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7. Conclusion
7.1 Observations and a possible theory

Like other natural phenomena, human music making can be described as a causal chain, consisting of components that are each subject to measurement and empirical investigation. Therefore, as a working definition, in Section 1.1 we proposed instrumental control of musical sound: the phenomenon where human actions make changes to a sound-generating process, resulting in heard sound which induces musical experiences within the brain.

To create a technique for making music, then, is to set up a causal relationship, between aspects of human action and changes in heard musical sound. The development of different techniques may then be motivated by a single, overarching question: How can the instrumental control of musical sound be improved? As discussed in Section 1.5, answering this question requires also answering another, fundamental question: What forms of instrumental control of musical sound are possible to implement?

Parts of the answer to this question are already present in the many techniques for making music that have been developed from prehistory onward. These techniques initially involved the human body only, or made use of mechanical technologies. More recently, electromechanical technologies have also come into development and use (see Section 1.2). However, it is only when computational technologies are given the central role of causally linking human action to heard musical sound, that a unique advantage appears: Unlike earlier technologies, Turing-complete automata combined with transducers explicitly minimize the constraints on implementable causations (see Sections 1.4.4 and 1.5).

There is evidence for this theoretical advantage resulting in the practical implementation of new forms of instrumental control of musical sound: The combination of electronic digital computer and electric loudspeaker, introduced in the 1950s, has enabled the development of a wide variety of new types of sound-generating processes, which have come into wide use. In Section 1.4, an overview of these types was given, based on how instrumental control moved away from direct manipulation of the wave table.

Considering this evidence, the following question in particular seems potentially rewarding: How can we systematically extend the scope of computational technologies, from the sound-generating process, to the other components of the causal chain? In Section 1.4.4, we first formulated a computed sound model, to describe the fundamentals which enabled the wide variety of implementable sound-generating processes. Here, a Turing-complete automaton must become causally linked, via a transducer, to human auditory perception. Then, in Section 1.5.1.1, we generalized this to the notion of completely computed instrumental control of musical sound. Here, the Turing-complete automaton can track, represent and induce all relevant aspects of human action and perception. This seems to approach a general capability for
implementing *all* perceivably different causal relationships between human actions and changes in heard musical sound.

Realizing a system capable of completely computed instrumental control seems hard. We can work toward this goal, however, by progressively developing transducers combined with Turing-complete automata. We call this process the *computational liberation* of instrumental control, as it will *gradually minimize constraints* on implementable causal relationships (see Section 1.5.1.2). We view computational liberation then as a *de facto* ongoing historical process, exemplified in the development of computed sound.

What area to consider next for computational liberation? Fingertip use is extremely important to the instrumental control of musical sound (see Section 1.2.5). Therefore, it makes sense to give priority to the area of fingertip touch.

To describe the prerequisites for computational liberation that are specific to fingertip use, we formulated a model for *computed fingertip touch* (see Section 1.5.2.1). Here, a Turing-complete automaton may be causally linked, via transducers, both to human somatosensory perception and to human motor activity involving the fingertips. The model is explicitly rooted in existing knowledge on fingertip movement and touch, including its anatomy, physiology, and neural processes (see Section 1.3 and Appendix A). This allows us to explicitly distinguish between different fundamental subtypes of touch. In Chapter 4, this resulted in working definitions for *computed passive touch*, *computed active touch*, and *computed manipulation*. These working definitions differentiate based on the presence and dynamics of a perceptually induced exterospecific component.

Within the area of fingertip use, a specific type of movement deserves additional priority. After considering fingertip use throughout time and across musical instruments, we identified *unidirectional fingertip movement orthogonal to a surface* as a widespread, common component (see Section 1.2). Here, fingertip movement approximates a single path of movement, at right angles with a surface, and extending across at most a few centimeters. Technologies implementing the computed fingertip touch model should support this type of fingertip movement with priority, because it offers advantages in terms of control precision, effort, speed, and multiplication (see Section 1.2.5). This motivated a number of choices directing transducer development: to have the human fingerpad as transducer source and target; to create transducers based on flat, closed, and rigid contact surfaces; and to provide orthogonal as well as parallel force output to the fingerpad (see Section 1.6.2).

