Dimensionality and Appropriation in Digital Musical Instrument Design

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ABSTRACT

This paper investigates the process of appropriation in digital musical instrument performance, examining the effect of instrument complexity on the emergence of personal playing styles. Ten musicians of varying background were given a deliberately constrained musical instrument, a wooden cube containing a touch/force sensor, speaker and embedded computer. Each cube was identical in construction, but half the instruments were configured for two degrees of freedom while the other half allowed only a single degree. Each musician practiced at home and presented two performances, in which their techniques and reactions were assessed through video, sensor data logs, questionnaires and interviews. Results show that the addition of a second degree of freedom had the counterintuitive effect of reducing the exploration of the instrument's affordances; this suggested the presence of a dominant constraint in one of the two configurations which strongly differentiated the process of appropriation across the two groups of participants.

Keywords

design, appropriation, interaction, mapping, embedded hardware

1. INTRODUCTION

Musicians often use instruments in unexpected ways. The history of musical instruments is replete with examples of performance practices which challenged the designer's original intentions. Jazz saxophone playing overturned many of the norms of classical technique. Distortion on the electric guitar was an engineering limitation before it became the sound of rock and roll. The turntable was a home playback device before it became a tool of scratch DJs.

In these examples, the process of *appropriation*, in which performers developed a (possibly idiosyncratic) working relationship with the instrument, came to define the instrument's identity. While how best to design for appropriation has been studied in the human-computer interaction literature [1], appropriation in musical instrument design is less well understood. If a performer uses a new musical interface in an unexpected way, should this be considered a design success or failure? What characteristics of instrument design make a performer more or less likely to discover personalised performance techniques?

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This paper investigates appropriation and the emergence of personal styles amongst performers of a simple digital musical instrument (DMI). Building on the results of a study by Gurevich et al. [6], ten musicians were given an unfamiliar instrument with highly constrained sonic capabilities. Through a series of rehearsals, performances, questionnaires and interviews, we sought to achieve three goals:

1. To verify and extend the results of Gurevich et al. [6] on the influence of constraints on musical style.
2. To study the role of *dimensionality* in how performers approach musical instruments. Specifically, we ask whether an instrument with more dimensions of control produces a richer set of musical interactions.
3. To identify signs of appropriation and personalisation in performers' interactions with an instrument.

1.1 Constraints and Personal Style

Constraints can be a powerful motivator for musical creativity. Magnusson [10] observes that musicians encountering a new instrument tend to explore its constraints rather than engaging only with the designer's intended affordances, a result which holds even for more complex augmented instruments which are partially familiar [11].

Gurevich et al. [6] conducted a study in which nine performers were given a one-button instrument; the button produced a tone of fixed frequency and loudness. This two-state device (tone or no tone) represents perhaps the simplest possible electronic musical instrument, yet the performers developed a broad array of playing styles. In addition to rhythmic variations, many performers discovered non-obvious playing techniques such as muting the speaker with the hands or tapping on the box. Despite the simplicity, many performers felt that they had not achieved mastery of the instrument during the study period. Reflecting on the diversity of styles, the authors proposed "that the very fact that the instrument was so constrained helped to make space for this personal element to emerge."

1.1.1 *Investigating Dependence on Context*

One aim of the present paper is to attempt replication of the results of [6] amongst a different group of musicians, with a different instrument possessing more degrees of freedom. We ask whether the emergence of diverse and unusual playing styles is a general feature of performer-instrument interaction, or whether this is solely a reaction to a particular set of constraints.

1.2 Dimensionality, Mapping and Creativity

Mapping between sensor data and sound production has been a central consideration of DMI design for over a decade [7]. Many approaches to mapping design have been explored, including one-to-one and many-to-many relationships between sensors and sonic parameters, hierarchical approaches [3], and mappings based on physical or gestural metaphors [13].

