic, including no-input mixer (feeding a mixing desk back on itself[a]), Theremin, radios, dictaphones, Vermona synthesiser, Sherman filters, and other assorted objects. The participant's attitudes to surprise and exploration fit the characterisations laid out in Sections 5.3.2.2 and 5.3.2.3: the participant has an ambiguous relationship with the idea of exploration as "finding new things," initially saying that finding new things is the point of being on the edge, but immediately adding the caveat that this might be misconstrued, and that "it's not about just, ok, I want to explore and get new things." The participant describes an openness to events that has much in common with the case study presented in section 5.3.2.3 where participant 8854 talks about of finding new things as a ‘‘fringe benefit’’ of the exploration process. Similarly, the word ‘surprise’ is seen as problematic, and not a good fit for the kinds of unpredictabilities the participant is interested in.

The ‘edge’ is discussed in a range of contexts, but often in the context of feedback:

> ‘‘I would go to this border of feedback — I use it until now generally — so you put everything on the edge, and this is where things start to happen, and this is where pleasant surprises start to happen’’

The participant states that ‘‘the edge is not a goal, it’s a method,’’ but makes it clear that this method is very important to his practice:

> Participant: Yes, after all it all comes to why I’m doing this and why I’m doing art. [...] Ok, so I want to create this artefact, this something, this is an interaction with something, this is about understanding something, this is about creating something new or remembering something, or I don’t know what is it, but this is something, and I find the best way to do it for myself is to find this threshold. That’s the reason. It’s very practical in a way. You try different reasons, and you see, OK, when you’re here in this mood, this is how you do it.
>
> Interviewer: So you’re saying this is how it seems to work for you for creating things?
>
> Participant: For me, exactly. So I know there are some people who use completely different things to create it, and that’s great and I’m very happy consuming it and listening to it, or reading it, or watching it, but this seems how it works for me. At least it has worked until now. I wouldn’t have at

> all a problem abandoning it if I found a better way, so for me it's not a goal at all.

'Edges' - or sometimes 'thresholds' - are presented very much as resources, as ways of developing work, of finding inspiration.

> "So then it's a [...] bit like being a jockey riding a crazy horse, because the potential of it, it's a very powerful tool, so you have to be very careful [...] It's more like going into such a state and, yeah, riding the horse and going to search a place with this horse"

> "sometimes I try other things, but I seem to come back to this because this is how it works for me, I put this on this edge and this creates a way, a road to somewhere, and then I just go to this road."

The participant provides a useful contrast for their approach, describing a book written by Marco Polo[b] that details each place he visited and what he saw. Despite the participant describing the book as interesting and beautifully written, he found that the endless variety became dull:

> "this variety is actually — well for me at least — it's a bit boring. For me at this point, it's much more rewarding to concentrate on one thing, and to deliberately not move, to go deep."

This relates closely to the distinction drawn in relation to the studies in Chapter 4, distinguishing between broad and deep exploration. The edge-like interaction appears to provide a method for deep exploration. This is returned to in Section 6.1.3.

[a]see Mudd et al. (2014) and Sanfilippo and Valle (2012) for more on this

[b]This is most likely a modern version of 'The Travels of Marco Polo'.

5.4.2 Conversations with the instrument

A second area that emerged across multiple themes — and that has links to the idea of the edge outlined above — is the notion of being engaged in a dialog with the instrument. Talking about the instrumental interaction in this way was surprisingly common, and was specified as a subcode of codes 1 and 2 on participant views of exploration and surprise (see Sections 5.3.2.1 and 5.3.2.2).

Dialogic interactions were seen by a several participants as being particularly helpful in conjunction with solo playing: they wanted to get something back, some outside influence to respond to, helping to develop something in a performance, recording or rehearsal (participants 1684, 8854, 1747, 1883, 3598, 4821, 9924, 8133, 7855, 7321, 8745). Participant 1684 felt that by adding feedback to the flute (see case study in section 5.3.2.4) the dialogic situation that emerged was akin to performing with another performer: "is similar to the desire to work in community with other people in order to develop sound."

This model of interaction with the instrument was traced in the literature review, particularly in conjunction with material-oriented interactions (Section 2.2.1). Viewing the tool as active rather than passive, and a creative mediation rather than an ideally transparent medium affords a different relationship, particularly in relation to the subtleties and idiosyncrasies of a particular tool. The idea of an instrumental engagement as a dialog, a conversation, as question-and-answer links closely to the analogies used in the previous discussion of edges: surfing, riding, fighting, etc. The edges are areas where the tool may be unstable enough to produce results that cannot easily be completely predetermined and can therefore generates questions and answers and a dialog rather than a monologue.

The term 'conversation' also invites comparisons with Donald Schön's concept of reflection-in-action traced in Section 2.3.1, which he often characterises as a "reflective conversation with the situation" (Schön, 1983). Reflection-in-action also prizes an openness to unexpected results, and to the "backtalk" from an emerging situation (Bennett, 1996). This concept is helpful here in finding a dividing line between the idea of surprise and exploration in relation to an emerging situation, and in relation to the specifics of an instrumental engagement. Schön's examples of the term are broad and numerous, ranging from pencil sketches made by architects (Schön, 1983), to design software (Bennett, 1996), to simple musical tasks with bells (Bamberger and Schön, 1983). As was discussed in Section 2.3.1, in these interactions, the instantaneous action of the user produces a known and expected outcome when considered in isolation (e.g. the specific pencil mark, the compute input, the sound of each bell in the musical task). The surprise and hence the reflective engagement arises instead through observations of how actions relate to previous actions and to the environment in which they are placed. This attitude can be traced clearly in the approach taken by two of the participants in the present ethnographically-informed study: 7321 and 5592. Notably, these are two of the three participants identified in Section 5.3.2.1 as having a stronger compositional focus, and deliberately distancing themselves from the particular mode of exploration attributed to many of the other participants. As noted in the case study for participant 5592, there is always a focus on the next thing rather than the present thing, and the surprise — and indeed the interest — is generally found in how different elements combine and relate to each other. Participant 7321's ideas and approach are presented below as a short case study, as they outline this distinction very clearly.

Mechanical surprise vs Compositional surprise: participant 7321 case study

Participant 7321 is a multi-instrumentalist and has a long background in both composition and improvisation "from a more classical side." In improvisation, the participant has used a range of tools, particularly the violin and the drum kit (often electronic). Both are played in conjunction with digital systems that are used to trigger excerpts of recordings of previously improvised material. The selection of these short phrases is often unpredictable, due to a link between the velocity of the trigger and the position that the snippet starts from in the larger audio recording. For example, in the case of the electric drum kit, hitting harder might trigger the playback of a section towards the end of a recording, while a gentle hit might trigger something towards the start of a recording. The difficulty of maintaining a consistent trigger velocity coupled with the fact that the recordings can be several minutes long and filled with very varied material makes the whole system quite unpredictable to play.

When asked about the role of exploration in their performance, the participant described improvised performance as a ‘‘crystalisation of prior exploration’’, rather than a new exploration in the moment. When asked about the role of surprise in his performance, the participant makes a distinction between two kinds of surprise: **mechanical** surprises and **compositional** surprises. The first is linked to the material aspects of the interaction, both in the system described above and in acoustic systems like a bowed violin:

> ‘‘It depends on how you're working with sound, and how you setup your tools to perform. I think for example this electronics system, this system whereby I trigger things has a lack of accuracy which surprises me, so I think you learn it gradually, but you always are surprised, I think you get surprised by [...] even the most perfect Stradivarius will give you a surprising tone at some point. So you do get surprise by that, but this is a mechanical kind of surprise, this is ‘‘oh my god, I can't believe my bow can produce that sound’’ it's this kind of surprise that has got to do with the fact that you haven't been playing your instrument for 200 years, you've been playing it for ten or fifteen years.’’

The second is characterised by combining things that are known individually, that produce surprising situations when presented together:

> ‘‘The other surprises are more comparable to composition, because you can be surprised by composition. [...] you could say [...] ‘‘I want to create

> this type of density by making the lower two, the cello and the viola in the string quartet play these ricochets, nine in the time of seven, and then the guys at the top are going to be doing things with glissandos,with a transition which is tremolando to normale, and all that's going to move from ponticello to sul tasto, so you can have a textural change" you can imagine all that, but I'm sure that [the composer will] have still heard parts of his string quartet number 2 and thought "that was pretty cool""
>
> "the material is such you kind of know what possible [...] will sound like, but you can't know what it sound like exactly."
>
> "I think the same thing applies with improvisation too. So I think what we were saying that you've got the mechanical unpredictability, but you have structural unpredictability and textual unpredictability, and that is something that surprises you and you might want to repeat it or change it [...]"

Whilst being enthusiastic about surprise in performance and his musical practices generally - particularly in relation to risk and tension - the participant didn't appear to prioritise any particular kind of surprise over any other. Randomness was also embraced with enthusiasm and related to the I Ching[a], to the use of simple iTunes shuffle functions on large sets of short sounds by the composer Richard Barrett, and was described in the participant's own work through the use of simple randomisation of duration and velocity in an arpeggiator function applied to the triggering of the processes described above.

[a]The Chinese book of changes, frequently used by John Cage and other composers in implementing chance processes.

The distinction made in the above case study between *mechanical* surprises and *compositional* surprises fits closely the distinction made between a reflection-in-action model of surprise and surprises that are embedded in the interaction itself. The compositional kind of surprise seems very close to Schön's descriptions of the emergent situation producing unexpected results that can help you to reflect back on and refine the processes that brought them about. The mechanical conception of surprise appears distinct however: the surprise is in the interaction itself, with actions producing instantly unexpected results. This distinction is developed further in Section 6.1.1.

5.4.3 Different attitudes to exploration for players of different instruments

In theme 1 (Section 5.3.2.1) it was noted that there may be relationships between the nature of the instrument a particular participant uses and their specific conception of exploration, and the role that this exploration plays in their musical practice. This is a potentially slippery topic, and the sample size in this study is too small to make any solid judgements. However, the trends in this study suggest that it may be a productive approach for further study. Where a musician has focused their practice around a single instrument, it seems possible that their understanding of musical creativity is led to some degree by the nature of that instrument. Table 5.2 presented four categories for attitudes to exploration, in terms of how important this was seen to be in the participants' musical performances. Section 5.3.2.1 highlighted the fact that there is a tendency for players of acoustic instruments to place a strong focus on exploration in their practice. This result is even more marked when the distinction made by Fletcher (1999) between ‘‘essentially nonlinear'' instruments and ‘‘incidentally nonlinear'' instruments is reintroduced (see Section 2.1.4.3). All the participants that exclusively used acoustic instruments capable of producing a continuous tone — and therefore in Fletcher's ‘‘essentially nonlinear'' category — stressed the importance of exploration in their performance practice. Participants playing bowed instruments such as the cello, violin, viola and double bass, and blown instruments such as the trombone and the saxophone were all in this category, with the single exception of participant 7321 who uses the violin in conjunction with a laptop, and frequently performs with an electronic drum kit rather than the violin.

The essentially nonlinear nature of these acoustic instruments may therefore be embedded in the understanding of performing music for certain musicians, particularly in an area such as free improvisation where the nonlinear elements appear to be particularly prominent. It is also possible that musicians with this perspective on musical exploration are drawn to essentially nonlinear instruments, although given that musicians often take up instruments at a relatively young age, this seems less likely.

As noted above however, these questions would require further investigation to reach any solid conclusions connecting musical attitudes to specific musical tools.

5.4.4 The role of Learning

The role of *learning* in participant practices and attitudes to interaction with their instruments was not explicitly asked about, and the majority of participants did not mention it, but seven participants (2999, 4692, 4821, 5173, 5559, 7855, 9924) were keen to stress the intrinsic link between learning and their improvisatory practice. The question of learning was often provoked by questions about the role of surprise and exploration in their practices. Participant 5559 preferred to frame their musical practice primarily as a learning process:

> Participant: I've talked about learning too quite a lot as a way of thinking about what I'm doing. I mean I'd rather talk about that than improvisation. I'd rather use that word than improvisation.
> Interviewer: So that's quite fundamental, the learning aspect?
> Participant: Yeah, because that's what I'm interested in, learning about the saxophone, learning about me, about what can work and what can't work.

Participants 2999, 5173, 7855 and 9924 all link surprise with learning. Participant 5173 echoes participant 8854 in describing surprise as a by-product of learning (participant 8854 describes the discovery of new sounds and behaviours as by-products of exploration, see the case study in Section 5.3.2.2). Exploration is seen as "a self development, and a learning [...] and to keep this sort of open-ended thing that can never quite be pinned down as to what is actually going on."