Finally, for reasons discussed in Sections 1.4.4 and 1.6.7, it is crucial that technologies implementing the computed fingertip touch model are developed in such a way as to be mass-producible, cheap, and powerful.
Figure 7.1  Overview: What forms of instrumental control of musical sound are possible to implement?

- Along the vertical axis: time. Along the horizontal axis: the number of implementable and perceivably different causal relationships between human actions and changes in heard musical sound.

- The rising edges then indicate the increasing contributions, over time, by body-only instrumental control and by different types of technology. The gradual shift in background hue at each edge is meant to indicate that these different contributions combine, to enable the overall total of implementable causal relationships.

- As is shown, body-only instrumental control has contributed from the earliest times. Mechanical technologies have contributed from at least 40 millennia BCE; while electromechanical technologies have done so, roughly, from the 19th century onward.

- From the 1950s onward, the labels are shown in white, to highlight the turn to a process of computational liberation: Here, the use of computational technologies enables an explicit minimization of constraints on implementable causal relationships.

- Zooming in, contributing technologies here include those implementing the computed sound model; the computed fingertip touch model; and other, as yet unspecified models.

- The star in the upper right of the graph marks a hypothetical point in the future where this development arrives at a theoretical endpoint: the completely computed instrumental control of musical sound.
7.2 Hypothesis

Based on the above, we formulate the following Hypothesis:

Developing technologies that newly fit the computed fingertip touch model enables the implementation of new forms of instrumental control of musical sound.

Here, the implementation of new forms of instrumental control should result after some limited amount of time and effort. This makes it possible to design experiments disproving the hypothesis, ensuring its falsifiability.

7.3 Testable predictions

In Chapters 2 and 3, we developed the cyclotactor (CT) system, which provides fingerpad-orthogonal force output while tracking surface-orthogonal fingertip movement. This system newly implemented the computed fingertip touch model. Then, by deduction, the Hypothesis yields the following Prediction 1:

The CT system developed in Chapters 2 and 3 will enable the implementation of new forms of instrumental control of musical sound.

In Chapters 2 and 3, we also developed the kinetic surface friction transducer (KSFT) system, which provides fingerpad-parallel force output while tracking surface-parallel fingertip movement. This system, too, newly implemented the computed fingertip touch model. Then, by deduction, the Hypothesis also yields the following Prediction 2:

The KSFT system developed in Chapters 2 and 3 will enable the implementation of new forms of instrumental control of musical sound.

7.4 Experimental results

The first part of the experimental results is about technology: How do the CT and KSFT systems each indeed newly implement the computed fingertip touch model? Tables 7.2a and 7.2b, below, first describe the main qualitative and quantitative aspects of both technologies. Their resulting capabilities, in terms of human action and perception, are then summarized in Table 7.2c. Here, the phrase “complete integration with computed sound”, used in Table 7.2a, means that input from human motor activity, output to somatosensory perception, and output to auditory perception are easily combined within a single written algorithm. Table 7.3 then concludes this part, by listing novel aspects of each technology. An important property here is to avoid the use of connected mechanical parts moving relative to the target anatomical site. We emphasize this as a general principle for transducer construction, with the potential benefit of enabling more precise output to somatosensory perception.
<table>
<thead>
<tr>
<th>qualitative aspect</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>based on the use of a flat, closed, and rigid contact surface</td>
<td>CT KSFT</td>
</tr>
<tr>
<td>provides fingerpad-orthogonal force output, tracks surface-orthogonal fingertip movement</td>
<td>CT</td>
</tr>
<tr>
<td>provides fingerpad-parallel force output and tracks surface-parallel fingertip movement</td>
<td>KSFT</td>
</tr>
<tr>
<td>I/O made programmable in physical units; via SuperCollider classes</td>
<td>CT KSFT</td>
</tr>
<tr>
<td>complete integration with computed sound</td>
<td>CT KSFT</td>
</tr>
<tr>
<td>precisely adjustable, personal fit, for more accurate &amp; comfortable I/O</td>
<td>CT KSFT</td>
</tr>
<tr>
<td>cheaply mass-producible</td>
<td>CT KSFT</td>
</tr>
</tbody>
</table>

