Rich gesture, reduced control: the influence of constrained mappings on performance technique

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ABSTRACT

This paper presents an observational study of the interaction of professional percussionists with a simplified hand percussion instrument. We reflect on how the sound-producing gestural language of the percussionists developed over the course of an hour session, focusing on the elements of their gestural vocabulary that remained in place at the end of the session, and on those that ceased to be used. From these observations we propose a model of movement-based digital musical instruments as a projection downwards from a multidimensional body language to a reduced set of sonic features or behaviours. Many factors of an instrument's design, above and beyond the mapping of sensor degrees of freedom to dimensions of control, condition the way this projection downwards happens. We argue that there exists a world of richness of gesture beyond that which the sensors capture, but which can be implicitly captured by the design of the instrument through its physicality, constituent materials and form. We provide a case study of this model in action.

CCS CONCEPTS

•Human centred computing → Interaction design theory, concepts and paradigms; •Applied computing → *Sound and music computing;*

KEYWORDS

physicality, dimensionality, musical gesture, digital musical instruments, constraints, percussion, materials, projection, richness

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1 INTRODUCTION

In this paper we present an observational study analysing the interaction of professional percussionists with a simplified percussive digital musical instrument (DMI). Rather than placing a novel constraint on the percussionists' interaction, this study focuses on a classical constraint of DMI design: velocity triggering. In our discussion of this 'simplest case' performer-instrument interaction, we focus upon the reduction in the variety of musical movement across a one-hour session and ascribe it to a characteristic of the instrument we term the *bottleneck*. This bottleneck is the manner in which the instrument constrains the gestural language of the performer, and encourages them to play in certain ways. By focusing on the variation and evolution of musical gesture we aim to identify the design parameters that produce this bottleneck.

Let us begin with an example. Imagine it was possible to have a perfect motion capture system that could record every detail of a pianist's movement while playing. This dataset would allow us to recreate the exact timing and velocity of key presses that the pianist performed, and hence the resultant music. If, on the other hand, we were presented with the performance as captured by the keyboard – if we were given the exact timing of note onset and the exact velocity of key presses – it would be impossible to recreate the body movement that led to the music. Although we might trace some information about the body movement from this second set of data (for example a certain note being played slightly later might indicate that the pianist has jumped from one area of the keyboard to another, or a quieter key press in certain positions might suggest it fell under weaker fingers), it would be impossible to work back upwards from the instrument's reduced input to the body language that led to this input.

In DMI design we are often faced with a similar challenge: DMIs are devices that foster musical expression but which are built upon the limitations of sensors, sound engine and the mappings between them. By taking a technology-centred view of sensor dimensions it often becomes difficult to account for the richness of the gestural language that performers bring to our instruments. In this study we focus on the dynamics of interaction in the encounter of performer and instrument, examining the body language of performers as they 'come to terms' with a new instrument which provides a very narrow and specific bottleneck.

2 RELATED WORK

2.1 Gesture and control

In the field of human-computer interaction (HCI) one of the primary understandings of gesture is as a control signal [11]. In this model the only relevant part of a gesture is its meaning-bearing component, e.g. a key press – the rest is seen as irrelevant as it does not carry meaning-bearing information. From this standpoint

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the constraints of the computer can be said to define the interaction [12], however many identical control signals can be produced by vastly different bodily movements. Recent trends in HCI have moved to understanding gesture more broadly as an expressive stream of bodily movement using Motion Capture technologies [11] and sensor fusion techniques [18].

2.1.1 Instrumental control. When designing DMIs the main concern is typically how a performer's actions can be interpreted by the instrument as input. From this perspective, we can again talk of the meaning-bearing components of a musical gesture; these are commonly referred to as *sound-producing gestures* [11], and generally occur through contact with an instrument. It has long been known that there exist gestures that are not directly sound-producing and yet coupled to musical intention. Such movements provide indirect support to these gestures (ancillary gestures [28]), and can relate to communication of musical or emotive concepts [11]. It is not our intention in this paper to decode what these gestures are, why they are chosen, or why they are musically meaningful, though there's much research on these topics [6, 13, 25, 29]. Our focus is on understanding the design of a DMI in terms of embodied control. In a recent paper discussing embodied control in HCI, Tuuri et al. define *instrumental control* as the manner in which a performer's embodied interaction with an instrument provides them with control, and equally the manner in which the same instrument enforces embodied control on the performer [26].