An important consideration is mapping dimensionality: in how many independent dimensions can the performer control the sound of the instrument? In DMI design, it is a common assumption (though by no means unchallenged [2]) that increasing the number of dimensions of control increases the expressive range of the instrument; accordingly, many new instruments tend toward a large number of controls to maximise the instrument's potential flexibility.

The cognitive and motor bandwidth of the performer places an upper limit on the usable dimensionality of the instrument [8], as do considerations of the learning curve [14]. But in this paper, we ask a more basic question: for even the simplest instruments (where there is no cognitive or motor limitation), is higher dimensionality a help or a hindrance to the performer's creativity? In particular, is appropriation more or less likely to occur on an instrument with a larger number of control dimensions?

2. INSTRUMENT DESIGN

One purpose of our study is to verify and extend the results included in [6] concerning the development of style in relation to constraints. Gurevich et al. argue that a musical instrument characterised by a highly constrained design leads performers to discover a diversity of style based on unexpected usage. On the other hand, stylistic variations flourish through the absence of strong externally imposed constraints, such as conventions established by common performance practice.

Starting from these considerations, we created a new simple DMI. Any resemblance with familiar musical instruments was avoided, including both appearance and main affordances, while a new set of design constraints was introduced. At the same time, we tried to maintain most of the fundamental design features of the one-button instrument used in [6], while expanding its sonic and control capabilities to assess the role of dimensionality on performers' responses.

"I think it would be neat if it had some sort of velocity sensitivity or something like that... I would make it something in the touch... If touch controlled timbre... but just with that one button." — Participant of the one-button instrument study [6]

2.1 Hardware

A self-contained instrument was necessary for the study, since the reliance on additional devices would have dramatically influenced the approach to practice and the performance usage of the instrument itself. Even a simple external PA inevitably introduces a set of extended controls over a system and makes available a track record of predefined possible interaction techniques (e.g., gain saturation, amplitude modulation). To be able to combine all the necessary components into a whole system, a Beaglebone Black[1] (BBB) was chosen as core of the instrument. The BBB is a small yet powerful embedded Linux board, hosting a 1 GHz ARM Cortex-A8 processor and equipped with a USB port for data connection and power supply, a uSD card slot and extensive General Purpose Input/Output (GPIO). To support audio output capabilities, we used a Beaglebone Audio Cape[2], an add-on board featuring stereo input and output.

The board is carried inside a cubic wooden enclosure 15cm on a side. This configuration was selected since the cube is an unconventional shape for an instrument, at first glance not deliberately ergonomic and not tied to any musical usage conventions. Given its geometry and its size (the minimum size to hold all the components), the cube-instrument can be either easily held in one hand or played on a surface such as a table or stand.

One of the sides of the box mounts a loudspeaker, which is almost fully exposed through laser-cut holes. On an adjacent face, two sensors are placed on top of each other: on the bottom, a Force Sensitive Resistor (FSR) and, on the top, a 5cm x 2cm capacitive multitouch sensor (XY position; originally from [9]). Both are directly connected to the GPIOs of the BBB using analog input and I2C, respectively.

An onboard battery allows use of the instrument without a power supply cord. Battery life is about 2 hours; a small hole on one of the sides of the cube exposes a USB connector for recharging. It is possible to switch the instrument on and off pressing the battery power button. An LED next to the switch lights when the BBB has booted and the instrument is ready to be played. Unlike [6], and due to the digital nature of our system, the charge level of the battery does not interfere with the audio synthesis and amplification process.

2.2 Software and Mappings

An audio engine written in C++ and built upon the Advanced Linux Sound Architecture[3] (ALSA) APIs was developed and compiled for the BBB's native ARM processor. The audio engine includes a FM synthesizer and a control thread capable of accessing sensor data from the circuitry attached to the GPIOs of the board.