**Table 7.2a** Qualitative aspects of the technologies developed in Chapters 2 and 3.

<table>
<thead>
<tr>
<th>quantitative aspect</th>
<th>CT system</th>
<th>KSFT system</th>
</tr>
</thead>
<tbody>
<tr>
<td>input spatial resolution</td>
<td>0.2 mm</td>
<td>0.02 mm</td>
</tr>
<tr>
<td>spatial range</td>
<td>35.0 mm</td>
<td>hundreds of cm²</td>
</tr>
<tr>
<td>temporal resolution</td>
<td>4000 Hz</td>
<td>125 Hz, average</td>
</tr>
<tr>
<td>output force resolution</td>
<td>± 0.003 N</td>
<td>N/A</td>
</tr>
<tr>
<td>force range</td>
<td>bipolar, varying over distance: see Chapter 3, Figure 3.2</td>
<td>0.14-1.43 N, kinetic friction</td>
</tr>
<tr>
<td>temporal resolution</td>
<td>accurate wave output up to 1000 Hz</td>
<td>features between 1-10 ms</td>
</tr>
<tr>
<td>I/O latency</td>
<td>4.0 ms</td>
<td>20.5 ms, average</td>
</tr>
</tbody>
</table>

**Table 7.2b** Quantitative aspects of the technologies developed in Chapters 2 and 3.

<table>
<thead>
<tr>
<th>resulting capability</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>force output can co-determine the movement of fingertip control actions</td>
<td>CT KSFT</td>
</tr>
<tr>
<td>I/O can induce aspects of haptic perception</td>
<td>CT</td>
</tr>
<tr>
<td>accurate mechanical wave output across the frequency ranges involved in fingertip vibration perception</td>
<td>CT</td>
</tr>
<tr>
<td>excellent support for real-time instrumental control of musical sound</td>
<td>CT</td>
</tr>
<tr>
<td>I/O can induce high-resolution aspects of fingertip surface texture perception during active touch</td>
<td>KSFT</td>
</tr>
</tbody>
</table>

**Table 7.2c** Resulting capabilities, in terms of human action and perception, of the technologies developed in Chapters 2 and 3.
explicit and specific support for unidirectional fingertip movement orthogonal to a surface

transducer *completely avoids* the use of connected mechanical parts moving relative to the target anatomical site

I/O specific to those flexing movements of the human finger that are independent, precise, and directly controlled by the motor cortex

transducer *partially avoids* the use of connected mechanical parts moving relative to the target anatomical site

inducing high-resolution aspects of fingertip surface texture perception using cheap, off-the-shelf optical mouse sensor input

<table>
<thead>
<tr>
<th>novel aspect</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>explicit and specific support for unidirectional fingertip movement orthogonal to a surface</td>
<td>CT</td>
</tr>
<tr>
<td>transducer <em>completely avoids</em> the use of connected mechanical parts moving relative to the target anatomical site</td>
<td>CT</td>
</tr>
<tr>
<td>I/O specific to those flexing movements of the human finger that are independent, precise, and directly controlled by the motor cortex</td>
<td>CT</td>
</tr>
<tr>
<td>transducer <em>partially avoids</em> the use of connected mechanical parts moving relative to the target anatomical site</td>
<td>KSFT</td>
</tr>
<tr>
<td>inducing high-resolution aspects of fingertip surface texture perception using cheap, off-the-shelf optical mouse sensor input</td>
<td>KSFT</td>
</tr>
</tbody>
</table>

Table 7.3 Novel aspects of the technologies developed in Chapters 2 and 3.

The final part of the experimental results is about forms of instrumental control: What new forms have been implemented using both systems? This is summarized in Table 7.4. In its first examples, computed fingertip touch was used to display the state of the sound-generating process – at a higher level of detail than provided by existing technologies. This to better inform, and thereby alter, fingertip control actions. In the final examples, new forms of instrumental control were pursued more directly: Here, computed touch was used to implement new types of fingertip control action.