2.1.2 Experiential control. While instrumental control is about how the designer provides technical means of control to the performer, *experiential control* considers the performer's conceived control of the instrument [26]. This is about the things a performer feels they can bring to bear with an instrument through their encounter: how the designed instrument manifests *push and pull effects* on the user's experience of control. Tuuri et al describe the *push effect* of a design as the way a performer feels forced, guided or disabled in control. In the case of a DMI this could be how the instrument pushes performers to play in a certain way through conflict between action and desired result. The *pull effect* is the feeling of being enabled in control and relates to an ease in conceiving how action relates to output, how the instrument affords control. Magnusson observes that the designer is often concerned with creating affordances, whereas the performer is more interested in navigating constraints [15]: the design process may relate more to instrumental control even if experiential control is more operative to the person encountering that instrument.

2.2 The projection model

DMIs often follow the HCI model of an information system where design is a question of composing the relationship of input to output. The classical model of sensor input (gestural controller) - mapping layer - sound generation best represents this approach [9, 19]. This model, while providing an accurate description of the technical implementation steps and flow of information in the system, does not account for the variety of movements that can result in identical input [16]. It also does not directly support thinking about the experiential aspects of musical interaction in which embodied intentional control and sensorimotor integration are central concepts [27]. An embodied approach to music cognition proposes that when we listen to music we hear action: bodily movement and the labour of performance are given prime importance in the formation of musical meaning [13, 29]. In the investigation that follows we want to underline the importance of looking beyond the input–output model [27], thus giving the embodied encounter of performer and instrument a clearer position in the design process.

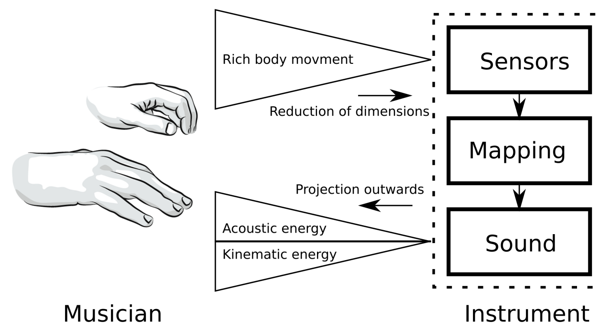

Figure 1: The projection downwards of gesture onto the bottleneck of the instrument's sensors, mapping, sound composition and the projection back upwards to the musician.

In order to gain a more nuanced understanding of musical interaction we propose a model of movement-based DMIs as a projection of sorts. The input to this model is the bodily movement of the performer which contains many biomechanical degrees of freedom and many event-based decisions made by the performer about how they interact and how their actions relate to the wider environment. The instrument takes that input and projects it down via the sensors of the instrument which capture only a small subset of that gesture, constituting a bottleneck in the interaction. From this bottleneck the instrument then projects out again to an expanded set of sonic and kinematic features and behaviours. The manner in which this projection happens, the reduction in dimensions and exact placement of the bottleneck, are direct results of an instrument's design: they delineate the performer's experiential control, deciding the elements of a performer's bodily movement that are maintained as musically meaningful and those that are rendered meaningless. Our aim with this model is to better account for the richness of bodily movement that a performer brings to an instrument, a richness that cannot be easily accounted for in the information system model. The projection of body language down to a reduced sonic space is exemplified in DMIs due to the common separation of gestural controller and sound producing mechanism, but is true for all musical instruments.

2.3 Touching an instrument: excitation

Again let us consider the case of the piano. There is an extensive discourse around body language in pianistic performance: fine control of the arms and shoulder, the exact degree to which one should raise the hand. All this rich vocabulary of body language is reduced to an action that is essentially control of a discrete event plus a single dimension of variation: note-on plus velocity control [22].

Nonetheless, pianists spend many years developing elaborate and rich body language just to be able to project it down onto this very restrictive interface. This is with good reason, as the importance of body language for the formation of musical meaning and interpretation of musical performance has been widely recognised [1, 3]. When discussing the role of touch in artistic pianism Doğantan-Dack provides a wealth of tactile descriptors from piano pedagogy that represent the complexity of this space at the level of finger contact with key, for example, 'sinking into', 'fusing with' the piano keys; 'clinging to the keys as to something soft, velvety or downy'; 'kneading the keys as if with silken fingers, as if moulding warm clay'; 'pressing the key as if grasping the hand of a friend with warmth' [3].