The synthesizer generates 2 overlapping but distinct sounds, a percussive hit resembling a snare and a sustained drone sound. The mapping design consists of a direct many-to-many strategy. Both the sounds are triggered when the touch sensor detects a touch hit; the percussive sound is automatically released while the drone stops when all the fingers are removed from the sensor. Whenever the touch sensor is triggered, the FSR pressure values control the velocity of the percussive sound and the cut-off frequency of a low pass filter applied on the drone, allowing for a continuous modulation within a deliberately restricted range.

Measurements estimated that the worst case event audio latency for this configuration of the instrument is below 7ms. The actual mapping happens in the control thread, which also logs all the retrieved sensor data onto a uSD card connected to the BBB. Data are timestamped and include number of detected touches on the capacitive sensor, X-Y touch positions, touch areas and maximum pressure; although only the first touch hit is used to trigger the synthesizer, the positions of up to three touches can be detected by the sensor, all of which are logged separately.

2.2.1 Two Parallel Mapping Implementations

Compared to the one-button instrument in [6], our instrument features a somewhat higher level of complexity. We aim to assess whether performers still develop diverse and unusual playing styles when the instrument is characterised by a higher number of affordances and different constraints.

Since we also aim to evaluate the role of dimensionality in the appropriation process, we developed two versions of the same instrument with identical hardware but slightly different mappings. The first version allows control of timbre using pressure, as described in the preceding section. The second encompasses all the capabilities of the first, but also adds control of pitch (both percussive sound and drone) using the X (longer) axis of the touch sensor. The pitch range is approximately 4 semitones. Such a small range was de-

[1] `http://beagleboard.org/`

[2] `http://elinux.org/CircuitCo:Audio_Cape_RevA`

[3] `www.alsa.opensrc.org`

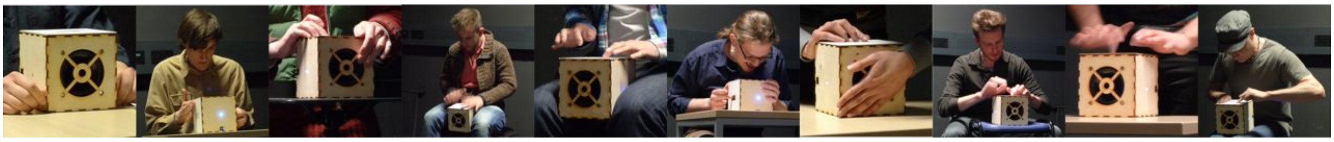

Figure 1: Pictures taken during the second performance, showing different ways of playing the instrument.

signed to discourage musicians from playing melodies on the instrument. Conversely, the pitch range was continuous rather than rounded to discrete semitones; this was done to provide both pitch and timbre controls with similar sets of degrees of freedom and constraints.

In both versions, multi-finger data and Y-axis touch position are not mapped to any control. For matter of clarity, from now on we will refer to the 2 different versions of the instrument as *1 and 2 Degree-of-Freedom (DoF)* instruments.

3. USER STUDY

Ten cube-instruments were constructed; five of them had one degree of freedom, and the other five had two degrees of fredom. The software running on each board was set to log sensor data as soon as the instrument was switched on, generating a new log file for each session.

3.1 Participants

A total of 10 paid participants took part into the study, and each received an instrument. Our call for participants aimed at enrolling 2 different groups of musicians with specific features. Out of the many people who replied to our advertisement, we selected: a first group of 5 musicians who shared a certain experience with unconventional electronic instruments and experimental approach. A second group of 5 musicians who, though coming from different music backgrounds (e.g., classic music, rock, folk), featured more "standard" musical skills, mainly related to the capability of playing an acoustic or electric instrument. Since no females replied to our call, the study includes only male subjects.

3.2 Rehearsal and First Performance

We met each participant separately, and details about the other enrolled musicians were not made known. This was done to avoid them influencing each other in the way they played the instrument. Instruments were handed out during individual first meetings, such that both groups included both types of instruments (1 DoF and 2 DoF). Participants were unaware that two types of instrument existed.