<table>
<thead>
<tr>
<th>see</th>
<th>type</th>
<th>system</th>
<th>key points</th>
</tr>
</thead>
</table>
| 4.2.2 | passive touch display | CT     | • display of granular synthesis at the level of individual grains  
via presence, duration, amplitude, and vibrational content of fingerpad-orthogonal force pulses  
using a timescale identical to that of sonic grains |
| 4.3.2 | active touch display | KSFT   | • during actions similar to turntable scratching: display more specific to the stored sound fragment  
via fingerpad-parallel friction, millisecond resolution |
| 4.3.3 | active touch display | CT     | • during surface-orthogonal percussive fingertip movements  
touch display expanded outside moment of impact |
| 4.5.2 | control action       | KSFT   | • pushing against a virtual surface bump  
using horizontally applied output forces, during horizontally directed fingertip movements |
| 4.5.3 | control action       | CT     | • fingertip tensing during force wave output  
can be used simultaneously with control based on surface-orthogonal fingertip movement |

Table 7.4 New forms of fingertip instrumental control presented in Chapter 4.
7.5 Discussion

We will now reflect on the main experimental results, presented above, after first discussing the results of the research excursions of Chapters 5 and 6.

The first research excursion followed the phenomenon of unidirectional fingertip movement orthogonal to a surface elsewhere. Chapter 5 presented one-press control, a fingertip input technique for pressure-sensitive computer keyboards, based on the detection and classification of pressing movements on the already held-down key. We showed how this new technique can be seamlessly integrated with existing practices on ordinary computer keyboards, and how it can be used to simplify existing user interactions by replacing modifier key combinations with single key presses. In general, the proposed technique can be used to navigate GUI interaction options, to get full previews of potential outcomes, and then to either commit to one outcome or abort altogether – all in the course of one key press/release cycle. The results of user testing indicated that effective one-press control can be learned within about a quarter of an hour of hands-on operating practice time.

The second research excursion followed the idea of using computation to induce aspects of human perception elsewhere. In Chapter 6, we first considered how the use of techniques incorporating stages of automated computation offers visual artists a control over perceived visual complexity that is otherwise unattainable. This motivated the question whether computed output also can induce 2D shape perception in the retinal afterimage: the familiar effect in the human visual system where the ongoing perception of light is influenced by the preceding exposure to it. A fundamental problem here is how to exclude the possibility that shape recognition is caused by normal viewing of the stimuli, which may occur simultaneously. To solve this, we developed a rasterization method, a model of the afterimage intensities it induces, and then a series of candidate formal strategies for concrete rule sets computing stimuli. The Electronic Appendix to the chapter provides video examples, the image sequences used in a pilot experiment, and also software implementing the approach, in source format. The results of the pilot experiment testing the approach confirmed shape display specific to the retinal afterimage. This result also demonstrated feasibility of the computed retinal afterimage in general.

Finally, the overview of the main experimental results, given in Section 7.4, provides a summary of how the research goals for the body of this thesis (see Section 1.6.9) have been achieved. Moreover, the results of Tables 7.2a to 7.4 confirm both Prediction 1 and Prediction 2. This supports the Hypothesis: Developing technologies that newly fit the computed fingertip touch model enables the implementation of new forms of instrumental control of musical sound. At the start of this chapter, we presented an articulated, empirical view on what human music making is, and on how this relates to computation. The experimental evidence which we obtained seems to indicate that this view can be used as a tool, to generate models, hypotheses and technologies that enable an ever more complete answer to the fundamental question as to what forms of instrumental control of musical sound are possible to implement.

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1 Some contributions discussed in this chapter are also briefly summarized in Appendix C.
7.6 The future: computed instruments

7.6.1 Algorithmic primitives for computed touch

Reflecting on how the examples of computed fingertip touch of Chapter 4 were implemented, a general issue becomes apparent: The algorithmic representations that are used, in reflecting transducer I/O, are still quite removed from describing the aspects of human action that are involved. To bridge this gap, we may develop a set of parametrized algorithms that implement:

- forms of computed passive touch (see Section 4.2.1);
- forms of computed active touch (see Section 4.3.1).

Here, the parameters offered could still be defined using physical units. However, instead of directly describing transducer state, they would enable control that is more specific to the patterns of passive touch and exterospecific components being induced in the user.

Parametrized algorithms like this can then be used as programming primitives, to build the more complex algorithms that implement new forms of instrumental control. Here, we can apply lessons on the design of complex algorithms from the field of Operating Systems: “As a general rule, having a small number of orthogonal elements that can be combined in many ways leads to a small, simple, and elegant system.” [Tanenbaum 2001]. Interpreting this, our computed touch primitives should be:

- conceptually simple;
- orthogonally combinable;
- expressive.

Here, by “expressive” we mean that the computed touch primitives, already when present in few different types, should enable the implementation of many perceivably different forms of touch.