The piano is only concerned with the meaning-bearing components of this rich gestural language, with the part responsible for the attack. The gestures that lead to the note-onset (ancillary gestures [28]) however leave their imprint on the tone quality perceived by the listeners. Shove and Repp describe this as follows: listeners do not just hear the onsets of sounds because "attacks are nested events, constrained by, affected by, and thus lawfully specific to the performer's actions. To hear the attacks is to hear the performer move. The dynamic time course of these gestures is reflected in the resulting sound stream" [24, p. 60].

2.4 Embodied control of an instrument

Nijs [20] proposes musical instruments as mediators between gesture and sound output, a concept deeply connected with the notion of *tool transparency* from embodied music cognition [13]. Transparency is the point where the performer does not need to focus attention on the individual operations of manipulating an instrument, instead focusing on higher-level musical intentions. Maintaining an ecologically valid link between action and sound is an important aspect of instrument transparency. It has often been recommended that DMI designers look to acoustic instruments for examples of tools that foster such a relationship between gesture and sound, one that is both intuitive yet complex [21]. An ideal instrument, it could be argued, should allow a performer to use a natural body language when playing it, maintaining the musical intentionality of a performer's actions. A related concept is that of *ergotic* instruments [14]: instruments that involve the preservation of energy through both digital and physical components of a system.

DMI design also relates back to models of traditional musical instruments due to a desire to support existing instrumental training. This is in part because DMIs want to take advantage of the existing musical skills of their performers, but also because acoustic instruments take advantage of familiar sensorimotor interaction patterns allowing the performer to use tacit knowledge they have from interacting with the physical world [5]. With traditional acoustic instruments, the mechanics of the instrument and the biomechanics of the performer are usually well matched. Organ players do not directly play the instrument's pipes but rather keyboards scaled to the size of the hands and feet. As designers we take charge of the *mechanism* of the instrument: understanding instrumental control is important from a design and technical perspective, but understanding experiential control, the performer's conceived control of the instrument, can provide rich insight into the dynamics of the interaction.

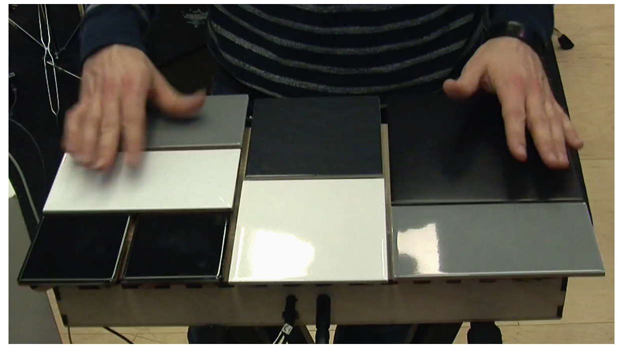

Figure 2: The instrument used in this study which has eight ceramic tiles with piezo pickups to detect vibrations.

In the following sections we will examine a specific instrument with a common bottleneck, velocity triggering, and demonstrate how the gestural language that people use is richer than what the sensors ultimately capture. Where many studies have looked at what to do with the fact that there is a bottleneck, in terms of how to choose sensors [16, 18] or map sensor dimensions to sound [9], key concerns for instrumental control, we are including reflections on the experiential control of the performer.

3 EXPERIMENTAL SET-UP

3.1 The instrument

The musical instrument that we used in this study is a 'simplest case' digital percussion instrument. It consists of eight ceramic tiles that were transformed into drum triggers with the use of piezo elements and a peak detection algorithm that ran on an embedded Linux computer [1] [17].

3.1.1 Sensors, mapping and sound engine. The piezo elements that are attached to the back of each tile sense the vibrations created by striking the tile surface. This signal is then passed to the embedded computer for signal conditioning and peak detection and used to trigger samples. Further technical details of the instrument's design can be found in [10]. The intensity of the strike is measured when a peak is detected and mapped to the amplitude of the sample playback. This results in an instrument with discrete triggering with one dimension of control, velocity.