Participants were first asked to prepare an unaccompanied performance using the instrument, 1 to 3 minutes long, structured or totally improvised. Complete freedom was given in terms of how to play the instrument, imposing no constraints on posture or setup (e.g. sitting, standing, using a table). They were asked to come back and perform after a rehearsal period of 2 weeks.

The first set of performances took place in a small black box theatre in the authors' department, spread over 10 different days, again to prevent participants from meeting; the audience was composed of the authors only. Each performance followed the same structure: performers were instructed to start playing the instrument when ready; once finished, they were asked to complete a Likert scale questionnaire including 4 groups of sentences regarding their perception of the instrument, covering:

1. General mastery – whether they had completely mastered the instrument or they needed more time to refine their technique.
2. Affordances' discovery – to what extent they explored the (hidden) capabilities of the instrument.
3. Degrees of freedom usage – whether they used all the affordances discovered, or just a subset of them.
4. Style and behaviour – how unconventionally they played the instrument compared to what they expected other performers to do.

Then, a structured interview was held, addressing areas of interest similar to the ones featured in [6]:

1. Musical content of the performance – improvised or structured, variations, range of material played.
2. Physical interaction with the instrument – posture, technique.
3. Impressions of the instrument – initial reactions, understanding of the interface, perception of a separated components vs. a self-contained instrument, expectations, perceived features and limitations or problems, previous experience with other similar instruments.
4. Rehearsal experience – frequency and duration, engagement, perceived improvement through practice and skill self-assessment.

Both the performance and the interview were audio and video recorded, and logged data from the rehearsal period and performance were saved. Before leaving, participants were asked to prepare a second performance in two weeks, under the same constraints, but this time fully structured (repeatable). This would happen in front of a real audience.

3.3 Second Performance with Audience

All the participants were asked to come back and do the second performance on the same day, in the same venue as before. The event was publicly advertised, and an audience of 31 people attended the show. This provided participants with a more realistic performance scenario. Participants went on stage one at a time and played their piece while the rest of the group waited backstage (Figure 1). None of them was allowed to attend other participants' peformances, even after the conclusion of their own; moreover, they were asked to refrain from discussing about any topic related to the cube-instrument while together.

After the conclusion of this second set of performances, two questionnaires were distributed among the participants. The first one was an identical copy of the Likert scale questionnaire filled in after the first performance. The second one consisted of a written version of the structured interview, extended with some questions about differences between the 2 performance experiences and suggestions for further development of the instrument.

The audience was also asked to fill in a questionnaire. This consisted of open-ended questions about the level of mastery of the instrument and the diversity of style perceived throughout the 10 performances, as well as about the general understanding of the instrument.

Performers were then asked to give an *encore*, exactly repeating the piece previously played. This time they had the opportunity to attend the other participants' performances. After this session, a group discussion concluded their involvement in the study. This was meant to focus on the perceived differences between the instruments and between the different participants' techniques, to leave space for free comments and questions about the instrument or study, and to elicit general inter-participant debate.

All the performances, including the encore, and the group discussion were audio and video recorded.

4. RESULTS AND DISCUSSION

In this section, qualitative and quantitative data collected throughout the study are combined to investigate how constraints and dimensionality affect style and appropriation.

4.1 Diversity of Style

The 10 participants showed a significant diversity of styles in their performances. Following the methods of [6], this diversity was estimated by annotating the behaviours observed in the video recordings. Four main categories were coded: *Affordances, Musical Variations, Postures* and *Interaction Techniques*. Although these categories partially overlap with those of the one-button instrument study [6], some grouping differences were introduced to account for the effects of the more complex instrument metaphor.

