INVESTIGATING THE EFFECTS OF INTRODUCING NONLINEAR DYNAMICAL PROCESSES INTO DIGITAL MUSICAL INTERFACES

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ABSTRACT

This paper presents the results of a study that explores the effects of including nonlinear dynamical processes in the design of digital musical interfaces. Participants of varying musical backgrounds engaged with a range of representative systems, and their behaviours, responses and attitudes were recorded and analysed. The study suggests links between the inclusion of such processes and the affordance of exploration and serendipitous discovery. Relationships between musical instruments and nonlinear dynamics are discussed more broadly, in the context of both acoustic and electronic musical tools. Links between the properties of nonlinear dynamical systems and the priorities of experimental musicians are highlighted and related to the findings of the study.

1. INTRODUCTION

This paper explores the complicated relationships between artists, tools and creative output. Worth [1] highlights a distinction between two perspectives on engagement with musical tools. The first — referred to as *idealist* — focuses on the tool as a device for realising an artistic idea formed in the mind of a composer or musician. In this case the tool is ideally a transparent medium for realising this idea with as little mediation as possible. This is essentially a communication-oriented model where a message needs to pass from A to B, and distortion of the message is undesirable. This is contrasted with a more material approach in which the tool plays a significant role in forming ideas, and the creative process is seen as a back-and-forth engagement with the tool.

Worth examines this latter attitude in the work of electronic musicians associated with the Mego label, but similar attitudes can be found in other musical practices, notably free improvisation where instruments are variously referred to as "allies" [2], things with which to have "relationships" [3], things with their own "intentions" [4], and where the performer may be "played by" the instrument [5, p 57]. Keep [6] discusses similar attitudes in experimental music, where the exploration of inherent sonic properties plays a significant role. Gurevich and Treviño [7] discuss the tendency towards a communication-oriented model in the New Instruments for Musical Expression community, noting that the term *expression* seems to include a tacit assumption that the performer's role is to communicate something "extramusical", and that this assumption risks excluding alternative modes of engagement such as those found in experimental musical practices. Musicians concerned with a more material-oriented approach often seem to value instabilities and unpredictable elements in their engagement with a given tool [3, 6, 8, 9].

A central motivation for this research is considering tool design with the latter interaction model in mind: if tools are something to form a dialog with, to have a relationship with, and to collaborate with, how do different designs facilitate or impede this approach?

2. NONLINEAR DYNAMICAL SYSTEMS

This paper links the material approach outlined above to the properties of nonlinear dynamical systems (NLDSs), and examines connections between the inclusion of such processes in musical tools and particular approaches to engaging with these tools. NLDSs are systems in which the state at any given time is at least partly determined by previous states via feedback of some kind, and in which the determination of successive states is not a linear combination of current inputs and previous states. From an interaction perspective this means that timing can be a crucial element; *when* something is done can be as important as what is done. Such systems can at different times be stable and unstable, cyclical and unpredictable, chaotic but deterministic, and exhibit a range of complex behaviours.

NLDSs have been explicitly employed by composers and musicians in a variety of ways. [10] links their properties to compositional approaches to pitch and rhythm. Many others, including [11], [12], [13], [14], and [15] have implemented systems as structuring elements, synthesis elements, mapping elements, or combinations of these. Such systems exist in more subtle ways in many other musical practices however. Feedback has been used by a broad range of musicians in different musical areas [16–18], whether with microphone and loudspeaker or with feedback loops inside electronic systems. Many acoustic instruments themselves incorporate nonlinear dynamical processes, such as in the feedback relationship between reeds and resonating air columns [19], and in bowed strings [20].

The exploration of instruments and musical tools that takes place in many areas of free improvisation and experimental music [6, 21, 22] appears to be reflected in the choice of tools in these domains, as there is a tendency towards engaging with the unstable, unpredictable aspects of instruments [3, 6, 9] and often an explicit acknowledgement of a more material-oriented approach [6, 8]. The term "experimental" is used here in a very specific context, referring to an approach in which the outcome of an action or method is genuinely not known or unpredictable, associated particularly with post-Cagean musical practices as discussed by [23].