The latter point about being embedded in a situation which is not entirely understood is particularly interesting to consider in the wider context of instrumental engagement and interaction design. It is similar in many respects to situations described above in Sections 5.4.1 and 5.4.2 where a lack of control is desirable and productive. Not having a complete understanding of a situation can presumably contribute to this lack of control, but there are important distinctions between a lack of control and a lack of understanding. A lack of control may come about in a situation that is completely comprehensible, as can be seen in some of the approaches to surprise detailed in Tables 5.3, 5.4 and 5.5 (e.g. using random functions, dipping into large samples or records, hitting physical limitations). Encountering surprises that suggest unknown or incomprehensible aspects can therefore be thought of as a particular subcategory of surprises. These may be particularly productive in opening up new territory for exploration, raising new questions for investigation, and provoking creative curiosity.

Two further aspects of this perspective on the triangulation of surprise, exploration and learning are considered here: the relation to Schön's reflection-in-action, and links with the concept of *flow* as articulated by Csikszentmihályi (1990). In certain respects, this model of surprise in relation to learning is a close fit with Schön's position on the role of surprise in professional practice (Schön, 1983, p. 153–155). Productive surprises that initially hinder practitioners are helpful in gaining a broader understanding of a problem. However, the attitude to learning articulated by these participants does not appear to view the learning as a means to an end, and is not a way of developing towards any specific end, but is an end in itself. In Schön's descriptions of practitioners, surprises occur and are reflected upon, leading to new perspectives on a given problem, and therefore allowing them to be more effective at this activity, whether this is psychiatry, architecture, composition, or design. The subgroup of participants listed above talk about the process of learning through unpredictable situations as being desirable in itself: being in a situation that in some respects cannot be fathomed. Participant 2999 puts this across particularly clearly:

> "I find it very beautiful that there are things that we can't understand and we never understand, and I think it's important for us that there are these things [where] we don't know what's going to happen. I think we'd be extinct as a human race if we understood everything, so for me it's something to cherish, to open up open-ended processes. Not in a random way, just open them up and follow them and try to stay connected."

This focus on the experience, and of being in a situation that is uncertain and challenging can be related to an extent to the concept of 'flow' as outlined by Csikszentmihályi (1990). Csikszentmihályi describes an "optimal experience" state where the challenge is well matched to the skill level of the subject, navigating a channel between boredom on the one hand and anxiety on the other (Csikszentmihályi, 1990, p. 74). Flow has frequently been discussed in the context of musical interactions (O'Neill, 1999; Parncutt and McPherson, 2002), and particularly linked to improvisatory musical performance (Kenny and Gellrich, 2002, p. 119–120; Caines and Heble, 2015).

Similarities can be drawn between aspects of flow and some of the above discussions. Csikszentmihályi highlights the importance of surprise in flow and the creative process more broadly (Csikszentmihályi, 2013, p. 347), the importance of complexity (ibid. p. 350 and Csikszentmihályi, 1990, p. 52), nuanced ideas of control in creative situations ("what people enjoy is not the sense of being in control, but the sense of exercising control in difficult situations." ibid. p. 59), and that this activity is intrinsically rewarding (Leman, 2008, p. 107).

There may be limitations with this comparison however. Participant 5559 explicitly distances their practice from Csikszentmihályi's concept of flow. These ideas are not clearly articulated in the interview, but the participant suggests that there is an idea of momentum inherent in flow (“the flow thing has this idea of narrative or linearity”), of being caught up in some sort of linear motion (“I don’t want it just to be this endless sort of ... line”). This notion can be found to an extent in Csikzsentmihályi’s descriptions of flow, e.g. “enjoyment is characterised by forward motion” (Csikszentmihályi, 1990, p 46), or “in flow there is no need to reflect, because the action carries us forward as if by magic.” (ibid. p. 54). It may be that this distinction helps to articulate a difference in instrumental interaction between the kinds of musical terrain considered by Csikszentmihályi — particularly via his study of jazz pianist Oscar Peterson (Csikszentmihályi, 2013) — and the less idiomatic approach generally taken in free improvisation. That is, that being caught up in the momentum of musical performance may not apply so readily, or may lack the same connotations in free improvisation as it does elsewhere.

5.4.5 ethnographically-informed study summary

The study presented in this section has provided a range of useful perspectives and distinctions on the nature of surprise and exploration in relation to interactions with instruments. Section 5.4.1 examined the frequent focus on edge-like interactions that was found to be common among many of the participants, where unstable or uncontrollable regions of the instrument were deliberately sought as resources for exploration. Section 5.4.2 discussed the common attitude that *dialogic* tool engagements were often sought out, where the instrument has some agency of its own, and the musical process is a back-and-forth between performer and instrument. Distinctions were made between surprises that arise in considering an “emerging situation” (as described by Donald Schön) on the one hand, and on the other, surprises that appear instantly in the interaction itself. Section 5.4.3 highlighted distinctions between participants using instruments that are *essentially* nonlinear and instruments that are merely *incidentally* nonlinear, with the former seeming to place a greater emphasis on exploration in their musical practice. Finally, in Section 5.4.4, participant attidudes to *learning* were considered, focusing on a subgroup of the participants who placed learning at the absolute centre of their practice. Further connections and distinctions were drawn between these attitudes and both Schön's reflection-in-action, and Csikszentmihályi's notion of flow.

The role of nonlinear dynamics was considered in relation to these distinctions, connecting with mechanisms for achieving unstable, edge-like interactions, supporting dialogic interactions where surprises may occur in the interaction itself, supporting (or possibly being supported by) exploration in free improvised musical practices, and helping to create interactions that cannot be easily understood but helping to provoke fascination and further exploration.

The following chapter brings the findings of this study together with the comparative studies presented in Chapter 4, developing these perspectives on surprise, exploration and nonlinear dynamics in musical interactions more broadly, and considering wider implications for creative HCI and interaction design.

Chapter 6

Discussion

Chapters 4 and 5 presented two approaches to investigating nonlinear dynamics in musical interactions, and to unpicking wider questions around surprise, control and exploration in these interactions. The virtue of the mixed methods approach taken is that the largely quantitative, lab-based studies and the more qualitative interview-based study can be triangulated allowing for a more nuanced view of the subject matter. This triangulation is performed in the present chapter, which brings together the study-specific discussions from Sections 4.5 and 5.4. Confluences and divergences are examined, and related to established ideas on musical interaction and HCI outlined in the literature review.

The comparative evaluation studies presented in Chapter 4 provide a very specific example of nonlinear dynamics being linked to the potential for long term exploration and discovery in musical interfaces. The ethnographically-informed study examined nonlinear dynamical processes more broadly as they manifest in a specific area of musical practice: free improvisation. The quantitative results from the former demonstrated concrete links between the inclusion of nonlinear dynamical processes in digital musical interfaces, and both an increased sense of the possibility of exploration and discovery, and an increased sense of surprise. Furthermore, it showed that there was no significant perceived loss in a sense of control, or in the scope for repeating particular events when these processes were included.

The ethnographic informed study helped provide some context for these results, enabling a more nuanced view of how surprise and exploration may be understood by musicians involved in a specific practice, providing specific examples of surprise and exploration in relation to nonlinear dynamical processes.

Participants engaged in free improvisation provided clear examples of nonlinear dynamical processes being drawn on as resources for creative engagement (see Sections 5.3.2.3 and 5.3.2.4). A mode of interaction that seemed to draw specifically (although not exclusively) on the properties of nonlinear dynamical processes was briefly characterised as "edge-like" interaction (Section 5.4.1).

Many of the characterisations of this mode of interaction bear the hallmarks of a material-oriented engagement as described in Section 2.2.1. Participants expressed an openness to surprises, and were content with or even actively working towards situations that were not completely under control. Interactions with instruments were frequently characterised as two-way and "dialogic" (see Section 5.4.2). Some of the participants suggested that in solo performance, the "cycle of exchange"[1] with the instrument could provide some of the interaction they would normally have with another player. Nonlinear dynamical processes make advanced planning very difficult, but may be considerably more applicable in material-oriented interactions where unpredictability and contingency are embraced. In this respect, they produce situations that call for *situated action* as described in Section 2.3.1.

Section 6.1 below discusses important distinctions around the notion of surprise in interaction, and how these distinctions are pertinent for both theoretical and practical understandings of creative engagements with tools. Section 6.2 develops a characterisation of *edge-like* interactions where musicians deliberately push their tools into unstable regions. The properties of nonlinear dynamical processes are examined in greater depth to demonstrate how they can play an important role in creating interactions that can be explored in this way. Section 6.3 considers the significance of nonlinear dynamical in rendering the temporal aspects

[1]see, for example, the case study of participant 8854 in Section 5.3.2.2

of gestures significant in musical interactions, providing a practical approach to gestural interaction that contrasts with much of the existing literature on the subject. Section 6.4 reflects on the musicological significance of the research conducted in this thesis, highlighting the importance of understanding the nature of instrumental interactions in articulating the concerns of specific musical practices. Finally, Section 6.5 explores the ramifications for HCI and interaction design more broadly, showing how nonlinear dynamics can support creative, explorative interactions in other domains.

6.1 Distinctions in unpredictabilities

This section examines distinctions in manifestations of — and attitudes to — surprise and exploration in musical interactions. These distinctions help to provide a detailed understanding of tool interactions within a specific musical context. This context is helpful in formulating specific answers to the central research question — the roles that nonlinear dynamical processes can play in musical interactions — and the various subquestions laid out in Section 1.2.

Section 6.1.1 explores a key distinction that emerged in both the comparative and ethnographic studies: between compositional, combinatorial surprises that emerge from the conjunction of known elements, and surprises that emerge directly in the interaction with a tool where the outcome is not what was expected, or intended, or produces an element that couldn't have been easily foreseen. Section 6.1.2 returns to the distinction between deterministic surprises and stochastic surprises, initially encountered in relation to the comparative evaluation studies in Section 4.5.3, developing the discussion based on the findings of the interviews in the ethnographically-informed study. Section 6.1.3 looks at differing attitudes to exploration found in the comparative and ethnographic studies, and, particularly *deep* exploration as opposed to *broad* exploration. Finally, Section 6.1.4 examines different scales of surprise, particularly the role of very subtle surprises.

While the discussions below are drawn in fairly binary terms, this is done largely for the sake of clarifying particular distinctions. In practice, these distinctions may not be so clearly defined, and there is no claim here that particular practitioners subscribe uniquely or completely to either pole being presented.

6.1.1 Combinatorial surprises and interactional surprises

A central distinction posited in Section 2.3.1 of the literature review distinguished between combinatorial surprises that emerge as different elements are put together to form a whole, and surprises that emerge in real-time interactions with tools. The kinds of surprise associated with the former were related to Schön's examples of reflection-in-action, such as pencilled architectural sketches, ordering melodies to be played on small bells, and various design tasks. In these situations, an aspect of the surprise appears to be due to cognitive limitations in anticipating how these individually known elements will combine.

The surprise/reflection model described in Schön's reflection-in-action, echoed in Suchman's situated action, and Sengers et al's reflective design also seems to be predicated on a time delay between the various stages of the process: the surprising result, the reflection on the nature of the emerging situation, and the consequent action based on this reflection. Section 5.4.2 linked this model of surprise to the practices of some of the musicians interviewed in the ethnographically-informed study. This approach can be seen in the case study of participant 5592 in Section 5.3.2.1, in the discussion of participant 1747s use of the piano in Section 5.3.2.5, and in participant 7321's description of ‘‘compositional’’ surprise in the Section 5.4.2 case study.

Interactional surprises differ from this combinatorial model of surprise, emerging in the moment-to-moment interactions with the instrument. They are tied more centrally to the specifics of the tools that are being engaged, and can be linked with the ‘edge-like’ interactions outlined in Section 5.4.1. The analogies used to describe such interactions compiled in Section 5.3.2.4 — riding a horse, surfing, sliding down water rapids, fighting, stretching an elastic band, kneading, pushing/pulling — seem to be a poor fit with a term like “reflection”. They are closely linked to participant 7321’s description of “mechanical” surprises in the Section 5.4.2 case study, established as a contrast to “compositional” surprises.

The kinds of interactional or mechanical surprises that appear in interaction may vary considerably in scale, from micro-unpredictabilities that the performer may not even consider to be particularly surprising (e.g. the specific harmonic content of a bowed interaction), to sharp dramatic transitions between states such as a reed instrument jumping into a higher register.

The distinction between these surprises is important for HCI. Following a reflection-based, combinatorial model of surprise, there is no reason for the *interaction* itself to be unpredictable or unstable to trigger creative reflection. The architect in Schön’s case study is surprised by the combination of pencilled elements, not the response of the pencil directly, and the architect would presumably not want a pencil that behaved erratically, producing unexpected patterns and movements. This can be contrasted with forms of painting where the engagement with paint and paintbrushes is a source of creative unpredictabilities (see Section 2.3.4). Here, the particularities of brushstrokes, the complex movement of the bristles, and the dynamic behaviour of the paint are all material to be explored and developed. The musical contexts explored in the ethnographically-informed study provide analogous situations: the interactions with the tools themselves, rather than the combinations of their outputs, can be the surprising aspect, and a source of creative development.