The use of a vibration sensor naturally gives us an ergotic link [14] between action and sound. Unlike using force sensors, there is no need to adjust response curves: producing a linear software relationship between input level and output level naturally preserves the relationship between physical energy at the input and perceived physical energy at the output. The system was designed to be capable of extremely low latency and low jitter; this was one of the test conditions of the study [10]. The sample set used in this experiment was of metallic gamelan instruments with microtonal tunings characterised by a sharp attack and bright sound.

[1] https://bela.io

3.1.2 Materials and physical design. The instrument can be seen in Figure 2. Pitch arrangement goes from low to high, from the bottom right to the top left in three columns. As pitch increases the size of tile decreases. Each of the tiles are mounted on a cradle, constructed from laser-cut wood with felt pads at the point of contact, that support the tile at its nodes allowing it to vibrate freely [23]. Our reasons for creating the playing surface of this instrument from ceramic were twofold: firstly, the resonant properties of the tiles allow for a high level of signal transmission to the sensors meaning that even very light strokes on the tiles can be registered; secondly, we thought that ceramic as a material carries ecological evocations of instantaneousness and immediacy of acoustic response, aspects we wanted to make central to the instrument's character.

3.2 The study

3.2.1 Participants. This instrument was tested with two groups of musicians. The first group consisted of eleven amateur musicians with a variety of instrumental expertise [10]. The present paper presents findings from the second group that consisted of ten professional percussionists (one female). The percussionists that took part in this study had on average ten years of experience, had completed at least a bachelors degree in performance and were working professionally, either as a performer in an orchestra, as a session musician or in education. Percussionists represent a group of musicians that are relatively well catered for in terms of DMIs but that are also implicitly multi-instrumentalists. In the interviews that followed the study, presented in Section 4.2, each percussionist talked at length about having the ability to adjust to the response and action of a new instrument in a matter of seconds, an essential part of an orchestral percussionist's role.

3.2.2 Procedure. In this paper we present an analysis of the first and last 15 minutes of the hour-long encounter that each of the percussionists had with this instrument. The majority of the hour-long encounter consisted of the percussionists being asked to focus on the difference between two randomised settings on the instrument in several different performative contexts (free improvisation, rhythmic tasks, structured improvisation). We noted that there was nothing from the settings (which involved variable amounts of action-sound latency) that encouraged the percussionists to choose any set of gestures over the others, aside from an impact on subtle details of their temporal performance (discussed in [10] alongside a full description of the study design). For our investigation into how the gestural language evolved during the session we have analysed the first and last section of each session. The first section can be best described as exploratory and evaluative (through free improvisation the percussionists actively tested out the instrument), while the last section is best described as performative (the percussionists were asked to structure improvised rhythmic performances that utilised the best functions of the instrument).

3.2.3 Data collection and Interviews. The entirety of each session was audio and video recorded. The session ended with a 15 to 20 minute structured interview where we asked the percussionists to describe their experience of the instrument, the techniques used throughout the session and their impressions of what worked well and what didn't.

3.3 Performance analysis

When analysing the video recordings of these sections we employed thematic analysis [2]. The first pass of annotation involved identifying the descriptive categories that best explained the range of sound-producing gestures on display. This included *motor effector* (the part of the hand that made contact with the instrument plus the parts of the body that were in motion as part of the ancillary gesture), *temporal behaviour* (the distinction between individual strikes and compound gestures like rolls, multiple finger strikes and fast finger-thumb or finger-finger combinations), *local spatial behaviour* (the location of strike on an individual tile), and *global spatial behaviour* (the arrangement of the hands on the instrument as a whole). Each of these gestural characteristics were identified on the timeline of the video and coded with a relevant tag.

A similar thematic analysis was then performed on the interview material which allowed us to reinforce the codings from the video and identify established techniques and styles of playing. When taken in isolation the observations from the video analysis don't necessarily give the full picture of the decision making processes the percussionists employed. Accordingly, after reviewing the interview material, we performed a second pass of annotation, this time focusing on stylistic techniques employed and sound-facilitating gestures. The stylistic categories that we formed came from the techniques and instruments mentioned during the interviews and from our own knowledge of percussion.

4 FINDINGS

4.1 The evolution of gesture

In Table 1 we present a summary of our observations from the thematic analysis of the performances.