3. MAPPING AND DYNAMICAL PROCESSES

The study presented in this paper examines the ways in which different participants react to systems that include nonlinear dynamical processes, and considers whether this can be related to the participants' own practice regarding music making and engagement with musical tools.

As such, the present study is related closely to studies into the effects of different parameter mappings for musical tools, such as the work done by [24] and [25]. The study conducted by Hunt and Kirk [24] into the effect of complex cross-coupled mappings on musical engagement is of particular relevance. The study found that although the isolation of individual parameters in a controller through one-to-one mappings allowed for accuracy in completing very simple sonic tasks, the complex mappings were better suited to producing more complicated gestures, and perhaps more importantly, were often seen as more fun and potentially more interesting to use over longer periods. Menzies [25] extended this work through an investigation of the inclusion of linear dynamical processes in controlling musical systems, arguing that we are used to engaging with dynamical processes in our everyday life — moving limbs, manipulating objects, playing sports, etc. — and that dynamics lend a richness to these interactions.

The extension into *nonlinear* dynamics is perhaps counterintuitive from the communication-oriented perspective described in section 1; the nonlinear element provides scope for chaos and bifurcations, making direct, predictable control potentially difficult. However, it may open the door to the kinds of relationships discussed in relation to the material-oriented perspective. As an example, consider the response of a reed instrument where too much pressure is applied to the reed, producing a sharp high-pitched squeak. In terms of interaction design, this result is very unpredictable, and can be difficult for beginners to control and remove from their playing. In the domain of more experimental music however, this bifurcation point becomes a potentially interesting site for investigation and experimentation, and can provide a means to find new and unexpected situations, even after many years of studying an instrument (see for example John Butcher describing his relationship with the reed in his saxophone playing [9]).

The study presented in this paper questioned participants about control, surprise, and potential for exploration in relation to a range of systems designed to differentiate the impact of the nonlinear dynamical elements.

4. STUDY METHODOLOGY

The study itself involved 28 participants of differing musical backgrounds each using four different representative digital interfaces (described in detail in the following section), all of which were controlled via a simple MIDI controller consisting of two dials and a slider. The participants were recruited such that half of the group were musicians consistently engaged in experimental musical practices. Each participant was asked to spend a period of 4-8 minutes trying out a given interface, before making a short recording of 1-4 minutes. The order in which the interfaces were presented was randomised for each participant, and no information was given as to how they worked, what each input might do, or how they would differ from each other. Data from the controller was logged from both activities. Participants then answered a range of Likert-scale questions (detailed in 4.2) before repeating the process with the remaining interfaces. After completing this process with all four interfaces, they provided information on their musical background (level of experience, instrument(s) played, experience with electronic musical tools, experience of free-improvisation, and a short overview of their musical practice), and conducted a short, semi-structured interview. The results presented here focus primarily on the data from the Likert-scale questionnaire with some context provided by the interviews.

4.1 The interfaces

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 many different decisions to be made regarding the nature of the input device, the mappings and sound engine will all combine and interact with the user's own background, experience and taste. The specific design of the four interfaces in this study attempts to address some of these considerations, differing along two key variables: whether or not the interface incorporated a nonlinear dynamical process as a core aspect (NLDS vs static), and whether the mappings from the inputs to the parameters of the system were continuous or discontinuous (summarised in table 1). The former is the central concern in this study, whilst the latter provides a useful control, to test to what extent differences in the participants' responses were determined exclusively by the inclusion of nonlinear dynamics. Audio excerpts from the four interfaces can be heard at `http://tommudd.`

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Interface	Nonlinear Dynamical	Mapping	Audio Engine
1	Yes	Continuous	Resonated Duffing Oscillator
2	Yes	Discontinuous	Resonated Duffing Oscillator
3	No	Discontinuous	Resonated Oscillator
4	No	Continuous	Audio Sample Based