This distinction can also be though of in terms of linearity and nonlinearity. For linear functions, the following holds:

$$f(x + y) = f(x) + f(y) \tag{6.1}$$

The function, f, can be thought of as the result of a particular action with a musical tool or instrument. This then describes the case for combinatorial surprises, where the result of two particular events together is the same as combining the results of the separate events. A fundamental aspect of nonlinear functions is that this property doesn't hold, and therefore that the combined result of $f(x+y)$ may be substantially different from the combination of the individual results for $f(x)$ and $f(y)$. With the combinatorial approach to generating surprises, disparate elements combine in a linear fashion. As described in Section 5.3.2.5, with combinatorial surprises, some action, A, combined with another action, B, is potentially surprising due to the conjunction of A and B. This may well yield many surprises, and highlight different aspects within A and B, but the surprises fit within the definition of linearity: the result is a superposition of the two elements. With nonlinear systems however, event A combined with event B may lead to a third event C with potentially emergent properties that could not have been conceived of from the separate events A and B.

To summarise this distinction briefly: combinatorial surprises stem from reflection on the emerging situation as different elements are brought into conjunction with each other. This appears to be a good fit for reflection-in-action, predicated on a time delay between implementation and reflection. The individual interactions themselves are not seen as surprising themselves however. Interactional surprises, by contrast, place the surprise in the interaction, where the instantaneous outcome of a particular action may not be completely known. Edge-based interactions as elaborated in Section 5.4.1 provide a more specific example of this category of surprise and are therefore examined in more detail in Section 6.2. It is important to clarify that theses two types of surprise are not seen as mutually exclusive and there is likely to be overlap between the two kinds of surprise in any given situation.

6.1.2 Deterministic surprises and stochastic surprises

The distinction between surprises that come about due to deterministic systems and surprises that come about due to random processes was identified in relation to the comparative evaluation studies in Section 4.5.3. The topic was also taken up by several participants in the ethnographically-informed study, discussions that were deliberately provoked by one of the structured interview questions.

An important difference identified in Section 4.5.3 was that stochastic surprises may be very difficult to develop, a concern that appeared important to several participants involved in the comparative evaluation studies: as participant 637565 said, ‘‘what I want is a surprise that leads somewhere, rather than a surprise that's a dead end’’. A chance surprise might provoke an interesting change in approach, or provoke an improviser towards a sonic area, but it may not permit investigation and exploration in the same way as a deterministic surprise.

In the ethnographically-informed study, participant 8133 was keen to make this distinction. The participant uses digital feedback networks, where surprises are the result of complex-yet-deterministic interactions within the system. Surprises based on random events were seen as extraneous to the system. The participant expressed a desire for ‘‘unpredictability to be a real emergent feature,’’ as something immanent to the system.

The discussion around the relation between learning and surprise in Section 5.4.4 following the ethnographically-informed study also provides some insights into this distinction. Some of participants highlighted the desire to be in unfamiliar situations which are not fully understood, and where the surprising element of the interaction reveals something about the situation or the interaction. Surprises due to deliberately random processes may not reveal anything new, and are unlikely to change someone's understanding of a situation. The use of radios for example, as discussed by participants 1948 and 4692 may lead to very unexpected sonic outcomes through the interaction, but they do not generally inform the understanding of the interaction with the system under consideration. Similarly with the process of dipping into audio files, or records as described by participants 1948, 1883, 3598 and 8684, the result may be surprising, and the result can be explored and developed, but nothing is revealed about the nature of the system or the interaction through this surprise. Further, the fact that there *is* a surprise, is itself not a surprise: random processes are usually deliberately invoked and the outcome is already known not to be known. By comparison, the surprises articulated by participants 5173 and 2999 in relation to their bowed instruments, although potentially more subtle, are intrinsically linked to the complex nature of the interaction being engaged. With these instruments, it may not be so simple to encounter a surprising result, particularly if the instrument has been used for a long period of time. The emergence of a surprise may therefore itself be a surprise. Participant 5173 describes an approach that has much in common with the idea of deep exploration traced in Section 4.5.5 where surprises are unearthed through extended exploration of minute aspects of the interaction. The hidden nature of these unpredictable regions is therefore different in kind from chance surprises that can be easily and deliberately provoked, as they reward long-term exploration.

Participant 2999's description of finding beauty in "things that we can't understand and we never understand" seems clearer in the case of surprises that result from deterministic systems than from random systems; in the latter, the system can be surprising but completely understood, whereas in the former the system may be too complex to grasp completely.

6.1.3 Broad and deep exploration

A distinction arose in the comparative evaluation studies between *broad* exploration and *deep* exploration with a particular tool or instrument (see Section 4.5.5). The former was characterised as the kind of exploration where one rapidly orients oneself by attempting to find the extremities and boundaries, thereby having a broad sense of the overall range of possibilities. The latter was associated with mining a very narrow aspect of the tool or instrument, focusing on potentially minute aspects and exploring their subtleties. Both modes of exploration were observed with the systems presented to the participants of the comparative evaluation studies (see the participant vignettes in Section 4.4.2.3).

The ethnographically-informed study provided several explicit examples of deep exploration, with this mode of exploration seeming to play a key role in certain participants' performance practices. Participant 4692's discussion of edge-like interaction presented in Section 5.4.1 typifies this approach:

> "For me at this point, it's much more rewarding to concentrate on one thing,

and to deliberately not move, to go deep."

Similar examples of depth can be found in other interviews:

- "depth of information that comes out of every corner of that instrument", participant 7321 discussing the violin,
- "it's more rewarding because there's more depth to focusing on one set of material and really going deeper and deeper into it." - participant 5173, a double bass player,
- "I like the idea of the solo of just going right into, very deep, narrow and deep, and just holding on to something and staying with it" - participant 3284, a trombone player,

The specific examples given by participant 4692 were generally nonlinear feedback processes. The examples given by participants 7321, 5173, and 3284 also pertain to instruments that are "essentially nonlinear" in the sense used by Fletcher (1999; see Section 2.1.4.3). The link between depth and nonlinear dynamical processes was suggested in the literature review in conjunction with several properties of such processes. Firstly, the sensitivity to initial conditions means that repeating a particular input action twice with only tiny variations may nevertheless lead to very different results (Scipio and Prignano, 1996, also highlight this point in relation to digital synthesis with nonlinear dynamical functions). Secondly and perhaps more importantly, the hysteretic nature of nonlinear dynamical processes means that the timing of events can be just as pertinent as the content of the events themselves. This was explored in the description of the clarinet given in Section 2.1.4.3.1, and noted in conjunction with the instrumental engagement in compositions by Scott Mc Laughlin (see Section 2.2.2). These hysteretic aspects play a part in interactions with any essentially nonlinear instrument. Thirdly, and related to the first two points, the increased instability that many nonlinear dynamical processes exhibit when they are driven close to chaotic regimes and bifurcation points appears to be a close fit for the edge-like interactions characterised in Section 5.4.1 and discussed further below in Section 6.2.

Nonlinear dynamics may therefore provide a useful method for fostering this deep kind of exploratory engagement in digital tools more broadly. The examples given in Section 2.3.4 of the literature review of nonlinear dynamical digital models of paint brushes, and the employment of nonlinear dynamics in relation to creative play in computer games support this idea. Deep exploration connects closely to edge-like interactions discussed further below in 6.2.

6.1.4 Micro surprises

Whether or not a particular interaction is seen as surprising is dependent on what is expected. As noted above, this was reflected in certain interviews (e.g. with participants 7855 and 4821) where it became clear that bowed interactions could generally not be *completely* predicted. For example, the timbral structure of what emerges when the string is initially bowed may not be accurately predicted, but the musician knows the possible bounds of what might emerge, and can begin to focus the timbre more precisely as they continue to bow the string. This was not initially thought of as a surprise, as it is only unpredictable within certain expected boundaries.

The greater attention often brought to timbral detail in material-oriented musical interactions may mean that the unpredictable nature of such details are actually more likely to be viewed as surprises in these contexts, whereas they may pass unnoticed in more communication-oriented, note-based musical situations. Musicians can choose to turn their attention to these aspects, and treat these aspects as a resource or impetus for exploration, or they can be left as minor chance aspects that add subtle variety and detail, or potentially they can be ignored as minor aspects compared to higher level concerns such as pitch class and rhythmic phrasing.

6.2 Edge-like interactions

The distinctions in attitudes to surprise and exploration laid out in the previous section help to characterise a specific approach to musical interaction, paving the way for an examination of how nonlinear dynamics may play a part in these interactions. This section examines this particular approach to interaction that emerged from the studies conducted for this thesis, described in Section 5.4.1 as 'edge-like' interactions. This mode of interaction involves an instrument being driven to an unstable state (often at the border of two more stable regions), where it may behave in unpredictable ways, respond in unexpected ways to inputs, and provide a rich set of behaviours and outputs that can be explored. There may be an aspect of tension and risk involved, and it may be a challenge to maintain such a volatile state, but these are also elements that can contribute to the appeal of such interactions.

A crucial aspect of this mode of interaction appears to be the close, temporal coupling of the performer and the instrument. The performer must be attentive to the behaviour and response of the instrument, as it cannot be easily anticipated, and may frequently be surprising. The performer is in a constant state of reacting: not constantly dictating the instrument's output, but negotiating it (hence the emphasis on the interaction as a dialog). For many of the participants of the ethnographically-informed study, engaging with these aspects is a very deliberate decision. The openness to the unexpected aspects of the interaction links closely with material-oriented perspectives of creativity traced in Section 2.2.1.

The edge-like mode of interaction will be further elaborated here, as it appears to provide a specific context where nonlinear dynamical processes play a key role in the interaction. This helps to address both the central research question, and many of the subquestions laid out in Section 1.2. The discussion of edge-like interactions that follows in this section also draws on the results of the studies in Chapters 4 and 5, and brings together many of the aspects discussed more broadly in this thesis, such as:

- the creative roles of complex, unstable systems,
- material-oriented interactions,

- questions of control and agency,
- creating situations that cannot be understood, but can nevertheless be engaged with (see Section 5.4.4),
- surprises that "lead somewhere" (see Section 4.5.2),
- broad vs deep exploration (see Sections 4.5.5, and 6.1.3).

Edge-like interactions also provide a specific site for examining interactional surprises as opposed to combinatorial surprises as distinguished above in Section 6.1.1. This allows for a more focused examination of exactly how the properties of nonlinear dynamical processes may manifest in these kinds of interactions, and how they may be drawn on as creative resources.

6.2.1 Examples of edge-like interactions described by participants

A brief list of edge-like interactions derived from participant interviews in the ethnographically-informed study is given here to aid the discussions that follow, drawn from Section 5.3.2.4.

- Participant 4692 describes the use of mixer feedback, where a mixer channel is fed back on itself to produce a tone[2]. The EQ dials of the mixer are thus changed from being very stable predictable controls to being very complicated controls, with dynamic, contingent thresholds which, once crossed, can cause severe transitions in the sonic output.

- Participant 5559 describes harmonics "fizzing about" when the saxophone is pushed into extreme, unstable regions.

- Participant 1684 using a microphone inside a bass flute and exploring transitions to feed back through the instrument.

- Participant 2999 bowing the cello very close to the bridge, and playing very high, unstable harmonics across multiple strings.

[2]described in more detail in by Kuivilla (2004) in relation to David Tudor, and by Sanfilippo and Valle (2012) in relation to Toshimaru Nakamura.

- Participant 5173 bowing the double bass very close to the bridge whilst running the left hand lightly but rapidly up and down the string. In this situation, the emergence of particular harmonics is influenced by which harmonics have sounded recently, with sympathetic harmonics tending to reinforce each other (see the description given by Mc Laughlin (2014) in Section 2.2.1).

- Participant 4821 adding paperclips a violin to create a complex (and unstable) situation to explore.

- Participant 7864 describes highly interconnected modular synthesiser setups that reach a point of complexity that "which could go really crazy, but you kind of try to retain it within, so it doesn't spill out of the... like if you have water so it doesn't spill outside of that scope."

6.2.2 Edge-like interactions as nonlinear dynamical interactions

All of the examples of edge-like interactions given above can be thought of in terms of nonlinear dynamical processes. As laid out in Section 2.1 of the literature review, nonlinear dynamical systems may contain unstable regions and sharp boundaries where the behaviour of the system changes abruptly. The properties of such systems appear to be a very good fit for the kind of continuous reciprocal interaction with unstable situations that characterises this edge-like mode of interaction.