4.1.1 Motor effector. From the motor effector category in Table 1 we can see a summary of the ways contact was made with the instrument. By comparing the fourth and fifth column we can identify the effectors that persisted throughout the session and those that did not appear in the final 15 minutes. Many techniques that have minimal acoustic impact on the output of the instrument, but that would be meaningful techniques on an acoustic percussion instrument, ceased to be employed: scratching, playing with fingernails, dampening of tiles, drumming on the rim of tiles with the sides of straight fingers, playing with the palm, swiping the finger across the tile like a touch screen. The techniques that continued to be used were those with a clear and straightforward sound-producing function. This includes playing with the thumb, multiple simultaneous fingers, finger-thumb combinations and, most commonly, playing with fingertips.

4.1.2 Local spatial exploration. All 10 percussionists explored the local response of at least one tile in the first 15 minute and only 1 percussionist in the final 15 minutes. Local spatial exploration was about testing the active areas of the tiles and finding the physical constraints of the instruments design: repeated strikes were typically performed whilst moving from the centre to the rim of the tile. As the response did not vary much locally this kind of gesture did not provide useful acoustic differences in the signal. The scale of the tile was also a factor in the local exploration patterns of the percussionists. In the interview 3 percussionists mentioned that for bigger tiles they would expect a wider variety of sonic responses, for example different active areas or varying response toward the edge of the tile. When asked, all 3 stated that this was not an issue for the smaller tiles.

4.1.3 Global spatial exploration. The global spatial arrangement of the percussionists' movements was one of the important indicators of the established percussion technique that they were employing. The geometrical layout of the tiles encouraged the percussionists to arrange their hands in different ways in relation to the instrument, including splitting the interface into sections with different musical purposes (down beats on one third (left hand) and ornamentation on the other two thirds (right hand)) or anchoring their movement around a central tile so that they were always moving away from the same position. The most common pattern of global spatial movement was free movement across the interface with no anchor point – this was employed by all percussionists in both the first and last sections. The greater reduction in variation of local spatial gesture than global gesture implies that the percussionists came to realise that there was not a lot of musical function in local spatial variation, yet varying their global behaviour gave them the ability to play in established percussion styles.

4.1.4 Established technique. A summary of the main established percussion techniques that were used is presented in Table 2. For a percussion technique to be successfully supported by the instrument its base components had to have an acoustic effect, and the movement patterns of the style had to be supported by the layout and physical characteristics of the instrument. Techniques carried into the final fifteen minutes and named by the percussionists in the interview were as follows: tarabuka split hand technique (sharp strikes with fingertips, single hand rolls with fingertips of curved fingers, wrists rotating), hang drum playing technique (detached strikes with fingertips, middle or index finger), tar (frame drum) technique (middle eastern split hand technique, again all fingertips with straight finger rolls, no wrist rotation), conga thumb-finger technique (compound gesture with thumb-finger combinations [2]).

Conversely, if the basic elements of an established technique did not have an acoustic effect the technique was subsequently removed from the gestural vocabulary of the performers. Examples of this include: tabla strokes (relies heavily on palm muting, resting wrists and varying note duration with dampening from the striking finger); Cuban/Latin finger percussion (relies on heel-finger motion, rocking the hand back and forth with combinations of palm and flat finger slaps); Djembe techniques (relies on palm hits, slaps and changing the tension of the drum with a dampening finger).

4.2 Interviews with percussionists

The percussionists were asked to describe the techniques they found particularly effective on the instrument and those they found less so. The interview was conducted in front of the instrument with demonstrations encouraged. They were also asked how the instrument related to other instruments they had played (acoustic, electronic and digital) and to established hand percussion techniques.

[2]Note that palm strike and flat-handed slap were removed from this style of playing in most cases – see Section 5.2.3 for further discussion.

Table 1: Analysis of gesture occurrence. The column titled *start* shows the number of percussionists who used this technique more than once in the first 15 minutes, *end* does the same for the last 15 minutes. Techniques marked with a dash produce a sound from the instrument but there is no difference in the quality of that sound compared to the more commonly used motor effectors. The symbol × represents the case where the technique had no acoustic effect.