Table 1. The four interfaces used in this study

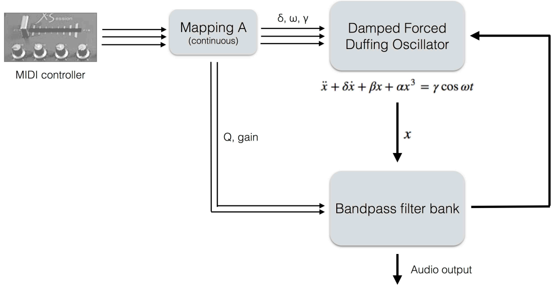

Figure 1. Interface 1. A damped forced Duffing oscillator coupled with a bank of linear resonators. The user interacts with the system via three MIDI controls.

co.uk/smc2015-examples/. A demonstration version of the MaxMSP software is also available at the same URL for reference. Each interface is discussed below in more detail.

4.1.1 Interface 1: Nonlinear dynamical system with continuous mappings

Both interfaces 1 and 2 are based on a damped forced Duffing oscillator [26], shown below in equation 1 as a discrete map. This is a nonlinear dynamical system that models the forced vibrations of a beam that is fixed at one end.

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

This equation is implemented at sample rate (44.1kHz in this instance) 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 [19] and hence to many physical models [20]. The specific structure of interface 1 is shown in Figure 1.

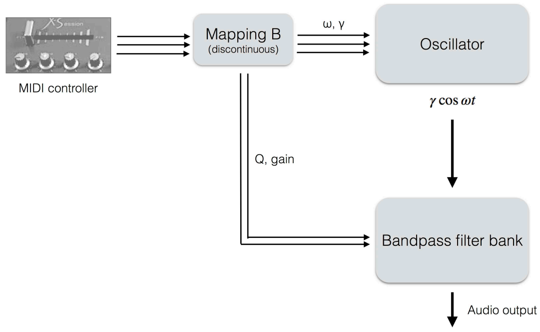

Figure 2. Interface 3. Duffing system and feedback are removed, leaving an oscillator and resonant filter bank. The discontinuous mapping is otherwise preserved from interface 2.

4.1.2 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. This distinction was included to assess how significant the nonlinear dynamical component was in comparison with the static discontinuities in the mapping. In other respects this interface is the same as interface 1.

4.1.3 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 2, rendering the interface non-dynamical and linear. The discontinuous mapping is retained however. Although the system is 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.

4.1.4 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 by basing the interface 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 to positions in the sample, playback rate and overall volume respectively.

4.2 Data Collection

The key data from the study presented in this paper comes from the questionnaire data and the MIDI control data, with some contextualisation provided by the interviews. The questionnaire asked each participant to what extent they agreed or disagreed with the following six 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**"
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 paper. Participants were also asked to rank the four interfaces in terms of which they found the most satisfying to use.

5. RESULTS

The results presented in this paper form an initial evaluation of the data from this experiment, but there are some significant trends that emerge from this initial analysis. This section details some of the key findings both in terms of how the variation in the interfaces affected the participants' responses, and how participants of differing musical background reacted to variations in the interface.

5.1 The influence of nonlinear dynamics

Figure 3 presents the questionnaire data provided by the 28 participants. Two statistically significant trends emerge from this data:

- The responses to the first two questions regarding control and ease of recreating sonic events both correlated with the nature of the mapping, with the discontinuous mappings for interfaces 2 and 3 seeming to elicit less agreement with the two statements (as determined by an ANOVA with $F(1, 27) = 9.45$, $p < 0.01$ and $F(1, 27) = 7.18$, $p < 0.025$ for control and recreate respectively).
- The responses to the third and fourth questions regarding surprise and scope for exploration and discovery correlate with the inclusion of the nonlinear dynamical processes, with interfaces 1 and 2 being linked more closely with these statements ($F(1, 27) = 13.11$, $p < 0.01$ and $F(1, 27) = 11.81$, $p < 0.01$ for surprise and explore/discover respectively).