Edge-like interactions are significant for the present thesis in a number of ways. Firstly, as discussed above, they help to characterise a very particular view of exploration and surprise. Secondly, they provide a concrete link between these more particular views of surprise and exploration and the specifics of the creative tools being employed. The distinction that the first study evidences — between the kinds of edges found in nonlinear dynamical processes versus the kind of edges provided by simple mapping discontinuities — helps to highlight this: that an edge may not be interesting simply because it is a boundary, but because of the amount of complexity and detail that may exist around the boundary (see Section 2.1.2.3). In the case of nonlinear dynamical systems, the detail at an edge point can be potentially infinite - the same kind of detail found at boundaries in fractal images for instance[3]. The link with fractal imagery is not merely an analogy, as such images are also the product of iterated nonlinear functions. The switch from static images to sonic interactions may seem odd, but as fractal images are static descriptions of the behaviour of iterated systems, they are essentially a map of time-based behaviours for specific initial conditions.

A simple discontinuous boundary does not provide the same level of nuance and variation potentially found at bifurcation points in a nonlinear dynamical system[4]. The application of nonlinear dynamical processes posited in the literature review, and employed in the interfaces for the studies in Section 4, creates sounds by sonifying a particular trajectory through the phase space. Bifurcations caused by alterations to the system parameters alter the nature and number of attractors present that influence the behaviour of particular trajectories (see Section 2.1.1.3.1). However the effect that these bifurcations have is dependent on the particular trajectory when the change is brought about. There may be a sudden change in behaviour, a subtle change in behaviour, or no change in behaviour, depending on the specific history of prior parameter changes.

6.2.2.1 Examples of edge-like interactions with nonlinear dynamical processes

To give a more concrete picture of boundaries in nonlinear dynamical processes and the motion of specific trajectories, examples of complex behaviours around critical thresholds are considered here.

The flexibility in possible trajectory behaviours can be demonstrated by looking again at the Lorenz attractor. When ρ in Equation 2.4 is pushed past a certain threshold, trajectories

[3]Thompson and Stewart (1986, p. 227) go further and point out (in relation to the Lorenz system) that "[...] if one looks with sufficient refinement and rigour, there are qualitative changes at an infinite number of [ρ] values in any interval."

[4]Which is not to say that a hard, discontinuous boundary cannot be explored in lots of other senses: e.g. in different contexts, in combination with other musicians, moving through the boundary at different rates, to and from different points.

may move back and forth between the two spiral attractors shown in Figure 2.2 in a deterministic but unpredictable manner. When ρ is then reduced sufficiently, the trajectory will settle into a particular orbit around one of the two spiral attractors. Which attractor the trajectory settles to is governed by the state of the specific trajectory under consideration at the point where the system bifurcates, and therefore, the previous inputs to the system. When interacting, a user can effectively attempt to hop a particular trajectory from one spiral attractor to the other by increasing ρ past the critical threshold, allowing the trajectory to cross to the opposite attractor, and then reducing ρ sufficiently that the trajectory stays in the attractor. This provides an example of hysteresis, and can be compared to the overblowing clarinet example discussed in the literature review (Section 2.1.4.3.1), where a performer can increase breath pressure to the point where the system jumps to a higher harmonic, and then reduce the pressure again retaining the higher harmonic. Thus, for a particular given input from a musician — however precise — there are different possible sonic results depending on past activity.

The Logistic map provides an example of increasing complexity close to a definitive threshold, beyond which chaotic behaviour may occur (at $r = 3.56995...$ in Equation 2.3, see Section 2.1.2.1). This is an example of the period doubling route to chaos, where there are a rapid series of period doubling bifurcations, close to the threshold of chaos for the control parameter, r. As the critical threshold is approached, the period doubling bifurcations are closer together (Lakshmanan and Rajasekar, 2003, p. 97), presenting a highly sensitive control region just prior to the onset of chaos. The period doubling route to chaos can be found in a variety of musical situations, such as wind instruments (Gibiat and Castellengo, 2000), bowed interactions (Inácio, 2008, p. 135–137) and the voice (Neubauer et al., 2004).

A second route to chaos is termed *intermittency* (Lakshmanan and Rajasekar, 2003, p. 132). As a system parameter is pushed close to a threshold for chaotic behaviour, the system may exhibit intermittency behaviour, where almost periodic trajectories are interrupted by occasional, unpredictable bursts of chaotic behaviour (ibid. p. 130, and see also Pomeau and

Manneville (1980) for intermittency in the Lorenz system). As the threshold for chaos is approached, the chaotic bursts become more frequent.

Grebogi et al. (1987) describe the behaviour of trajectories as chaotic attractors undergo sudden discontinuous changes in response to alterations to system parameters. When a chaotic attractor is destroyed by moving past a critical threshold, a particular trajectory may remain in the region of the chaotic attractor for an indeterminate amount of time before jumping to another attractor (potentially stable or chaotic):

> “they are initially attracted to the phase-space region formerly occupied by the attractor [...] they then bounce around in this region in a chaotic fashion, which, for most purposes, is indistinguishable from the behavior of orbits on the chaotic attractor; finally, after behaving in this way for a possibly long time, they suddenly move away from the region of the former attractor (never to return) and approach some other attractor. The length of time an orbit spends on the remnant of the destroyed chaotic attractor depends sensitively on its initial condition” (ibid. p. 5366)

The authors also describe situations where a trajectory may intermittently fluctuate unpredictably between the old region and the new region made available by crossing the critical threshold.

The examples given above provide only a small selection of possible behaviours that exist around critical thresholds. They nevertheless give an idea of the richness and complexity of interactions that may exist, the role of hysteresis, and the necessary difficulty in having complete and accurate control close to these thresholds. These examples of complex interactions are demonstrated in mathematically simple nonlinear dynamical systems, but it seems likely that the complexity of interaction will be magnified when considering the more complicated situations found in real acoustic instruments. Further, the examples above are generally only considering changes to a single system parameter. As (Lakshmanan and Rajasekar, 2003, p.130) point out in relation to the Duffing oscillator, “one can change not only the parameter

[γ] but also [ω], for example, in [Equation 2.6]. Then a very complex picture of bifurcations phenomena, present even in such a simple nonlinear system as the Duffing oscillator, can be realized''. These properties relate to the attitudes to edge-like interactions discussed above, in terms of finding new things, fostering surprise, undermining the agency of the musician, and being able to explore a very small control region in depth over extensive periods of time.

6.2.3 Edge-like interactions summary

While nonlinear dynamical processes may not be the only method to achieve edge-like kind interactions, they nevertheless appear to yield a very effective method. The variety and subtlety of changes in behaviour found close to critical thresholds seem to facilitate a deep rather than a broad approach to musical exploration as discussed above in Section 6.1.3. This provides a close fit with the attitudes traced in Section 2.2.3.1 of the literature review, where improvisers such as John Butcher describe an interest in edge points as resourceful areas (in Butcher's case, where the reed ''seizes up and breaks down'' and is ''on the edge of controllable sound'', Warburton, 2001). Edge-like interactions can be considered in relation to the discussion on small-scale surprises in Section 6.1.4. Sonic variations that emerge in interactions due to the complexity of nonlinear dynamical processes may in some cases be too subtle to be recognised as genuine surprises, e.g. the subtle variations in harmonics that may emerge in bowing a string. As some of the participants pointed out, they may find it difficult to predict exactly which harmonics may be present when the bow is initially put to the string, but they will have an idea of the general effect. Whether that detail is important, and therefore whether it is surprising can depend on the context for the performance, and which aspects of the sound the musician is focused on. Edge-like interactions can be viewed as a way to make these unpredictable aspects more significant, e.g. either focusing in on the sound to the point where the specific timbral spectrum is a key aspect, therefore making the unpredictabilities musically meaningful, or by finding regions where these unpredictable aspects have a much greater significance (as with the case study of participant 4692 in Section

5.4.1, and the John Butcher example quoted above).

Edge-like interactions provide a clear example of an approach to instrumental engagement that supports interactional surprises. The distinction made above in Section 6.1.1 showed how such surprises that take place in the interactions themselves may differ from the combinatorial models of surprise considered in relation to reflection-in-action and reflective design. Edge-like interactions as described in the musical contexts for the present thesis seem to relate closely to the former model of surprise. Andy Keep's description of improvisatory practices within contemporary music provides a similar assessment:

> "Within improvisation sounds are generally emergent or in constant flux, not affording the performer the luxury of contemplation or exact repetition during assessment." (Keep, 2009)

Edge-like interactions and interactional surprises more generally provide a helpful perspective on the role of surprise in creative interactions. They serve both to demarcate specific distinctions, and to highlight approaches to interaction design that may be more commensurate with material-oriented approaches to creative interactions. They also provide a specific example of how nonlinear dynamical processes can and do fit into creative interactions, and how they can be drawn on as resources for creative exploration.

The remaining sections in this chapter explore how nonlinear dynamics relate to physical gesture (Section 6.3), and some of the key musicological implications of this work (Section 6.4).

6.3 Gesture and nonlinear dynamical processes

The above discussion highlights the importance of the recent history of parameter inputs to a nonlinear dynamical system in determining the output at any given moment. This opens up a novel and potentially important perspective on linking physical gestures to musical results, a site of much recent research in music and HCI, particularly with the rise in availability of gestural sensors (Kanga, 2016; Caramiaux et al., 2015).

The reliance on the recent history of the parameter inputs in nonlinear dynamical systems means that moving from setting A to setting B can lead to different results depending on the dynamics of the gesture. Accelerating quickly at the start of a particular gesture and slowing towards the end of the gesture may mean that the sound being produced at setting B can be very different to a gesture that started out slowly and sped up towards the end. A simple microphone-loudspeaker feedback example can demonstrate this reliance on the dynamics of a gesture. If a performer moves a microphone from point A to point B, lingering in a particular position in the middle of the gesture may allow a particular harmonic to feedback sufficiently that it remains dominant when the microphone arrives at point B. A faster gesture may not allow this harmonic to become strong enough, and the dominant harmonic at point B is therefore potentially different. There can be an unlimited amount of subtleties available in even a one-dimensional gesture that lead to a wide variety of different outcomes based on only changes in the speed of movement.

This approach to incorporating gesture in digital musical interactions represents a very different approach to many current approaches to gesture that involve gesture vocabularies, classification and prediction (e.g. Bevilacqua et al., 2010; Caramiaux et al., 2013; Sarasua et al., 2016)[5]. Nonlinear dynamics can afford exploration of the subtle nuances of particular gestures, allowing speed and acceleration to play a major part in the interaction, without requiring an extra parameter mapping from derivatives of the sensor inputs.

6.4 Perspectives on musical practices

The examinations of tool use conducted in this thesis offer nuanced perspectives into the relationship between musical practices and tool engagements. The ethnographically-informed

[5]see also the recent RAPID-API project that several of these authors are associated with. Many of the specific technologies developed as part of this project use a vocabulary-based approach to gestural interaction: `http://rapidmix.goldsmithsdigital.com`

study in particular provided a set of concrete examples that expand the concept of *instrumentalizing* elaborated by Keep (2009), exploring how tools may afford a long-term "live investigation of sounding objects," and the potential importance of nonlinear dynamical elements in this process (see Section 2.2.5.1.1).

The different conceptions of unpredictability and exploration that emerged from participant interviews in Chapter 5 help to provide insights into the process of making music in a contemporary musical context. In particular, they expand on Keep's stated desire to engage "discussions about *how* one approaches the activity of sounding an object as a musical performance tool" (Keep, 2009, p. 114, emphasis in the original). The detailed case studies presented in Sections 5.3.2 and 5.4 allow for a close examination of instrumentalizing practices in relation to nonlinear dynamical processes. The edge-like interactions discussed above in Section 6.2 highlight one specific way of sounding musical objects that several participants found to be useful. Edge-like interactions fit in well with Keep's characterisation of experimental musical practices as exploring "an object for its inherent sonic properties," and the notion of material-oriented musical practices more broadly. The strong connections traced above in Section 6.2.2.1 between edge-like interactions and nonlinear dynamical processes are therefore a useful response to this drive to unpick some of the connections between musical practices and approaches to engaging with musical tools.

Section 5.4 traced relationships between learning, unpredictability, exploration and discovery in free improvisation. Examining these relationships can be helpful in unravelling exactly what is important for musicians in their practices, and what motivates them to embrace exploration and unpredictability. Seven of the participants were keen to stress the importance in their own practice of learning as a reward in itself, rather than as a means to improve or develop their performance in some way. Participant 2999 described the beauty of being in situations that are not completely understood. This connects with the focus on "openness" raised by participants 5173 and particularly 8854 (see case study in Section 5.3.2.2). While both participants saw exploration as being central to their practices, they made it clear that this wasn't a means towards finding particular things, or an attempt to deliberately provoke surprises. Surprises would likely emerge from an open attitude to engaging with the instrument, but they are not ores to be mined. The wider process is the focus.