	Description	Acoustic effect	Start	End
Motor Effector	fingertips	✓	10	10
	fingernails	–	9	1
	thumb	✓	7	4
	palm	–	3	0
	dampening	×	6	0
	drumming on rim with side of fingers	✓	2	0
	flat hand slap	–	6	2
	scratching tile	×	4	0
	touch screen swipe	×	2	0
Compound gestures	finger-thumb combination	✓	4	4
	chords	✓	6	4
Temporal	single hand rolls on one tile (fingertips)	✓	10	3
	two hand roll on one tile	✓	10	3
	strumming fingers (straight)	✓	6	0
	split hand technique	✓	6	3
Spatial	exploring tile surface area	×	10	1
	hand anchored on central tile	n\a	2	2
	splitting the interface in thirds	n\a	2	2
	ascending / descending patterns	n\a	2	1
	free movement across interface, no anchor point	n\a	10	10

Table 2: Stylistic techniques and comparable instruments from the second pass of the video analysis and interviews. The dash symbol represents the case where some gestures work but are timbrally flattened. The symbol × represents the case where elements of the technique had no acoustic effect.

	Description	Acoustic effect	Start	End
Stylistic technique / comparable instrument	Tabla strokes	×	3	0
	Cuban/Latin finger style	×	4	0
	Djembe	–	3	0
	Tarabuka	✓	7	3
	Hangdrum	✓	7	5
	Tar	✓	1	1
	Conga	–	3	2

Two distinct categories of reasoning for the success or failure of certain percussion techniques became clear from our coding of the interviews: *acoustic* and *ergonomic*. In Table 3 we present some paraphrased examples of this reasoning. The acoustic reasons tend to address the instrument's ability to produce an accurate response to a type of playing, and so included comments about the sensing and sound engine. For example: "*I noticed with the fingertips it's more accurate and easier to get feedback*", "*when you hit it you know what volume you'll get", "there was something more musical about using the fingers rather than the palm*", "*to get the most reliable impact and the most control I used my index finger*".

Ergonomic reasoning tended to address the physical form of the instrument, its layout, the ceramic as a playing surface, its stability or durability. For example: "*this sort of motion is really nice and natural*", "*when using hands it's better to have something harder to dig into*", "*I was doing a lot of fast stuff with these two* [demonstrates top two right tiles] *and then longer notes here* [demonstrates the left two thirds of the instrument]", "*I tried a little bit of thumb action but I found it a bit too clunky*". The percussionists also related the tile instrument to other percussion instruments and established percussion techniques with which they had experience. For example: "*you can do all the tarabuka stuff, also middle eastern tar* (frame drum) *playing*", "*it's similar to clay udu drums in the hardness of the tiles*", "*I can play it like a hangdrum, all fingertips*".

5 DISCUSSION

In this section we will discuss the implications of the study for the projection model of DMIs introduced in Section 2.

5.1 The acoustic and the digital

With the exception of the swiping gesture derived from touchscreen interaction, all of the sound-producing gestures came from acoustic hand percussion instruments. Hand percussion has a large but nevertheless limited vocabulary of gestures that involve many different parts of the hand and various striking patterns – a set of techniques that are predicated on a richer transfer of gesture to sound than our instrument affords. When this gestural language meets a mapping system that is more constrained than most acoustic instruments, we see it getting narrower. After interacting with the instrument for a while certain actions are decided to be more musically useful than others, and the vocabulary of gestures is reduced to a smaller set of techniques. This reduction involves the percussionists employing a subset of the degrees of freedom that they would expect from an acoustic instrument, suggesting a reduction in the bandwidth of interaction.

The instrument, instead of creating its own gestural language, borrows the gestural language of the instruments that it is most similar to. This is in part due to the high degree of training of the percussionists and their specialism in percussion, but also is due to ecological factors regarding familiarity with patterns of interaction [4] and enactive aspects of how action translates to sound [5]. Our instrument conforms to physical principles about the transferral of energy and errs towards a simulation of an acoustic instrument but differs in some fundamental ways: limited timbral variation, each tile remains a trigger, limited active areas, not possible to dampen notes. These differences select the set of gestures that are appropriate for playing the instrument.

Time is another factor in the development of the gestural language. Within the span of an hour the performers go from techniques derived from traditional percussion instruments to a narrower and more focused set of techniques that seem catered towards the specific characteristics of this instrument. Over a longer period of time, based on previous work by Gurevich et al. [7] and Zappi and McPherson [30], we might expect to see performers coming up with novel techniques that take advantage of non-obvious affordances specific to this instrument.