In certain respects these results are not surprising: it seems natural for a mapping that may abruptly change at a certain threshold to be deemed uncontrollable, and for a chaotic system to be linked with surprise and discovery. The more interesting aspect is that the nature of the mapping *does not* seem to impact upon the questions regarding surprise and exploration ($F(1, 27) = 3.81$ and $F(1, 27) = 0.06$ respectively, $p >> 0.05$) and — significantly for this paper — that the inclusion of nonlinear dynamical processes

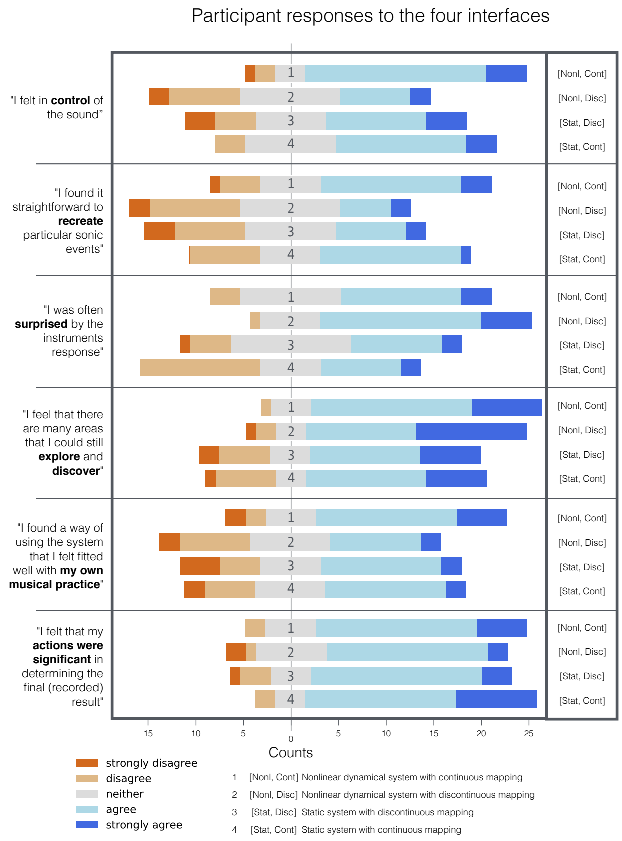

Figure 3. Participant agreement with six different statements in Section 4.2 as they apply to the four different musical interfaces described in Section 4.1.

does not seem to affect perceptions of control and repeatability ($F(1, 27) = 0.06$ and $F(1, 27) = 0.12$ respectively, $p >> 0.05$).

5.2 Interface preferences

The responses to the question "which interface did you find the most satisfying to use?" which asked participants to rank the four interfaces are shown in Table 2. The overall scores for each interface are calculated by awarding +2, +1, -1 and -2 for ranks of 1st, 2nd, 3rd and 4th respectively. This shows little clear consensus between participants, with only minor differences in rankings, with the scores all averaging out very close to zero. There was generally no correlation between the responses to the six statements detailed in Section 4.2 and interface preference. The only correlations found were for interface 1 (NLDS with continuous mappings), where participants who ranked this interface highly in terms of satisfaction also tended to feel in control, able to recreate sonic events, and that their actions were significant in determining the sounding result.

5.3 Differences between participants

The twenty eight participants can be grouped into many different categories based on the questionnaire and interview data, but as discussed in section 2, a concern for this research is whether there is a specific link between approaches to engagement and experimental musical prac-

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Interface	Rated Most Satisfying	Rated Least Satisfying	Overall score
All participants			
1	10	7	2
2	5	7	-1
3	6	5	-1
4	7	9	0
Experimental group			
1	6	4	-1
2	2	2	1
3	2	3	-1
4	4	5	1
Non-experimental group			
1	4	3	3
2	3	5	-2
3	4	2	0
4	3	4	-1