In Table 1, **Affordances** lists all the actions that were explored by participants to produce sounds and music (similar to the "ways of playing" category in the reference study). *Main affordances* relate to the use of the sensor to trigger sounds and to modify the built-in timbre/pitch parameters. Examples include hits and slides on the sensor. *Hidden affordances* (shown with a star in the table) are those which were not intentionally built into the instrument, and not directly perceivable from its design [4]. They rely on the exploitation of features of the instrument not necessarily connected to the sensor, such as rubbing on the wooden sides of the box or touching the speaker.

Musical Variations lists how the discovered affordances were used musically. Entries in *Affordances* and *Musical Variations* support many-to-many relationships: different affordances can be used to obtain the same musical variation (e.g., filtering the sound either using the hand or another surface); conversely, different musical variations can capitalise on the same affordance (e.g. a constant drone or a rhythmically modulated sound can be both generated pushing the finger on the sensor).

Postures includes both bodily positions and ways of holding the instrument. **Interaction Techniques** refers to the specific ways in which the actions suggested by a perceived affordance were carried out. For example, the sensor can be pushed (the affordance) using both a single finger or the entire palm (the interaction techniques), to generate a drone (the musical variation).

Analysis of Table 1 suggests that the nature of the instrument elicited a remarkable variety of styles and behaviours. Such a simple but important observation confirms the results of Gurevich et al. [6], highlighting that the emergence of diverse and unusual ways of playing a DMI does not necessarily depend on one specific set of constraints.

A deeper analysis of the first two table columns (*Affordances* and *Musical Variations*) hints at why, for this instrument, style variety is even wider than [6]. In contrast to the one-button instrument, style variations related to the main affordances of the cube-instrument (the non-star entries) are many and determine almost the 30% of the overall diversity (13 out of a total 47 entries). Indeed, the cube-instrument is characterised by a more complex metaphor than the one-button device; more degrees of freedom seem to have led to the exploration of a wider set of affordances.

Despite of the degrees of freedom intrinsically available within the instrument, comments from the interviews make clear that participants perceived the device as *very constrained*. Interaction was defined as *"limited"*, *"frustrating"*

Affordances	*Musical Variations*	*Postures*	*Interaction Techniques*
Push	Drone	Sitting	Fingers
Hits	Rhythmic drone modulation	Standing	Palms
Slides	Arhythmic drone modulation	Instrument between legs	Both hands
Complete sensor coverage	Rhythmic hits	Instrument on laps	More than one sensor touch
Rubbing box sides*	Arhythmic hits	On surface	Combined techniques
Rubbing over sensor*	Unpredictable timbre/pitch	Static	
Tapping box*	Riffs	Flipping sides	
Licking sensor*	Glide	Speaker towards audience	
Manual filtering*	Vibrato	LED towards audience	
Table filtering*	**Rhythmic rubbing***		
Fingernails hits*	**Arhythmic rubbing***		
Singing*	**Rhythmic filtering***		
Touching speaker*	**Arhythmic filtering***		
Objects on speaker*	**Rhythmic tapping***		
Combined affordances*	**Poliphony***		
	Distortion*		
	Rattling objects*		

Table 1: Diversity of style. Marked with a star, entries related to hidden affordances; entries in light grey are found in the 1DoF group only, entries in dark grey are found in the 2DoF group only.

and artistic production was referred as *"a challenge"*. Performers' reactions to these limitations consisted of searching and finding novel and *"interesting"* solutions to play the instrument. As argued by Gedenryd [5], from this perspective the presence of limiting design features is only apparently negative, especially in creative fields where structure (i.e., constraints) mediates excessively wide ranges of options.