5.2 Voluntary self-constraint

To return to the terminology we introduced in Section 2, from our observations and from the percussionists' reports we can hypothesise about their experiential control when interacting with this instrument: the *push and pull effects* [26] of the instrument. In this study we observed three different examples of such effects, and reasons why performers reduce their range of gestures:

5.2.1 *Performers discard gestures which have no meaning on the instrument (push effects).*

Dampening, for example, was a technique employed multiple times by over half the percussionists. The instrument's physical construction and behaviour led the percussionists to believe that it had this affordance, yet it did not, and hence this action ceased to be employed. Percussion techniques that required dampening as an essential element also stopped being used. Scratching the surface of the instrument is another example where the percussionists would perhaps expect some kind of timbral change but that was not maintained by the instrument, and hence not used by the end of the session. These are both examples of push effect in the instrument's design, ways in which the performer's expectation of how control gesture should relate to sound output were disrupted, pushing them towards an alternative set of gestures.

5.2.2 *Performers choose the most ergonomically convenient ways to play (pull effects).*

The pull effects of the instrument are displayed in the most widely employed control strategies chosen by the percussionists – playing with fingertips and performing fast single-hand rolls on a single tile for example. The percussionists identified these techniques as the most convenient and effective ways of playing the instrument, where they were certain about the quality of output they would receive from their input gesture.

5.2.3 *Performers optimise their gestures to be maximally efficient with respect to the instrument's capabilities (also pull effects).*

Projecting downwards onto a more limited space of interaction may cause people to adjust their body language accordingly to achieve some sort of *efficient* representation between what they do, and what sounds come out. The presence of a bottleneck in the interaction reflects back onto the body movement used in control, and the performer self-constrains their body movement based on this response. An important point to note is that gesture is not something that exists independently from an interface, it rather exists in relation to an interface: the specific bottleneck of this instrument led to the selection of a specific set of musical movements.

Table 3: Summary of paraphrased reasons for why percussionists continued to use or discontinued a particular technique.

Reasons for ceasing to use a technique		Reasons for continuing to use a technique	
Acoustic / Sensors	*Ergonomic / Physical*	*Acoustic / Sensors*	*Ergonomic / Physical*
The instrument didn't respond well to this type of technique	This type of gesture was uncomfortable to play / didn't fit	When I play like this the note is just right there	The feel of the tiles was just right for this kind of playing
I couldn't hear the sound that corresponded to this technique	The size/layout of the tiles didn't allow me to play like this	I liked the velocity range that this technique allowed	The layout suggested that I arrange my hands like this
This technique didn't change the sound	This gesture was too forceful for this instrument	Like this I was able to play quickly and feel in control	The tile size encouraged me to play with this technique

5.3 Physicality and material concerns

While we have compared our instrument with acoustic percussion instruments, this study could have been equivalently done with any of numerous commercially available drum pad interfaces. The same set of sensor-mapping dimensions (presumably the same set of push effects) could result in different gestures as changing the physical properties of the instrument introduces different pull effects. For example, with a small rubberised plastic drum pad certain types of gestures (single hand rolls in which the fingers are strummed across the tile surface, or split hand percussion tarabuka technique) would not be supported. We can posit that the ceramic interface, vibration sensing strategy and fast response of the system all contributed to the maintenance of these particular gestures. The differences lies in things like the warping of the energy transfer curve, which is inherent in piezo discs rather than force sensitive resistors (commonly used in drum pads), in the geometric disposition of the instrument which changes the gestural language in comparison to a grid of equally sized squares, in the use of ceramic for both the feel and expectations as opposed to rubberised plastic.

We observed the gestural language becoming more focused and tailored towards the affordances of the instrument but nonetheless remaining much richer than the sensors can actually capture. Physical design factors are central to the bottleneck of this instrument. The way these factors are reinforced through mappings create pull effects on the instrument: they support the performers in their control of the instrument, enabling them to employ their tacit knowledge of such an interaction and their prior training [5]. These aspects of the instrument's design go beyond obvious mapping descriptors yet are crucially important on the basis of the gestural language that we have observed. Pull effects act as metaphors of control present in the material properties of DMIs [8]. Layout and size are also crucial factors: they restrict and guide the trajectories of movements, the speed with which it is possible to move across the instrument, the patterns of triggering that are possible.

5.4 Projection in the case of our instrument

In Section 2.2 we proposed a model of movement-based DMIs as a projection. In Figure 3 we illustrate the specific projection of our instrument as an inverted pyramid that projects downwards from a rich body language to a bottleneck then outwards to sound output. On the right hand side of the illustration we have noted some of the aspects of the gestural language that are discarded at each step of this projection.