Edge-like interactions can be posited as an example of this kind of approach, with nonlinear dynamical processes again providing a candidate mechanism for facilitating this kind of interaction with musical tools. The tools can be driven into unpredictable regions, not explicitly to find new material, but in order to find states which cannot be easily fathomed, and that invite curiosity. Musicians may learn new things about their instrument or find new sounds and behaviours, but these may be seen as "fringe benefits," (as participant 8854 put it) of being open to unknown situations.

6.5 Considerations for HCI

As nonlinear dynamical processes are at the core of many acoustic musical instruments, it seems natural to examine how these processes may play a part in digital interactions, and what this may bring to HCI research in domains beyond music. Whilst nonlinear dynamical processes are hard to avoid in the acoustic world, they do not exist in digital tools unless they are explicitly implemented. They are frequently employed in digitally modelling the physical world (for example physically modelling acoustic instruments, or modelling the behaviour of analog electronics), and in systems that draw on feedback as a resource (see Section 2.2.5). As discussed in Section 2.3.3.1.3, nonlinear dynamics have also been employed as mapping layers in digital musical (and audiovisual) tools, with the mapping layer often taking the form of a physical model itself (e.g. a mass-spring network). Many of these processes bring the complexity of physical behaviours into digital interactions, and often attempt to draw on our intuitive experience of managing dynamical processes in the physical world (Momeni and Henry, 2006; Menzies, 2002).

The characterisation of edge-like interactions with nonlinear dynamical processes detailed above in Section 6.2.2.1 brings together the results of the studies in this thesis to highlight certain roles that such processes may play in musical interactions, and how the nonlinear dynamical properties relate to unexpected outcomes and musical exploration in contemporary musical practices. Edge-like interactions demonstrate an approach to engaging instability and unpredictability in interaction that is distinct from either chance-based unpredictability, or combinatorial unpredictability (see Section 6.1.1), and that may be of interest in domains beyond music.

Section 6.1.1 discussed distinctions between combinatorial surprises that come about from a combination of known elements, and interactional surprises that emerge directly in an interaction with a tool, drawing on participant 7321's distinction between "compositional" surprises and "mechanical" surprises respectively. The participant — a user of both acoustic and digital instruments — highlights the difficulty with achieving mechanical surprises with digital technology:

> "Well, in terms of the mechanical aspect of surprises, there is a distinction between the two [...] the violin is capable of producing a massive range of long uninterrupted sounds [...] it has an extremely rich harmonic sound [which] lies in the fact that there's a depth of information that comes out of every corner of that instrument, any instrument really that has materials like metal, resonating bodies that are connected with various mechanisms, a violin is a very very advanced music technology, but then when you [use] digital technology, what you don't get is that you will never push the pads and the pads won't actually produce surprising harmonics, so there's one thing there which is lacking [...] there's no mechanical element" (participant 7321).

The computer arguably makes linear combinatorial surprises relatively easy to achieve. A vast array of different sonic material may be called up and combined (e.g. through the use of audio files or digital synths), allowing for novel contrasts and juxtapositions to be explored.

However, it appears to be more difficult to find simple methods for encountering interactional surprises (see Section 6.1.1). The general focus on simplicity, clarity and efficiency in HCI (see Section 2.3.3.4) seems to deliberately work against the possibility of encountering interactional surprises, even in tools that are designed to be engaged with creatively. HCI is generally concerned with allowing users to attain particular goals with the minimum of difficulty and the minimum mediation.

However, there are existing areas of interaction design beyond music that present examples to the contrary. As pointed out in Section 2.3.4, computer games can be thought of as one such example, providing further examples of creative engagements with nonlinear dynamical processes. Although input methods are often be designed to be as simple as possible, the realisation of objectives in games generally requires the player to engage with increasingly complex situations. The comparison is particularly clear in games where the management of simulated physical bodies is a key gameplay component, such as controlling vehicles. The dynamics of a vehicle cornering on even a flat surface can be a complex nonlinear dynamical process, with the negotiation of a particular corner achievable in an almost limitless number of ways, becoming an art that is mastered across long periods of gameplay. In more sophisticated driving games the user is being asked to engage with a range of interrelated elements: acceleration and momentum, friction, weather conditions, tyre temperature, vehicle centre of gravity, and so on. This can be thought of as an example of deep exploration, in that it involves exploring a specific aspect in more and more detail (see Section 6.1.3 above).

This approach to interaction connects closely with Gaver's notion of ludic design, discussed in Section 2.3.1.4: the designed tool or artefact is considered to be a site for exploration, rather than for achieving something pre-established. Nonlinear dynamics can provide a mechanism to engage ludic interactions that invite exploration. They can assist designers in creating artefacts that allow users to collaborate with the technology: rather than focussing on allowing users to achieve immediate desires, users are instead drawn in to engaging with the interaction itself, encouraging them to find their own goals within the specific behaviours of tool. This approach to design therefore takes into account the material-oriented approach to creative interaction that often seems to be overlooked in interaction design (see Section 2.2.1).

Painting and drawing provide a second example of interactions that are in not simple, clear or efficient in an HCI sense, and that draw on nonlinear dynamical processes. As discussed in Section 2.3.4.2, paint and paintbrushes can be examined in terms of nonlinear dynamical processes, such as the network of springs that comprise the bristles or the complex non-Newtonian nature of paint. Interactions with paint and paintbrushes necessarily incorporate the temporal aspects of gesture (e.g. speed and acceleration), making these aspects exploration in their own right (as discussed in Section 6.3. Examples of digital painting tools that do incorporate nonlinear dynamical processes are found with physical models of paint and paint brushes that incorporate nonlinear dynamics processes, and therefore include time-sensitive gestural interactions (e.g. Baxter et al., 2004; Chu and Tai, 2002). This provides a close parallel with digital physical models of acoustic musical instruments. A thorough investigation into the nonlinear dynamical behaviour of visual art materials in relation to visual art practices would be a very useful point of comparison with the music-focused research presented in the present thesis.

We have seen in earlier chapters how nonlinear dynamical interactions can be drawn on as a resource by musicians. The present section has articulated how these interactions are inherent in many visual art materials, and present in certain computer games, and may facilitate explorative, ludic interactions in many other design contexts. While nonlinear dynamical processes are abundant in the physical world, they must be explicitly included in digital interactions, making this research of particular relevance for HCI.

6.6 Summary

This chapter has drawn together the key aspects of this thesis: the significance of nonlinear dynamical processes in musical interactions (Sections 6.1.1, 6.2.2.1, 6.3 and 6.4), wider questions around exploration and productive unpredictability in interaction and creative processes (Sections 6.1, 6.2 and 6.5), close considerations of specific musical practices in terms of interaction (Section 6.4), and considerations of how the research presents new perspectives and practical approaches for HCI and interaction design in both musical and non-musical domains (Sections 6.1, 6.2.2.1, 6.5). The following chapter summarises the key contributions of this research, and examines how this work may be taken further, in relation to instrument design, musicology, interaction design in non-musical domains, and theoretical understandings of interaction.

Chapter 7

Conclusions

This chapter highlights the central contributions made in this thesis. These are laid out below in Section 7.1, and then related to the initial thesis research questions in Section 7.2. Key limitations are then summarised in Section 7.3, and potential avenues for further research are considered in Section 7.4.

7.1 Contributions

1. **Empirical findings on the role played by specific nonlinear dynamical processes in digital musical interactions**.

   The inclusion of a particular implementation of a nonlinear dynamical process was shown to be linked to the potential for both surprising interactions, and long-term exploration and discovery in digital musical systems (Section 4.5.1). Users of these systems did not view them as uncontrollable however, and felt able to repeat and explore certain actions, despite their surprising nature. This finding has implications for the design of digital musical tools and creative systems where designers wish to create explorable systems on three levels. Firstly, it provides a novel perspective on the nature of engagements with creative tools, and the relation between surprise and exploration (developed further in Contribution no. 4 below). Secondly, it evidences the role that nonlinear dynamical processes can play in supporting certain types of creative exploration. Finally, it provides a specific example of how nonlinear dynamical processes can be embedded in digital musical interfaces.

2. **Empirical research into the role played by nonlinear dynamical processes in improvisatory musical practices**.

   Nonlinear dynamical processes were examined in a range of acoustic, electronic and digital instruments in relation to improvisatory musical practices (Chapter 5). Evidence was presented demonstrating that nonlinear dynamical processes can act as resources for exploration over long time periods. Numerous practices were identified in which musicians deliberately engage with the more unstable, nonlinear aspects of their instruments (see Section 5.3.2.3), and deliberately modify their instruments to render them more complex and unpredictable.

   Based on the case studies and earlier experiments, a range of perspectives have been characterised, with implications for interaction design and HCI. A variety of motivations and practical approaches are articulated for engaging with difficult, unstable tools. These studies also demonstrate specific ways in which free improvising musicians place the nature and behaviour of the tool at the centre of their practices.

3. **Evidence of an approach to creative interaction that explicitly draws on the properties of nonlinear dynamical processes.**

   A clear account of how nonlinear dynamical processes are leveraged in a specific approach to creatively engaging with musical tools has been presented. The term edge-like interactions is proposed to characterise an approach to interaction where the particular properties of nonlinear dynamical processes are exploited. In these interactions, the wide range of behaviours exhibited by nonlinear dynamical systems close to critical thresholds provide rich situations for creative exploration, with a wide range of possible outcomes accessible from only minor adjustments to the size and timing of input actions (Section 6.2.2.1).

Evidence for this approach to interaction was demonstrated for users of electronic tools (Section 5.4.1) and in the use of acoustic and digital tools (6.2). Edge-like interactions have been proposed as providing a clear and productive link between nonlinear dynamical processes and material-oriented approaches to interaction. It has been shown that acknowledging the material-oriented approach to creative interaction can open the door to the use of nonlinear dynamical processes as being creatively helpful rather than frustrating and inhibiting.

4. **Evidenced characterisations of the relationships between surprise, exploration and control in creative interactions, drawn from the instrumental engagements of musicians engaged in free improvisation and experimental music**.

   The studies in this thesis provide useful insights into artists' perceptions of unpredictability, exploration and control in their interactions with musical tools and instruments. A range of perspectives are presented, ranging from a desire to avoid surprises, to an ambivalent openness to unpredictable events, through to an active search for unpredictable situations, and a keen enjoyment of situations which cannot easily be fathomed.

   The notion of *deep exploration* is introduced and developed to characterise approaches to sonic exploration that examine very small but detailed ranges of interaction with particular tools and instruments. This was evidenced in both the quantitative data from the studies in Section 4 and the interviews conducted for the ethnographically-informed study in Section 5. The term 'deep exploration' is used in contrast to broad exploration, approaches that cover a wide range of territory in a short amount of time. The kinds of surprise afforded by nonlinear dynamical processes appear well suited to the creation of tools that contain unexpected areas of vast detail (Section 6.2.2.1), that can be discovered and explored. The blend of unpredictability and determinism in interactions with nonlinear dynamical systems can provide scope for surprise, but allows these surprises to be revisited, explored and developed.

An openness towards the potentially surprising outcomes of particular actions was demonstrated by many of the study participants, with some going further and requiring that something unexpected should happen as part of their creative process. The edge-like interactions, discussed above, provide a particularly clear demonstration of how creative tools are explored and pushed into deliberately unpredictable areas. This open attitude to interaction provides a subtle but potentially important perspective on interaction design: the complexity of the interaction can be at the centre of the creative process. From a material-oriented viewpoint (2.2.1), the usefulness of the tool is not judged by how transparently it provides direct access to some material beyond itself. The exploration of the complexities of the tool are integral to the creative act. Nonlinear dynamical processes fit well into this framework by providing rich sets of possible sounds and behaviours, many of which are not easily accessed, but which can be provoked, explored, uncovered, and revisited, and can directly "kick back" against the user.

5. **Identifying and addressing a gap in existing HCI theories regarding creative interactions**.

   The studies in this thesis highlight the creative potential of *interactional* surprises, that is, unpredictabilities that emerge from the instantaneous interaction with the tool. This provides a perspective on surprise that appears to be absent from existing HCI and interaction design literature (see Section 2.3.1), which often focusses instead on combinatorial surprises that result from the unexpected implications of the conjunction of otherwise expected elements. The contrast presented in Section 6.1.1 can be thought of as the difference between surprise in the context of Schön's pencilled architectural sketch examples — where the surprise stems from the ways that the drawn shapes reveal what does and does not fit together, suggesting unexpected avenues for development (combinatorial) — and surprise in the output of a paintbrush, where the instant imprint of paint on the canvas is a complicated function of brush angle, pressure, the consistency and density of the paint, the prior states of the many bristles, the nature of the canvas, and so on (interactional). In the latter example, the brush exhibits a range of nonlinear dynamical properties that simultaneously render the tool unstable, complicated and difficult, unpredictable, controllable, learnable, subtle, expressive, capable of repeatable effects, and open to deep exploration and development over a lifetime of painting.