Performers apparently explored unconventional techniques both because of and in spite of the perceived constraints. Two examples of these parallel approaches are Participant ID 0 (P0), who defined this process in these terms: *"I found that the subtlety which was within its limitations was where something interesting musically could happen…"*; as opposed to P5, who said: *"I found the normal interaction, I mean the pad, a little limited. So, once I got a bit acquainted with the pad itself, I looked for a way to extend the possibilities, to enrich sound and control."* These comments align with the style diversity in Table 1. Style variations ascribable to hidden affordance exploration (star entries in first two columns) are copious; covering more than the 40% of the table entries, they form the most diverse cluster. This suggests that the number and the strength of the perceived constraints stimulated the discovery of unconventional ways of playing and the development of a personal style. Such a result is in line with Schon's general theory of *reflection-in-action* [12], according to which the clash between sought goals and limitations stimulates critical inquiry, on-the-spot experimentation and *artistry*.

4.2 The Role of Dimensionality

The preceding analysis combined data from all 1DoF and 2DoF groups. To investigate the role of dimensionality on style and interaction techniques, we will next consider the behaviour and reactions of each group separately.

In Table 1, entries observed only in the 1DoF group are assigned a light grey background, while entries observed only in the 2DoF group are given a dark grey background. Entries with white backgrounds were found in both groups.

Overall, diversity of style is strongly present in both the groups. However, the performers who played the 2DoF instrument explored hidden affordances and related musical variations in a more limited way. Out of the 19 hidden affordance-related entries, only 11 were observed in the 2DoF group; conversely, variations of style found in the 1DoF group use 17 of the same 19 entries.

A comparative analysis of main affordance exploration reveals interesting and unexpected results. The number of musical variations strictly based on pitch control introduced by the 2DoF group is only two, *glide* and *vibrato*. Furthermore, main affordance-related entries in the first and fourth table columns (non-star; *Affordances* and *Interaction Techniques*) completely overlap between the groups. This suggests that no additional main affordances were perceived by the 2DoF group and that the physical usage of the instrument was exactly the same.

This qualitative result is also supported by log data analysis. For each participant, mean and standard deviation of the sensor activation during the performances were computed and compared across the two groups. Three dimensions were taken into account: pressure, X and Y position of the first touch (the one which triggers the synth), all normalised between 0 and 1. A two-sample Kolmogorov-Smirnov test indicated that the two clusters of sensor usage data do come from the same continuous distribution, thus showing no significant difference between them.

The spatial distribution of touches over the sensor for the two groups is in line with this result. The heatmap shown in Figure 2 represents the number of touches detected by the sensor, quantising its surface in 230 small squares. A tendency to spend more time on the edges of the sensor is noticeable in both the 1DoF instrument (left) and the 2DoF instrument (right). Some traces of spatial exploration of the sensor along both X and Y axes are also visible. While in the 2DoF group, X-axis exploration can be connected to the search for a desired pitch, extensive X-axis usage was also found in the 1DoF group. P3 accounted for this spatial exploration as follows: *"Using two fingers in two different places in the touch pad...I can trigger [notes] quicker than using one finger."* The same technique was also used by P4. Other participants from the same group used modulation techniques which combined changes of both pressure and position, for example P8 and P3. P8 and P0 flipped the instrument sideways, thus reaching the sensor from a different angle, touching its edges rather than the centre.

These behaviours and the related quantitative data seem to confirm previous speculations on style diversity across the groups. Indeed, they clearly show how different ways of playing the instrument (e.g., pitch-based or rhythmic-based) were based on the same affordances and techniques (e.g., touching the sensor in different spots), regardless of the number of degrees of freedom of the instrument.

4.2.1 Two Instruments, a Dominant Constraint

In accordance with both [6] and our own expectations, the addition of a control dimension significantly changed the perception of the instrument between groups. As previously highlighted, many of the affordances and musical variations appeared in only one group (e.g. touching the speaker to distort the sound or licking the sensor to have an infinite-sustain drone).