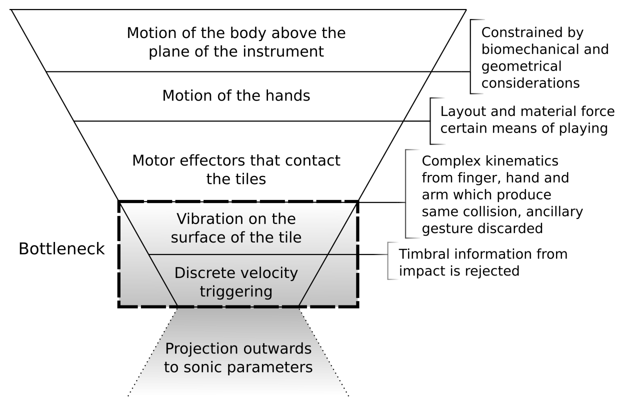

Figure 3: A simplified representation of the specific projection in the case of the ceramic tile instrument. On the right-hand side are the elements discarded at each layer of reduction. The bottleneck is highlighted.

In order to trace this specific projection it is best to work upwards from the bottleneck, which includes the measurement of vibration on the tile and its reduction to discrete velocity triggering. The vibration on the tile is approximately equivalent to the strength of an impact between that tile and another object – timbral qualities are rejected from the mapping. There are many different parts of the body that can make contact with the tiles and trigger notes, many of them with the same or very similar effects as read by the sensors: information again is lost here. For any given part of the body that strikes the tile there is a complex kinematic system going up the fingers, hand and arm which could produce an identical type of collision: this is another place where information is discarded. From the perspective of the instrument, and the bottleneck which in many ways defines it, all motion of the performer's body above the plane of the instrument is irrelevant, except insofar as it was needed as a preparation to strike the tiles.

5.5 The moveable bottleneck

The designed *mechanism* of an instrument (physical construction, sensor choice and placement, material properties, mapping, sound engine and their relationships) essentially place this bottleneck. As discussed in Section 5.3, with our instrument there is approximately the same sized bottleneck as one would have with drum pads, in that it allows for a similar bandwidth of information to pass, but in this case it is put in a different place, and hence we have received a different gestural space. It is possible to capture a different subset of available gestures and influence the performer in different ways depending on where we place this bottleneck and how narrow it is. This bottleneck does not go away; it is present in all DMIs and acoustic instruments as we demonstrated with the piano. As designers we choose where to place the bottleneck: by beginning to think in terms of this model, with a projection down to a bottleneck which is them expanded back out, we can better consider the implications of having such a bottleneck for the embodied control of the instrument. Our aim in this paper is to show how, even in a short period of time, a specific bottleneck given to experienced musicians can make them adapt and reduce their gestural language to a set of actions that fit through the bottleneck.

6 CONCLUDING REMARKS

This paper has proposed a model of movement-based digital musical instruments as a projection downward from a high-dimensional space of body movement to a reduced space of sonic and kinematic features and behaviours. Our study suggests that this lossy projection in turn influences the gestures performers choose to employ: in their initial interaction with the instrument, percussionists used a rich gestural language which became narrower and more focused by the end of the study. Many design guidelines for DMIs take the technology-centred approach of describing the instrument as sensor - mapping - sound [19]. This representation often short-changes the dynamics of interaction between performer and instrument. Even within the traditional paradigm of sensor-based DMIs, without attempting to quantify what gesture means, considering the instrument as the locus of a projection downwards can influence design decisions: if we think from the top of the projection, the body language, to the sound it may actually help make decisions about the kinds of musical movement we want to maintain through the design of the instrument. In other words, when designing DMIs we should start by considering the body language of the performer, with the understanding that the richness of this movement is going to encounter a bottleneck where it will be captured in a very reduced way (lower bandwidth) before being extended back out via the mapping. The important point is that this bottleneck in the interaction won't go away, and in fact is essential for meaningful interactions, but is moveable and is positioned through our design choices. Making a different set of design decisions means potentially selecting a different subset of musical movement. As designers we place this bottleneck through the choice of sensors, their placement, the constituent materials and scale of the instrument, and many other decisions about the instrument's craft and mechanical behaviour.

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