Unlike Schön's notion of reflection-in-action, interactional surprises can lead to reflection on the nature of the tool itself, as well as the more general reflections on the wider context and the emerging situation. The value of interactional surprises — both for musical and non-musical tools — has been situated in contexts where creative outcomes are negotiations of the affordances of particular tools, such as is found in material-oriented interactions (Section 2.2.1).

Nonlinear dynamical processes have been established as a method of achieving interactional surprises that differ in important ways from chance-based processes. The latter do not easily support further development, or deep investigation of the phenomena affording the surprise (Sections 4.5.3 and 6.1.2). The deterministic nature of nonlinear dynamical processes has been established as a valuable 'sweet spot' between on the one hand complexity and unpredictability, and on the other hand the capacity for actions and events to be repeated, refined and explored in a detailed fashion.

6. **Implications for creative interaction design and HCI across a range of other domains**

   The empirical research presented in this thesis is based on investigations of musical tools and practices. The contributions presented in this section have nevertheless been shown to be relevant to interaction design and HCI more broadly (Sections 6.1 and 6.5). The domains of visual art and computer games have been identified as fields that seek to support long-term creative exploration in digital interactions (Sections 2.3.4 and 6.5), and consequently, these are domains in which strategies for affording interactional surprise may be of particular relevance. Nonlinear dynamical processes have been shown to be of particular importance for digital interactions, because, unlike the physical world, such processes are not present by default and must be explicitly implemented.

The research proposes an alternative approach to thinking about *gesture* in creative interactions, that takes a different direction from much recent research on the topic (Section 6.3). The importance of the timing of input actions in engaging with nonlinear dynamical processes has implications for the design of gestural interaction (Section 6.2.2.1). Progressing through a particular gesture at differing rates can lead to very different outcomes, particularly due to the potential for mode-locking behaviours. This indicates the potential for nonlinear dynamical processes to support gestural interactions that are infinitely varied, nuanced and deeply explorable.

7.2 Addressing the research questions

In this section, the research questions are brought forward from Chapter 1 and responded to individually. The central research question was “how is interaction affected by the inclusion of nonlinear dynamical processes, in particular in the domain of digital musical instruments?”. This question was broken down into the following more specific questions, which are laid out as section headings below, and addressed individually with reference to the contributions listed above, and relevant sections in the thesis.

7.2.1 What roles do nonlinear dynamical processes play in existing instruments (whether acoustic, electronic or digital)?

This question was approached from several perspectives, particularly in relation to Contributions no. 2, 3 and 4 in the preceding section. Section 2.1.4.3 of the literature review highlights some of the existing work in this area, showing how the nonlinear dynamical nature of wind and string instruments provides a rich terrain for exploration. Section 2.2 highlighted some initial links between musical practices and nonlinear dynamical processes in acoustic, electronic and digital instruments, with some specific examples of nonlinear dynamical processes being specifically implemented to set up situations with emergent properties.

The studies presented in Chapter 4 demonstrate a link between the inclusion of specific nonlinear dynamical processes in digital tools, and a sense of both unpredictability, and the potential for exploration and discovery with those tools. This presence of these processes did not appear to lead to a perceived loss of control, or prevent the possibility of repeating similar sonic events.

The interviews conducted for the study detailed in Chapter 5 suggest links between the use of “essentially nonlinear” instruments (Section 2.1.4.3) and a strong focus on exploration in performance (Section 5.3.2.1). A specific approach to interaction was traced in relation to engagement with both acoustic and electronic musical tools: *edge-like* interactions. This approach embraces the unpredictability of systems pushed close to boundary points, where they are particularly unstable. These sites are seen as resources that can be explored and can connect to a desire to have a dialog with musical tools, providing a way to provoke creative outcomes that are not the product of individual contemplation, but that emerge through an engagement with the specific properties of the tool. Nonlinear dynamical processes provide a very effective method of achieving these kinds of interactions, evidenced both by the nonlinear dynamical nature of the systems described by the study participants, and the close fit between the behaviours of the abstract mathematical systems and the qualitative descriptions of the instrumental interactions provided by the participants.

Participant interviews support the idea that unpredictability in interactions with nonlinear dynamical systems can differ in important ways from unpredictable interactions with chance-based processes. Surprising results with nonlinear dynamical processes can open up new areas for exploration, whereas chance-based surprises may be difficult to engage with or to develop. This subject is proposed as an area for further investigation however (Section 7.4 below).

7.2.2 How do the properties of nonlinear dynamical processes relate to affordances in musical instruments?

Contributions no. 1, 2 and particularly 3 provide a range of perspectives on this question. The properties of nonlinear dynamical systems, such as the sensitivity to initial conditions, the complex behaviours around critical thresholds, the emergence and disappearance of metastable states, and the potential for hysteresis in nonlinear dynamical processes can support rich interactions that permit deep, long-term exploration. The latter property means that for a given input, there are a variety of possible outputs. The history of the input is significant in determining the result, placing an importance on the speed and acceleration of input gestures. A change in even a one dimensional input from value A to value B can potentially lead to a wide range of highly divergent outcomes, depending on the rates-of-change within this single dimension. Section 6.2.2.1 provided detailed descriptions of the more complex interactions that occur with nonlinear dynamical processes when the systems are pushed close to critical thresholds, which provided close parallels with edge-like interactions found with existing acoustic and electronic musical instruments. This link with edge-like interactions demonstrates how nonlinear dynamical processes can afford certain approaches to musical exploration, as detailed in Section 5.4.1 and 6.2.

7.2.3 How are nonlinear dynamical processes incorporated into existing musical practices?

This question is addressed directly in Contribution no. 2, that evidences a range of approaches taken to engaging with the nonlinear dynamical properties of exiting instruments in free improvisation. The edge-like model of interaction noted in Contribution no. 3, and detailed in Section 6.2, provides one very specific example of how nonlinear dynamical processes are drawn on in existing musical practices, as discussed above.

The examination of experimental music, contemporary computer music, and free improvisation in Section 2.2.3 of the literature review suggests that the explicitly exploratory approach taken by these musicians to engaging with their tools often leads to a close engagement with the more nonlinear aspects of their instruments. In free improvisation particularly, the openness to unpredictability and to creating a *dialog* with the tools found in such practices, and the material-oriented focus on the specific properties of the tools at hand creates a situation in which nonlinear dynamical systems are a good fit. This is supported by the conclusions of the comparative evaluation studies in 4, where digital systems incorporating nonlinear dynamical processes were seen as providing more scope for exploration and discovery compared to those that didn't. The ethnographic interviews highlight a link between improvisers using ‘‘essentially nonlinear’’ instruments, and a strong focus on exploration in their practices (Section 5.3.2.1).

The interviews also provide insight into a range of motivations — noted above in Contribution no. 4 — for engaging with the kinds of unpredictability afforded by nonlinear dynamical processes, such as the desire to find new sounds and behaviours, the desire to be in unfamiliar territory that is not completely known, the desire undermine one's own agency, or the desire to be in a situation in which one finds out new things about an instrument or one's use of an instrument (Sections 5.3 and 5.4). The comparative evaluation studies and the ethnographically-informed study also highlighted a range of perspectives on unpredictability in interaction, and the relation to both exploratory interactions, and to nonlinear dynamical processes. The deterministic-yet-unpredictable nature of these processes appears to provide interactions that can be both unpredictable but repeatable (Section 4.4.2.1), allowing this relationship between the unfamiliar, mixed-agency interactions, and learning and discovery.

7.2.4 How do people of varying musical backgrounds engage differently with instruments incorporating nonlinear dynamical processes?

This question was primarily addressed in the comparative evaluation studies (see particularly Sections 4.4.2.4 and 4.5.7). The participants for the main comparative study were split by whether or not they had engaged significantly in experimental musical practices. There were no significant differences in the preferences of the two groups regarding their engagement with the various interfaces they were presented with, whether they incorporated nonlinear dynamical processes or not. The primary distinctions observed were, firstly, that the difference in attitudes between the nonlinear dynamical interfaces and the other interfaces used in the study was more significant for the non-experimental music group. Secondly, the correlations between the participant responses to the various likert-scale questions were noticeably different for the two groups. For the non-experimental music group, there was a strong negative correlation between whether they felt in control, and whether they found the interface surprising, whilst for the experimental music group there was no significant correlation. Thirdly, the experimental music group spent significantly less time practising with the study interfaces and more time recording than the non-experimental music group.

Tentative explanations are suggested for these distinctions in Section 4.5.7, but it is felt that given the relatively crude categorisation of the participants (Section 4.4.1), these questions require further investigation. Section 7.4 below proposes concentrated ethnographic studies on other specific musical domains which can then be compared with the study in Chapter 5 as a more productive approach to examining this question.

7.2.5 Is there a link between nonlinear dynamical processes and exploratory approaches to engaging with musical instruments?

Although the answer to this question is largely covered in the responses to the other questions above — and highlighted in Contributions 1, 2, 3 and 4 — the answer is reiterated here for clarity. The question was explicitly addressed in the comparative evaluation studies presented in Chapter 4. As noted already, these studies provide evidence for the idea that there is a link between the presence of nonlinear dynamical processes in digital musical interfaces, and that including such processes can provide richly explorable situations for musicians to engage with. Interfaces without nonlinear dynamical elements were awarded lower questionnaire scores by participants for ‘‘scope for exploration and discovery’’. The interview-based study approached this problem from a different perspective, showing that musicians engaged with instruments classed by Fletcher (1999) as ‘‘essentially nonlinear’’ were more likely to place exploration at the centre of their improvisatory practice. Finally, the detailed descriptions of the behaviour of nonlinear dynamical processes close to critical thresholds given in Section 6.2.2.1 show that from an interaction point of view there are many similarities with how improvisers engage with their instruments. The specific example of edge-like interactions with musical tools is traced in Section 6.2, providing a close fit with these critical threshold behaviours.

7.2.6 How can the effects of nonlinear dynamical processes in musical interactions be evaluated?

This still remains a difficult question. This thesis follows the advice of prior research into music and HCI that advocates a mixed methods approach. A considerable jump must be made across the gap that exists between, on the one hand, considerations of the specific mathematical properties and behaviours of nonlinear dynamical systems, and on the other, the ways in which people think of and engage with musical tools in their own musical practices.

The triangulation between the lab-based comparative evaluation studies detailed in Chapter 4 and the ethnographically-informed interviews presented in Chapter 5 provides a useful model for attempting to bridge this gap. The comparative evaluation studies explore specific implementations of nonlinear dynamical processes, allowing for variables to be controlled and tested, albeit in an environment that may be somewhat divorced from real-world musical practices. The ethnographically-informed study comes from the other direction, drawing on a thorough examination of tool engagement in musical practices. Where there is overlap between the two approaches, the studies are mutually supportive, providing weight to the specific conclusions and bridging the gap described above. The investigation of edge-like interactions (Section 6.2) provides a useful example of this: the discussions of practice connect very closely to both the raw mathematical descriptions, and the primary findings of the comparative evaluation studies.

7.2.7 What roles can nonlinear dynamical processes play in human-computer interaction beyond the musical domain?

Although the central area of concern for this thesis is musical practice, the research has been designed to shed light both on how nonlinear dynamics may be applied in supporting non-musical creative interactions (see Contribution no. 6), and on how the use of nonlinear dynamical processes in musical applications is helpful in understanding the nature of surprise, exploration and creative interactions in general (see Contribution no. 5). The material-oriented approach to art and music detailed in Section 2.2.1 provides an important link between the nature of surprise and exploration in creative practices, and considering the value of nonlinear dynamical processes in creative interactions.

Section 2.3.4 of the literature review established the potential importance of nonlinear dynamics in creative interactions with visual art media, and with computer games. The difference in interacting with real paint and paintbrushes when compared with digital equivalents provides a close analog of the situation with musical tools: while the tools may be very easy to pick up and engage with (even for young children), the nonlinear dynamical nature of the medium can be very complicated in terms of interaction, providing scope for the material to be explored in itself over long periods of time. In a different direction, computer games — particular those that rely heavily on simulated physics such as driving games — provide a similar analogy: they are usually simple to begin with, but navigation of the in-game dynamics proves a formidable challenge that can be creatively engaged with (e.g. cornering and managing momentum, see Sections 2.3.4 and 6.5).