Table 2. "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

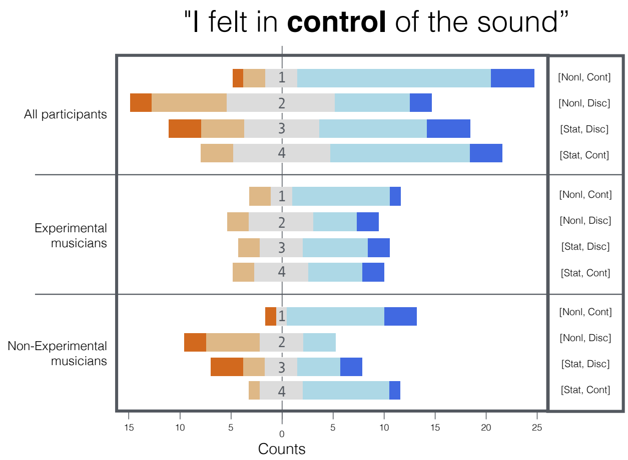

Figure 4. Comparison of response counts from musicians with and without experimental music backgrounds. The correlation between sense of control and the use of a continuous mapping (interfaces 1 and 4) is only significant for the non-experimental music group.

tices. Grouping the participants by whether or not they have a background in experimental music – in the narrow sense defined in Section 1 – highlights a number of differences in participant engagement. Figures 4 and 5 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 there was less variation in the responses from the experimental music group for each interface. Neither of the two points presented above in section 5.1 are significant for this group alone, whilst they remain significant for the non-experimental group (see table 3).

Table 2 divides the preferences for each interface by 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.

6. DISCUSSION

6.1 Control vs Exploration

The link between nonlinear dynamics and both *surprise* and *scope for exploration* is a potentially interesting one for several reasons. Firstly, it is of potential interest to musical systems designers interested in creating interfaces that allow for surprise and exploration for either their own use or for others to use. A similar mechanism for achieving such a response might be through the use of stochastic systems, but there is a fundamental difference between chance processes and the chaotic-but-deterministic nature of nonlinear dynamics. [5, p 1] claims that "randomness does not produce a sense of surprise, but rather confusion, dismay, or disinterest". The fact that the systems are deterministic means that although they are unpredictable and allow for exploration, they still allow for actions to be repeated, and as [6] puts it "to re-access fruitful results."

The fact that the inclusion of nonlinear dynamical processes did not have a statistically significant effect on the participants' sense of control, while the inclusion of discontinuous mappings did have an effect, initially seems to be a surprising result. Both systems incorporate relatively abrupt transition points, where a small change in an input control leads to a drastic change in the resultant sound. In the case of the discontinuous mapping these transition points are absolute: when the input value crosses a certain point, the resultant sound will jump. The abrupt transitions due to the nonlinear dynamical processes however are more flexible: the transition point will vary according to the state of the other inputs, and may in fact vary depending on the history of the input, and therefore the timing of the controller movements (again, analogous the complex range of factors that lead to an abrupt squeak in a reed instrument). With certain settings, the abrupt transition may not occur at all. Several participants noted in their interviews that the discontinuous mappings limited the range of input values that were available if one wanted to avoid such transitions (a problem no doubt compounded by the already limited resolution of the MIDI controls).

The conditional nature of the response of the nonlinear dynamical elements could explain the link between these elements and the scope for exploration: the fact that each input control can affect the behaviour of the other controls, coupled with the fact that the history of the input may also play a part in determining the state of the system provides a broad landscape of possibilities to be explored.

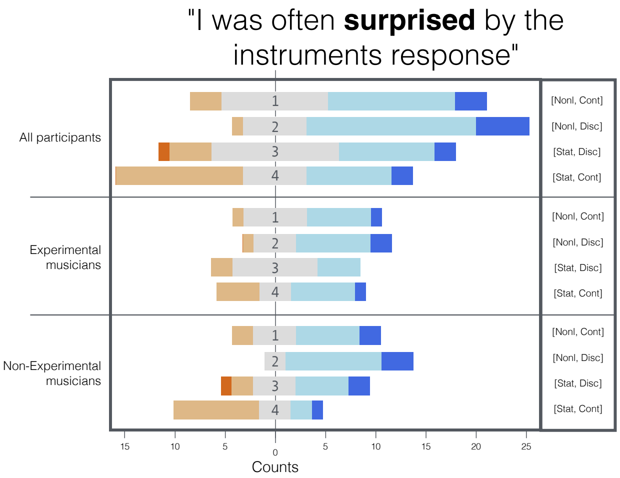

Figure 5. Comparison of response counts from musicians with and without experimental music backgrounds. The correlation between surprise and the inclusion of a nonlinear dynamics (interfaces 1 and 2) is only significant for the non-experimental group.