The numerical questionnaire filled out by the performers also shows a significant difference in reaction (Figure 3). On average, the two groups responded differently to Sentence 4 (*There are many other ways of using this instrument I still have to explore*), with the 2DoF group believing much more than the 1DoF group that all the instrument's features had been explored. Sentence 6 (*My performance was based on a subset of the interactions I have explored*) showed a high level of disagreement within the 1DoF group, indicated by a large variance, while almost all the 2DoF performers totally agreed with the statement. Overall, this suggests that the 2DoF sees an instrument which is incapable of providing additional affordances, while the 1DoF group see a richer and more complex device which they have not fully explored.

The reason for the 2DoF group feeling more limited than the 1DoF group is suggested by the participants' comments. In the final interview, 3 of 5 participants from the 2DoF group strongly agreed that the limited pitch range was their main concern. P2 expressed his frustration: *"Even though I had a couple of notes, I think I still found it a quietly frustrating experience just to have those notes instead of a couple of octaves."* Conversely, P6 commented: *"People who had the other version were doing more experimental stuff... as soon as I realised it had a pitch...I concentrated on that."* P7 had a 2DoF instrument, and he reacted strongly when asked about the 1DoF version: *"I already felt really restricted by only having a minor third [the perceived pitch range], I was already really angry about that! So, I think if I've just had one pitch, I would have just been like...I'm trying to be a musician darling! I can't work with one note!"*

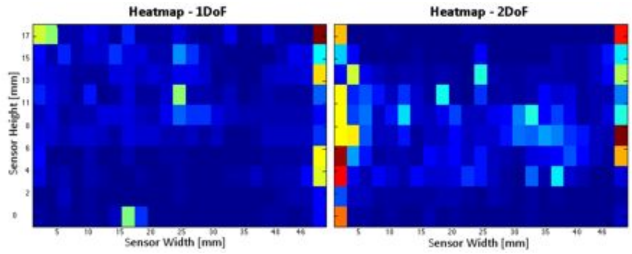

Figure 2: Heatmap representing the spatial density of touches over the instrument's sensor for the two groups of participants. Density is normalised over the total number of touches and goes from dark blue (lowest density) to dark red (highest density).

These comments suggest that participants with the 2DoF instrument not only tended to engage more with constraints rather than affordances, but specifically focused on a single, *dominant constraint*, limiting hidden affordance exploration. An additional clue supports this hypothesis. While suggestions for further development of the instrument were diverse within the 1DoF group (only 1/5 mentioning different notes), 4 out of the 5 participants in the 2DoF group asked for a wider pitch range, or for the extension of the length of the sensor to cover more octaves.

In particular, quotes like the one from P7 (*"I wanted to play discrete notes, I found it more musical somehow..."*) might imply that the pitch is related to common musical conventions; this would explain its dominant role in constraints. Probably, for the 2DoF group, the perception of new affordances (elicited by the new degree of freedom) was counterbalanced by the perception of a strong constraint on pitch range, resulting both in less evident unconventional usage of the instrument and only a limited inclusion of new techniques based on the pitch affordances themselves.

4.3 Appropriation and Cognitive Bandwidth

The appropriation process for any technology is strongly dependent on its design [1]. The user takes personal ownership of the technology by two nonexclusive approaches: the exploitation of the intended openness and interpretabil-

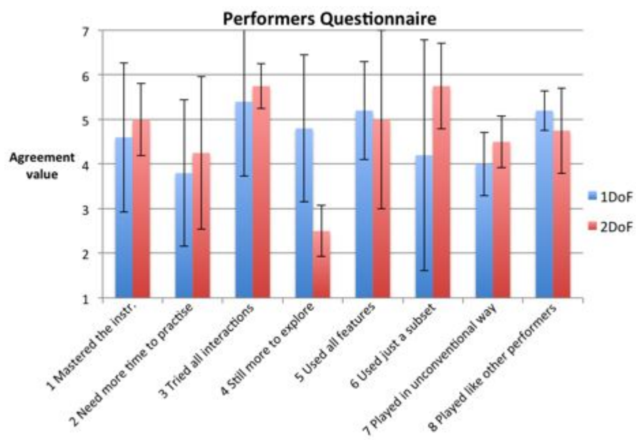

Figure 3: Mean and standard deviation of the Likert scale evaluation of performers' questionnaires.

ity of the system, and the deliberate subversion of design functions. Our user study shows how, for DMIs, these two approaches are tightly connected to the degrees of freedom and the constraints which together define the instrument.