Wider reflections on surprise and exploration raised by both studies provide important insights for non-musical domains and suggest refinements to existing HCI theory. An important distinction between surprises that come about as a result of combining known elements, and surprises that are inherent in the interactions themselves is raised in Sections 5.4.1 and 6.1.1. This distinction is particularly important in widening what is thought of as productive surprises in HCI, particularly in relation to Schön's reflection-in-action. The importance of interactional surprises in musical interactions highlighted in this thesis suggests that there may be applications beyond music for these kinds of interactions, and particularly for utilising nonlinear dynamical processes to achieve these kinds of interaction.

7.3 Limitations

Both the lab-based studies detailed in Chapter 4 and the ethnographically-informed study in Chapter 5 have inherent limitations in terms of what can be inferred from the respective results. The specific limitations of the two methods are therefore detailed in the following two sections below. The limitations of both studies were deliberately mitigated to an extent through the use of a mixed methods approach, triangulating between the more quantitative and qualitative approaches to provide a more nuanced perspective (see Chapter 3).

7.3.1 Limitations of the comparative evaluation studies

The lab-based comparative evaluation studies presented each participant with two interfaces that included nonlinear dynamical processes and two that didn't. The results are not easily generalisable beyond these specifically designed interfaces and their specific implementations of nonlinear dynamical processes. Section 7.4 below suggests particular ways forward that address this limitation.

A further limitation stems from the fact that any musical interface requires a great many design decisions to be made — beyond simply the independent variable to be tested — which cast a strong influence over how the interfaces will be used. The interfaces used in this study present only a single implementation of nonlinear dynamical processes, and these processes are only a single factor amongst many influencing the nature of the interaction. As an example, creating interfaces that allow easy access to polyphonic pitch control (e.g. a keyboard-like instrument) would set up a very different musical context within which to examine the role of nonlinear dynamical processes, whereas creating an interface capable of only a single pitch where pitch control is not simple (e.g. a saxophone-like instrument) sets up a very different context. Each context would likely exert a strong influence over musicians' attitudes to the tool, and to the role of nonlinear dynamical processes, unpredictability, and exploration (see for example the results of the second study linking particular attitudes to exploration with the use of essentially nonlinear instruments in Section 5.3.2.1). These distinctions would also be interesting to explore in further work.

7.3.2 Limitations of the ethnographically-informed study

The ethnographically-informed study is deliberately limited in that it focuses on a very specific community of practice. The results cannot easily be generalised to make conclusions about engagement with nonlinear dynamical processes in musical tools in other musical domains. Examining this specific community of practice nevertheless serves as a useful starting point in examining nonlinear dynamical interactions, as the community appear to engage more specifically with these aspects of their instruments and tools.

As noted in Section 5.2.2, it can be difficult to tackle questions around nonlinear dynamical processes head-on with performing musicians, as they are not generally used to thinking of their instruments in this way, and the complexity of the interaction is dealt with in a tacit, embodied fashion that is not easily accessible via conscious reflection. The questions were therefore necessarily indirect.

A further limitation from a musicological perspective — noted by several study participants — is that the data gathered from participant interviews would be significantly more interesting to many researchers if they were not anonymised. This would allow the data to be contextualised and potentially compared with the views of the musicians expressed in other articles and interviews, and the research could be examined in a more open and critical fashion. There are obviously potential drawbacks with this approach too: some musicians may be less inclined to participate under these conditions, whereas others may be more inclined to participate, and may answer questions differently if they know they are on the record under their own name.

7.4 Areas for future research

Both the contributions and the limitations of the research conducted for this thesis suggest a number of potentially valuable avenues for further research.

From an HCI perspective, the explicit inclusion of nonlinear dynamical processes presents a relatively novel approach. Research into this area suggests a plethora of potentially interesting topics which were largely beyond the scope of this thesis: wider ideas about how we engage with the physical world, embodied knowledge and functional, tacit understandings of highly complex physical interactions, the role of interactional unpredictability in creative practices.

The research can also be taken up more specifically for the field of HCI. The absence of nonlinear dynamical processes from interaction can be considered a typical characteristic of digital interaction. Acknowledging this provides a different perspective for HCI, opening up a vast potential design space that appears to have been overlooked. How is interaction different with and without these processes? What roles might they play in digital interactions?

A productive way to take forward the discussions in this thesis would be to bridge the gap between the field of acoustics and the field of interaction design. For the former, nonlinear dynamical processes are taken for granted to the point of being banal. In the latter, nonlinear dynamical processes are all but absent. Acoustically informed interaction design, or interaction design informed acoustics research would both be potentially illuminating approaches to further exploring the roles that nonlinear dynamical processes in creative interfaces. It would also be interesting to attempt to explore nonlinear dynamics in musical tools across a broader range of musical practices, to see how interactions differ in different contexts, and whether the kinds of engagement described in relation to free improvisation are more widespread.

In terms of addressing other domains, the discussion in Section 6.5 suggests that studies of nonlinear dynamical processes in visual art materials and in relation to visual art practices, and the presence of nonlinear dynamical processes in different kinds of computer games, might be productive starting points providing useful points of comparison with the sonic focus in the present thesis.

Addressing the limitation highlighted above in Section 7.3.1 — that the field of nonlinear dynamical processes is very broad, and these systems may be implemented in a variety of ways — a productive follow up to this research could examine different categories of implementations of nonlinear dynamical processes. For example, it would provide a useful next step to conduct similar experiments comparing attitudes to interfaces containing nonlinear dynamical processes as a control-rate mapping (as implemented by Momeni and Henry (2006) or example), with implementations that place these processes in the audio engine as with physical models of acoustic instruments and the designs used in this thesis. Other distinctions could also be tested, e.g. the use of nonlinear dynamical systems with different dimensions, autonomous versus non-autonomous systems (Section 2.1.1.1), and the presence of different qualitative behaviours within the systems, such as the different kinds of possible bifurcations (see Lakshmanan and Rajasekar, 2003, p. 75). Similarly, the nonlinear dynamical interfaces could be compared with other kinds of systems, e.g. comparing engagement with nonlinear dynamical processes with stochastic processes.

In terms of evaluating the results, another specific aspect of this thesis that might be developed is the analysis of the quantitative data logs taken from participants in Chapter 4. Small participant vignettes were presented in Section 4.4.2.3 that drew together what the study participants said about themselves and their practice in the inteviews with the logs of their input data and the audio recordings they made with the various digital musical interfaces. More detailed study of these elements may provide clearer pictures of the relationship between tool design, musician and musical practices, and lead to more specific ideas about how nonlinear dynamical interfaces are engaged with differently by participants of differing backgrounds.

7.5 Concluding remarks

The term "nonlinear dynamical processes" denotes a very broad variety of processes. As noted at the outset, they tend to be the rule rather than the exception in our daily experience of the physical world. Bringing these processes into digital interactions as discussed in this thesis is not an attempt to directly recreate particular aspects of the physical world in digital interactions, but a method for exploring how our interactions are different with such systems. Nevertheless, openly embracing the more complex aspects of such systems in interaction appears to be an interesting strategy for designing creative tools, helping to create tools that — due in particular to the potential for hysteresis and mode-locking in such systems — can be explored over long periods of time, yielding surprises within the interaction itself that can support a dialogic, material-oriented engagement.

Chapter 8

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Appendix A

Transcript of participant interview

A single interview with participant 2999 from the ethnographically-informed study detailed in Chapter 5 is included here for reference.

Interviewer: Could you start by describing the tools and instruments that you use in your practice?

Participant: I play cello. And the tools I use are very much quite conventional, just my usually acoustic instrument and a bow or two bows, and that's pretty much it. I very rarely have used preparations because I feel that - I may in the future - but at the moment I feel that there's so much to discover that I don't feel like I need some other tools to create new layers of possibilities of sound. At the moment at least.

Interviewer: Could you say a bit about the role of exploration and discovery in your playing? If you're performing or if you're recording or whichever situation.

Participant: I still feel that my playing doesn't change so much depending on if I perform or record, and exploration and discovery is the playing actually, it's very very important. That's what the playing is, just to me with the cello if I'm in the room, I never know what it's going to sound like, that's what I feel.

Interviewer: Because of the room you mean?

Participant: Because of the room, because the instrument might be a bit different, my fingers might be a bit different, things I've been listening to or have been thinking about, so to me personally, it's very much about what's there in the moment - I mean I'm speaking of solo playing - of what's there in the moment and what I find interesting when I start playing, and that's kind of the guiding line for me when I play. Of course, when there are other people involved then that information comes in as well, in combination with them in that context, what I find interesting to explore. So for me the exploration - I can't really separate it from playing.

Interviewer: For the moment just to limit it to solo playing, you're often surprised by what happens then? And what the instrument does, or what the response is in the room?

Participant: Yeah, if I'm not surprised I feel like things are not going very well [laughs]. Of course you have to be in the... because sometimes it just doesn't... I don't know, usually when I start playing these days, I trust that that moment will come. Sometimes it doesn't come - I don't know why [laughs] - and you also can keep searching, and maybe that's not quite, satisfying to me, but...

Interviewer: Do you have strategies for finding things like that, that you employ? Or do you try not to deliberately do that?

Participant: You have to start somewhere. And of course, there's material that I've been working with myself, so you might go to that material that's quite familiar, and you see what that does in that moment, so it's kind of patterns or just spaces on the instrument that I've explored over the years, and still it keeps changing.

Interviewer: Could you give an example of one of those spaces?

Participant: Yeah for example... issues of overtones. I remember when I started playing the cello, I remember my teacher telling me the cello has X number of overtones. I was quite impressed with that number, it was 20 something or 30 something, and I kind of forgot about that statement, but over the last years, really working with the instrument, it's such a strange comment, because there's just endless amounts of overtones when you really dig into the instrument. And I've discovered this one area of overtones where they came out and really surprised me, I'd never heard anything like it. It's a combination of strings, when I hit that combination of strings there's a whole layer of sound coming in that's completely something that just emerged one day and it's an area that I can go into just to see what that feels like, especially in the space, and then kind of go out again and discover something new.

Interviewer: So it's like a rich seam that you can return to to explore?

Participant: Yeah yeah for example, yeah.

Interviewer: What is it you're actually doing? You said there's multiple strings involved.

Participant: Yeah, I discovered that when I go - with the bow - to an area that's quite close to the bridge. So it's quite close to the bridge because depending on where you stroke the strings, how close it is to the bridge, it's a very different tension.

Interviewer: So this is sul pont?

Participant: Yeah yeah. And you get a lot of treble, and not so much bass, because it's probably the way it transmits through the instrument, it doesn't work, because the bass comes out of the back of the instrument, it doesn't travel through the back so much. There's lots of treble and that's where lots of overtones can come out. So for example, if I use three strings, just getting them into motion, I can't really explain it because for me it's a very tactile thing, and my touch point, kind of in harmonics can be slightly on one string, something happens and it's like a set of overtones just lifts off, and it goes, and it's quite independent of my movements with the bow. I think it came out of an exploration of me being really fascinated by circular breathing in reed instruments, because when you play an instrument with a bow, it goes back and forth and you get this rhythm. You can modify it, but it's....

Interviewer: The break where you reverse direction.

Participant: Yeah, how you break that rhythm of going back and forth. So I found this, and you get a set of sounds that are just lifted off that movement.

Interviewer: They sustain beyond it?

Participant: Yeah, it's a sustained note almost or a droney kind of thing, so yeah. That's kind of one little area that I've been playing with. But it's also, this sense of exploration, I don't really like to perform tricks. It just doesn't feel quite right to me, so it's an area I have to be careful with, not to overuse.

Interviewer: Because it's almost too easy?

Participant: Yeah, exactly. So when I find myself in that situation where I'm not quite sure where things are going, like oh yeah, lets go there for a while and see, and you kind of go into another kind of area that's familiar, it feels not quite - I don't know - for me it's this sort of integrity missing if I do that. Integrity is a big word, but yeah, that's when exploration is not there anymore, it's just about old stuff that I've discovered in the past. For me when I play in a concert and I find myself doing something I've never done before, it still happens and it's completely fascinating, and that's when I know it's going well, when I have this sense of freedom when you can go, "oh, I've never this before.". So after all these years, that's the kind of whole thing.

Interviewer: So is part of that like you say, you kind of limit it to the cello and the bows, and no extra preparations for the moment? Is there something you like about having a very consistent - not exactly limited - but you could find new things by adding things, but you prefer to find them within the cello?

Participant: At the moment yeah, because I still feel that I have so much to learn from it still, without the props. I still feel that I have so much to learn from it still, without the props. Because the instrument, it's built in a particular way to resonate properly, so I haven't found a way of sticking things in that adds something I suppose. Guillaume [Viltard] has this additional bridge that he sticks in, and that's fantastic, it's really beautiful what he can do with it, but that's something he made himself for the instrument to work, so that's amazing.

Interviewer: It's quite a specific thing to do.