6.2 Other Implementations of NLDSs

These results are not necessarily easily generalisable. A great many other decisions are made in the process of creating musical interfaces, all of which may affect participant engagement, and the nonlinear dynamical elements themselves may be implemented in many different ways. A useful next step might be to consider these possibilities in more detail, and to examine the affect that each has on participant engagement. For example, whether the systems are responsible for synthesis directly, whether they are an aspect of the mapping process (as with [25]), or whether they cannot easily be classified in these terms. The systems may also be implemented at different rates: sample rate, control rate, or perhaps iterating only at user defined moments. Investigating how attitudes towards the interfaces shift when used for longer periods of time may also be productive, as the short 5-12 minute sessions for each interface may not be sufficient for participants to adequately answer the questionnaire and interview questions.

6.3 Contextual Complexity

The complexities of the musical (and social) situations in which musical tools are used make it very difficult to describe concrete cause-and-effect links between specific design decisions, and specific changes in engagement.

The interviews conducted with participants at the end of each session provide some useful contextualisation for the participants' questionnaire responses, particularly with regard to their qualitative attitude to aspects such as control and surprise. The musical situation in which a participant imagined themselves when using the interfaces seemed to have a strong influence on these aspects. For instance, in an imagined studio context, many participants expressed the desire to be surprised by the response of the tool, and that this might be a useful creative relationship. In a hypothetical concert situation however, participants often said that

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Variable	Question	F(1, 27)	p value
Experimental music group			
mapping	control	0.17	$n.s.$
mapping	recreate	1.44	$n.s.$
NL dynamics	surprise	3.47	$n.s.$
NL dynamics	explore	3.74	$n.s.$
Non-experimental music group			
mapping	control	15.83	< 0.01
mapping	recreate	6.12	< 0.05
NL dynamics	surprise	10.35	< 0.01
NL dynamics	explore	8.16	< 0.025

Table 3. Analysis of variance results 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.

they would be less enthusiastic about surprises, or would distinguish between different kinds of surprises with some being more acceptable than others (some participants with a strong level of engagement with free improvisation provided notable exceptions however).

6.4 Distinctions between participant groups

The links that were sought and not found between the grouping of participants into experimental and non-experimental and their preferences for the different systems may also hint at the complexity of the domain under consideration. There are perhaps many over-simplifications in the idea that experimental musicians will tend to find more exploratory interfaces more satisfying, and such links might be highly context dependent. The categories themselves involve large generalisations and do not take into account the range and complexity of individual musicians' attitudes and musical practices.

The experimental music group's lack of any statistically significant differentiation between the different interfaces noted in Section 5.3 does seem to suggest a significant difference in engagement and attitude however, although clear interpretations of this result are difficult. One possible explanation may be that the experimental group were more accepting of the specifics of each interface (in line with the material-oriented mindset outlined in Section 2), and were less inclined to try and realise pre-formed musical ideas. To give a more specific example, having a sense of control with a 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 interfaces may not seem so surprising.

7. CONCLUSIONS

As stated at the outset, the purpose of this research is to investigate the relationships between musicians, their tools, and their musical practice. The paper presented a study into the specific influence of nonlinear dynamical components on the ways in which musicians respond to, and engage with, a range of digital musical interfaces. Links were found between the inclusion of such elements and the perceived scope for exploration and discovery within the interface, as well as the potential for the results to surprise the musician. Links were also found between the continuous nature of the input mappings and the sense of control felt by the musicians, and their perception of their ability to repeat particular sonic gestures. These findings were discussed in the context of different musical approaches, particularly in terms of experimental musicians who often prioritise exploratory engagements with musical tools, although no clear links between such practices and the nonlinear dynamical elements were found in this study.

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