7.6.2 Computed manipulanda

The algorithmic primitives that implement forms of computed active touch can then be used to implement forms of computed manipulation (see Section 4.4.1): by varying their parameters, over time, in response to specific transducer input. A *computed manipulandum* is then an algorithm that can:

- induce an exterospecific component in human touch perception;
- change this component, over time, in response to specific motor activity.

Computed manipulanda, running on a given system for computed touch, may well be complemented by forms of passive touch display and active touch display, executing simultaneously.

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2 Continuing from Chapter 4, proposed future work more immediately includes the pursuit of new forms of fingertip touch display, and of new fingertip control actions. This includes the touch display of sonic grains, and making the same time-varying content both heard and felt during control. This Section discusses a broader context for such future work.
7.6.3 Target properties for implemented control actions As discussed in Sections 1.3.3.3 and 1.3.4.2, during control actions, the activation of learned motor programs enables faster movement execution, with a reduced claim on attention and consciousness once movement has been initiated. This enables skilled and virtuose playing: Over a given time period, more changes may be made, intentionally and successfully, to the sound-generating process.

Then, effectively, the resulting musical sound will be a choice from a wider range of possibilities. In this sense, motor programs enable more powerful real-time control over the induced musical experience—e.g. during improvisation.

Also, in the player, the use of motor programs could allow attention and consciousness to become more occupied with the musical experiences that are the object of instrumental control.

Given the above fundamental advantages, it seems that the default for control actions, also when implemented using computed active touch or computed manipulation, should be that they are suited to execution by learned motor programs. As discussed in Section 1.3.3.3, this implies that, after some learning phase:

• movement execution does not need visual feedback anymore;
• movement execution occupies attention and consciousness less, or not at all.

7.6.4 The role of the computed image If, when making music, it is not known what the possible control actions are, it will not be possible to exercise control in the sense of reliably producing outcomes according to intentions. However, unlike predecessor technologies, the use of computed touch implies that the set of possible control actions may become highly dynamic over time. This raises a question: How does the user know what control actions currently are possible?

The answer may be: via some form of real-time display. One way of providing this seems inherently present: The user may probe using active touch. However, this will take some time, during which actual control cannot be exercised. An added visual display might well convey the relevant information more immediately. For the user to know what control actions are possible, active touch probing might then be necessary only during an initial learning phase, after which visual recognition would suffice.

This then justifies further refining the view discussed in Section 7.1 by adding a computed image model, to characterize suitable technologies for visual display. Here, a Turing-complete automaton will be causally linked, via a transducer, to human visual perception. Then, if we select a transducer technology that can induce aspects of visual perception that include spatial display at the scale of control action movements, the computed image may provide:

• symbolic display enabling cognition of possible control actions;
• to-scale spatial display of the induced exterospecific components.
7.6.5 **Computed instruments**  Hearing, touch, and vision are main areas of human action and perception via which traditional musical instruments enable forms of instrumental control of musical sound. Therefore, if an algorithm enables forms of instrumental control via computed sound (see Section 1.4.4), computed touch (see Section 2.1.1), and computed image (see above), it does not seem exaggerated to call it a *computed instrument*.

Naturally, computed instruments may combine computed touch, computed image, and computed sound in any way that is algorithmically possible. Certain specific types of causal relationships can be expected, however. Changes to heard musical sound will be enabled by causalities from computed touch to computed sound. Especially when, within the overall algorithm, this involves degrees of freedom controlling scalar parameters of audio synthesis, this will relate to the concept of *mapping* [Hunt et al. 2000] [Hunt and Wanderley 2002]. Also, as discussed in Section 7.6.4, cognition of possible control actions may be enabled by causalities from computed touch to computed image. This will relate to the concept of *affordance* [Gibson 1977] [Norman 1988].

A possibly interesting question here seems whether, beyond the execution of movement during control actions, all other aspects of touch and vision, too, can be made to disappear from consciousness, so that it may engage more purely in making changes to the induced musical experience.

The considerations presented in Sections 7.6.1 to 7.6.5 have guided work on a concrete system that can run computed instruments. With computed touch based on the CT system, at the time of writing, the work on its hard- and software is nearing completion.

![Figure 7.5 A view on computed instrumental control of musical sound.](image-url)