Participant: That's out of his own exploration. So I haven't found anything that I find particularly...

Interviewer: But you also haven't felt the need to?

Participant: No, and I also don't like gadgets very much [laughs] I feel like they keep an area of my brain too busy to focus on what I actually want to do. I wonder if I've ever... no I don't think I've ever really used preparations in concert. No. I mean I can also put my bows aside and use plucking, which is for me a different sort of

Interviewer: state

Participant: state.

Interviewer: In trying to prepare this, I tried to divide up different kinds of surprise and different unpredictable things that would happen. One distinction seemed to be between surprises where you are doing something with the instrument but you don't actually know what the response will be, and another one where you actually know what sound will come out - you deliberately make a sound and that sound happens, but the situation is surprising just through how that sound ends up fitting in with the previous sounds that you were making. So one is a result of the interaction being unknown, and the other is how a known result fits in with everything else. Is there one or the other that appeals more to you, or do you see that distinction yourself?

Participant: Yes, umm, consciously I wouldn't distinguish, but I can understand what you mean. But it's not really... they both sound quite appealing to me.

Interviewer: Does the latter one sound - because it's mainly the former one in mind, and what you were saying about that area that you described, it's an area where you're doing things, but it lifts off, not independently of what you're doing, but it's slightly unexpected.

Participant: Yeah, I mean it lifts off, I don't know how it lifts off, it depends a bit on the space, but that's what I find exciting, it lifts off and that bit, it's quite unpredictable how it will lift off in that space. Also this circular breathing has something I've been thinking of in my exploration of the instrument. Another thing I always found quite interesting is playing with electronic musicians, especially musicians using no-input devices, where it seemed to me that the way they make the currents come out, the currents that are there - the audible electricity, and then they do something which comes out and goes away again. It's kind of - can you understand? - a kind of constant current, and you kind of lift.

Interviewer: You accentuate a certain aspect of it?

Participant: Not accentuate, just reveal it and then conceal it again. At least that's what it often sounds like to me. You reveal it and it comes out "pooouuuff" and it goes away again.

Interviewer: You sort of unlock it and unleash it.

Participant: Exactly, that sort of energy I always find quite attractive in music. And that's also something I've been looking for a bit on the instrument. Not in the way of "OK today I'm looking into this," it's more of something that just, because I found it really interesting, how can I do this with the cello. So this kind of finding, almost like a kind of inaudible energy in the instrument, "poouuff" try to make it come out and go back again.

Interviewer: That definitely feels like a familiar impulse. So someone like Toshi Nakamura?

Participant: Yes, but also Daichi [Yoshikawa] has that kind of thing, or Paul [Abbott] when he was still... actually Paul had it when he played still a lot electronics. It was kind of like a fierce energy that's kind of not always audible. And once it has been there you kind of always sense it.

Interviewer: Yes, like a threat.

Participant: [laughs] Yes, a bit.

Interviewer: One more surprise distinction was the interaction or the result thing, another was introducing different objects to try and find things, we talked about that a bit. One other thing is doing things that are beyond your physical limitations, so because the thing that you're trying to do is too hard to do, something else happens.

Participant: Yeah, I like too. I really like to, maybe I often like to get to those places because then new things always happen. Issues like fatigue. I mean it's quite hard to push yourself there, but I realise when I see other musicians going there, I find it really beautiful. Because there's a certain thing that comes with fatigue, like surrender, like "well... [sigh]" and when it comes out in the music it can be really beautiful. So that's very important. And it's also how you learn, how you keep learning. You do want to discover new things, and for me that area is much more important than listening to other music and trying to integrate that in my playing. Pushing my own limits in that way, it's quite important.

Interviewer: Can you give a specific example again?

Participant: Um, yeah. For example this glissandi when I played with Toshi [Tsuchitori], I kind of came with a particular attitude. I was quite excited to play with him and I felt I could learn from that situation. People may not hear me but I thought, that's alright, that's just how it's going to be. So I just came just to play with him, and Seymour [Wright], and I knew Seymour is going to be quite excited about playing, so I knew it was going to get loud and my instrument is not built for these situations, and I've often thought maybe I should just completely avoid these situations because that's not what the instrument really is supposed... but I more cherish these situations because it kind of pushes me to this limit where the little details, the tactile details that I usually like working with, they're not, I can't go there. So I have to see how can I be present without pushing myself too much in that sort of really loud context.

Interviewer: Without just giving in and doing that you mean?

Participant: Yeah, and I've found two musicians who I found quite inspiring in dealing with this situation. It's a drummer

Interviewer: That's not a problem drummers normally have.

Participant: No exactly. I think it was a duo with Steve Noble and - what's his name - a South African drummer. London based South African. Already quite old. So he was playing with Steve Noble, drum duo, I think it was Wadada Leo Smith on trumpet at Freedom of the City festival. So the way that drummer was dealing with the fact that he wouldn't be so loud and so powerful as his counterpart on the same instrument. And I noticed he was kind of chiselling into the music, rather than trying to be at the same level, so he's really being very economical in the music that he was playing, almost like you had somebody chiselling into the music, almost like he was taking away things rather than adding, although of course he was adding.

Interviewer: Sort of masking? Like masking things?

Participant: Not masking things, but by adding really pointed sounds, the music almost started to slow down and become more ... shaped in a more clear sort of way. And I thought that was really interesting. And I saw [inaudible] he's a double bass player, he's doing something similar in a very loud context. And also he's very limp, almost taking away sounds.

Interviewer: Did you say limp?

Participant: Limp! Not limp. It was almost like he was taking away notes from his own playing to be heard. So that's kind of what I tried to do, and on Sunday I really tried to be economical with my sounds, and I think it really worked, and not try to put in lots of notes, but put in quite precise notes. It centres sort of - not in my playing, but in how it fits in. And if it gets too loud I just stop playing and let them get on with it for a while.

Interviewer: Rather than competing with it.

Participant: So that's kind of the limitations I suppose, where you hit your limits you just have to find a different approach.

Interviewer: You had to deal with the limits of that because you knew you couldn't play with your usual approach.

Participant: And also another approach would be, I quite like quite fast complicated rhythms. For me it's almost like a rhythm of speech. I'm not a virtuoso cellist, I'm not very good at really fast patterns in a traditional way, but I try to kind of hit, see how fast I can get, but then I often stumble, and I quite like the rhythm of stumbling or limping, but in order to go to a genuine limp, limping situation, you have to really make yourself limp! And that's maybe the result of being masochistic, but just to find something beyond what you try and do.

Interviewer: One thing I've been - again just to slightly diambiguate what people mean by surprise and what the specific thing they enjoy about that is - proposing a silly example where just as a sort of talking point, if I gave you a button that just made a random sound every time you pressed it, would that be interesting or could you still explore that, and if so why, and if not why?

Participant: Makes a random sound. You mean I can play the button?

Interviewer: You can press it and something will happen.

Participant: But I don't know what's going to come out?

Interviewer: Yeah, if you press it again it'll be something completely different.

Participant: You mean as an experience for myself or if I try to make music with it?

Interviewer: I guess more the latter, why that wouldn't be interesting or what would be interesting about it.

Participant: Um, it depends on the sounds that come out! And the button, the shape of the button and how easy it is to press.

Interviewer: It can be however easy you like in this hypothetical situation.

Participant: For me it's the tactility of something when I play, it's very important so the tension of things. So this taking away that's quite, plus I don't know what's coming out.

Interviewer: And you can't control it, it just plays the sound and stops. Can you explore that?

Participant: I don't know, I'd have to try, I can't quite say if it would be interesting or not. For me it seems more like a game than a constructive tool to make sounds. I suppose you can't really, for me it's the exploration of the sound that's happening and how you listen to it and react to it at the same time, that's how I play, and how I like to play, so if that thing that I'm exploring keeps changing in unpredictable ways then I can't really do that. Because I suppose this thing about improvised music - for people that are not familiar with it - that it might be slightly random and it's kind of free and wild, but it's not quite like that, for me when you deal with it, you practice it, you play a lot with it over the years. It's more like a craft, you try to get to know your own vocabulary as well as possible, and try to discover new things all the time. It's not random at all. Of course, a sense of surprise, you want to look for it, but it's still a surprise within your - I don't know what it is or what you call it.

Interviewer: Within the language of the instruments still?

Participant: Yeah, yeah. And that's connected to you and the musicians you play with. And that's also why more and more I appreciate playing with musicians I know and work with on a weekly basis. Because often I find when I play with a musician that I've never played with before it takes a while to really hear them. When you know somebody really well - they always do new things - but there's something about there sound, you really hear them. For example, last Sunday again with Toshi [Tsuchitori], Seymour [Wright] is on one side, and Toshi is in the middle. I couldn't always hear Seymour, but because I knew him so well, I really could hear him, like it's almost like you feel their playing, you know their kind of momentum in their playing, and I find it really fascinating.

Interviewer: You know why they're doing a particular thing.

Participant: They might be doing something completely different from what they normally do, but therefore you hear it. I feel like when listening becomes something so peripheral, and I think that's - in my own practice and practicing with other musicians on a regular basis - you really widen what you can hear I feel. And then to play with that is fun.

Interviewer: So you hone in more on the detail?

Participant: Yeah

Interviewer: Because you can get past the initial...

Participant: It's just the amount of detail that you can take in when you know something is potentially wider. But then, it's also fun to play with musicians that you're not familiar with and to start that process.

Interviewer: That seems like it's sort of analogous to your own playing on the instrument, you narrow in on the details of particular processes, like that example you said near the start, you sort of zoom into it, then you can go to it, but it's a very general area and you can explore the detail of that each time, partly because you know it so well.

Participant: Mmm, yeah, and for me I think the activity of listening and making a sound, I think in conventional music it's always slightly separate, so for me in improvised music when it's working well, it's almost like it kind of falls into one, collapses into one. You listen and make a sound at the same time. And it needs a lot of training to get there, that you can actually, you play yourself and your able to listen to yourself whilst also listening to what's around you. And to able to do that takes quite a lot of time. And I think that's the musicians that i really enjoy playing with kind of do that.

Interviewer: And that's something that communicates itself to you in there playing.

Participant: Yeah, and that comes over time. And I think that's what's so fascinating about their music. And even when you kind look at people who may play classical music I feel that if they also improvise and have that activity in their lives, you can kind of hear that in their approach to a piece of composed music.

Interviewer: They can't switch off and play it, they have to listen at the same time. That seems to link in to the button thing. With that, your listening is kind of arbitrary, because you press the button and the button is going to do that thing, and there's no listening and subtle refinement of what you're doing because you don't have room for that and you might get something new and interesting, but there's no room for that feedback loop of you hearing it and refining it and provoking it. I've got one more question which possibly we've already covered which is: what's the motivation for wanting unpredictable results - if that's a fair thing to say that you do?

Participant: That's complicated! It's a big question, but I think it has to do with learning. I feel like if I'm avoiding unpredictable, unstable outcomes, I'm not going to learn anything. The question makes my brain spin! There's lots of things that I could say. I find it very beautiful that there's things that we can't understand and we never understand, and I think it's important for us that there are these things we don't know what's going to happen. I think we'd be extinct as a human race if we understood everything, so for me it's something to cherish, to open up open ended processes. Not in a random way, just open them up and follow them and try to stay connected.

Interviewer: That's a very good answer. Is there anything that has been in your mind during this interview that has not been said, or anything that you wish to add?

Participant: I think one thing that's also quite important to me is how you can make different energies coexist in the thing. On my own or with others. How you can open up levels like for example very calm energy and then a much more frantic energy and how it can coexist. For me it relates very much to life, how these feelings can be so complicated and layered, and I find that very interesting. And contradictory as well.

Interviewer: So you'd be physically doing these two things at the same time?

Participant: Yeah, or I just connect to one energy and if it's there I can try to keep that going while opening up another layer. And that's also maybe relates to the material that's quite familiar, and material that's very unfamiliar and very on the edge and you can't quite master and have than happen at the same time.

Interviewer: Like collaging it?

Participant: Yeah, a bit. Collaging or just have like two poles - or three poles or four - and then see what happens in between. And that's also a way of creating an unpredictable field in the music by setting two or three ... poles.

Interviewer: Can you give a specific example again?

Participant: Yeah for example, one of the most obvious is bowing and plucking which for me is a very different sort of language and the way I relate to them is very different, and it's something I've been wondering how to bring those two together which is very difficult for me. But - and it's something I'm always working on, and haven't quite found out how to do it.

Interviewer: But that's a useful process?

Participant: Yeah, it's a process for me to discover things, and if I kind of do bowing and plucking at the same time there's always something happening between those poles.

Interviewer: If you were doing each individually you wouldn't get that thing between them?

Participant: So there's something that happens in order to make that possible, that's the unpredictable area that if it's interesting it's nice to work with.