We suggest that appropriation of a DMI can be measured partly by the number and extensiveness of the paths explored through the affordances of the instrument, as the player understands them. In other words, a user who has appropriated the instrument is likely to have found many combinations of ways to engage with the instrument's affordances (whether or not there might be other affordances the user is not aware of). This metric is related to the concept of style in [6], but it deals mainly with the *usage* of affordances to obtain musical output.

DMI appropriation is important, since the same instrument must often be reintrepeted to fit the needs and expectations of different musical situations, genres and audiences. Furthermore, every player is different; a DMI which is capable of being appropriated is one on which each player can build a personal style. The stylistic divergence of the 10 performances suggests that an appropration process was underway with each participant.

During the final performance and encore, technical failures and dead batteries required 3 instruments to be exchanged. In each case, the player performed on another instrument with identical degrees of freedom. Although the instruments were nominally identical, each player expressed discomfort at using a different instrument (investigator: *"Here is an equivalent box to play on"*; performer: *"But this isn't* my *box!"*). All three affected performers felt their original instrument was superior, preferring its particular touch response. In some cases, performers had also made their own marks and annotations on the box. These signs strongly point to the instrument having been appropriated by the performer.

The notion of a *dominant constraint* (Section 4.2.1) shows how dimensionality influences appropriation, even before the development of style. [2] suggests that DMI interaction and understanding of mappings will be influenced by the varying skills of each performer. Similarly, we suggest that the limited exploration of unexpected uses among the 2DoF group may indicate the existence of a *cognitive bandwidth for appropriation*. In other words, whenever a new degree of freedom is made available on an instrument, the strength of the constraints it brings with it determines to what extent affordances will be explored. In our study, the addition of a constrainted pitch parameter resulted in (on average) less exploration of other affordances and constraints of the instrument. But depending on the performer's cognitive bandwidth for appropriation, he or she may nonetheless perceive many affordances alongside the dominant constraints, developing a personal style based on a thorough appropriation of the instrument.

5. CONCLUSIONS

In summary, our study of 10 performers showed that a very simple musical instrument gave rise to a wide variety of musical styles. Confirming the results of the one-button instrument study [6], use of *hidden affordances* accounted for a large portion of style variations between performers. Though our instrument had more degrees of freedom than [6] and a correspondingly greater variety of styles, performers nonetheless found it to be very constrained. Our results suggest that the emergence of diverse and unusual playing styles is a general feature of highly constrained instruments rather than a reaction to one specific instrument design.

By comparing otherwise identical instruments with and without pitch control (2DoF and 1DoF), we found that adding a control dimension reduced the exploration of hidden affordances, and that performers in the 1DoF group thought that there were *more* features left to explore than those in the 2DoF group. Use of the sensor pad was similar between groups even though touch location only carried sonic meaning in the 2DoF group. We also found that the addition of pitch produced a *dominant constraint*; performers with 2DoF found the narrow pitch range to be the primary limitation of the instrument, where performers with 1DoF did not miss the lack of pitch control.

Appropriation is a feature of many human-technology relationships; for DMIs, we suggest it strongly relates to how the instrument's affordances (including hidden affordances) are used in musical practice. The diversity of styles amongst participants, coupled with the strong reactions when performers were asked to change instruments, indicates that appropriation took place across the study. The reduced exploration of affordances in the 2DoF group suggests that there may be cognitive limits to what any given performer can explore at once. This question merits further investigation. Further work will also examine the perspective of the audience and patterns of performer-instrument interaction revealed by the sensor data.

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