Sound-Based Sensors for NIMEs

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ABSTRACT

This paper examines the use of Sound Sensors and audio as input material for New Interfaces for Musical Expression (NIMEs), exploring the unique affordances and character of the interactions and instruments that leverage it. This paper first examines ten cases in which audio sensors, either microphone capsules or piezoelectric contact microphones, are used as a means of translating gesture into sound. We present the results of a user study comparing sound-based sensors to other sensing modalities within the context of controlling parameters. The study suggests that the use of Sound Sensors, and Dynamic Sensing Systems in general, can enhance gestural flexibility and nuance but that they also present challenges in accuracy and repeatability.

Author Keywords

User Study, Sensor, Contact Microphone, Audio Sensor

CCS Concepts

• **Applied computing → Sound and music computing**;
• Hardware → Sensor applications and deployments;

1. INTRODUCTION

Designers of NIME related work and DMIs are almost universally aware of how microphones and transducers work. They frequently have experience using contact microphones or condenser microphones as input into microcontrollers. Members of this community are usually equally aware of the use of audio modulation techniques such as convolution and peak detection as techniques for creating musical interactions. Audio is at the core of what we do in this field, so it might seem strange to write an academic paper examining the use of audio as a sensing technique. And yet, when the sensors in NIME related work are analyzed [13] [14] and when this material is taught [11] [5] [2], audio as sensed material is not treated as a special category among the range of approaches.

Medeiros' 2014 survey of sensor instrumentation methods in DMIs divides sensing methodologies into the broad categories of analog sensors, digital sensors, motion capture systems and consumer electronics[14]. Medeiros compares the results from Marshall's 2009 [13] dissertation and shows that the while some trends had changed between 2009 and 2014, the most common sensing techniques remained accelerometers and force sensitive resistors (FSRs).

Pigrem's 2018 study showed that people with a range of experience using DMIs have developed a literacy with sensors that enables them to predict the behavior and function of instruments without actually operating them or being given any instruction or background information [22]. This sophistication level suggests the ability to form a mental model of how various sensor types operate and the idiomatic ways in which they are typically mapped. Fels et al. [8] make a strong case that a clear interaction metaphor strengthens the interaction of musical instruments. Magnusson articulates that our tools strongly influence and prescribe our musical choices [12].

Sensing audio to control NIMEs is one possible method of creating an innate metaphor and intuitive mental model as providing a flexibility and transparency that is unique to Sound Sensors. In looking at previous work, the authors make the case that there are unique advantages to using audio sensors that can increase the nuance, materiality, technical transparency and playfulness of DMIs.

The authors then present a user study designed to investigate the ways that the use of Sound Sensors create interactions notably different from existing interface paradigms. Results from this user study are in keeping with the analysis of the prior work and point towards some of the elements of sound-based sensors that contribute to that uniqueness.

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2. AUDIO AS SENSOR DATA

2.1 Materiality

Armitage and McPherson [1] in *Crafting digital musical instruments: an exploratory workshop study*, describe a workshop where the *AirHarp* by Chris Heinrichs is deconstructed and reimagined by workshop participants. The workshop organizers provided a wide variety of wooden shapes, metal hardware and acrylic support pieces and prompted the participants to re-assemble their own functioning DMI. The accelerometer sensor that was in the original DMI was replaced with eight low-cost microphone capsules. The authors write, "This offered a high-bandwidth connection between physical behavior and sonic response, necessary for facilitating gestural interaction using a wide variety of materials."

In this case, the modification from an accelerometer to microphones increased the range of gestures and materials that could be sensed. Eight different DMIs were created, each quite different from the other. Instead of sensing the *AirHarp's* rotation in air, kalimba like tines were plucked, tubes were struck, metal mesh was scraped, and rubber bands were plucked. This represents a much wider pallet of gestures and materials. It also suggests a stronger connection to the physical and acoustical properties that constitute each instrument.

2.2 Playfulness and Technical Transparency

Using audio as data can also add to both the playfulness and the technical transparency of DMIs. The Ocarina iPhone app, designed by Ge Wang [27], is an excellent example of these qualities in a physical interaction. While the touchscreen is used to select the notes of the Ocarina, the iPhone's built in microphone drives the onset and articulation of each note.

In *Ocarina: Designing the iPhone's Magic Flute*, Wang writes, "The design aimed to use only the existing features without hardware add-ons—and to use these capabilities to their maximum potential." This simplicity creates a physical interaction that is intuitive for even those without prior experience using DMIs or other music technology. The analogy between the sensor choices and the user experience is so direct that in describing the design, Wang notes, “the statement was not ‘this simulates an ocarina,’ but rather ‘this is an ocarina.’”.

In *Acoustruments: Passive, Acoustically-Driven, Interactive Controls for Handheld Devices*, Laput et al. [10] describe a more ornate method that uses the speaker and microphone of an Apple IPhone as a sensing system. An ultrasonic signal is sent out of the speaker, sensed by the microphone and analyzed by software. The signal travels through different types of ducts, created from rubber tubing or 3D printed parts. The design of these physical ducts are created to mimic the behavior of passive electrical components such as switches, valves, tilt sensors, potentiometers and sliders. In the case of a valve, there is a portion of the duct that can be turned 90 degrees, thus blocking the sound transmission through the duct. The slider is created by a piece that can constrict the flow of sound through the duct.

This overt and observable system is not necessarily practical, but it playfully makes visible the types of structures that make up more conventionally constructed sensors. In a world of increasing obfuscation and “black box” technology, that sort of transparency is endearing. The authors describe a variety of whimsical applications for this technology such as an alarm clock, an interactive doll and a toy car. With the onboard microphone and speaker system, a wide variety of interactions and sensor types can be emulated in a unique and lucid manner.

2.3 Playfulness and Materiality

Mogees [18] and the work of Ono et al.[19][20] present two examples of using audio signals along with pattern recognition as a sensor methodology. In both cases, the result is work that engages materiality and playfulness.

Mogees is a commercial product consisting of a contact microphone and iOS apps. The apps use deep learning to recognize different types of gestures such as hits, scratches, and taps on the object to which the microphone is connected. Those different gestures are then mapped to synthesis parameters within the app. The system is marketed as a playful tool for musicians and dancers to engage with the physical world. The website features examples of the inventor playing a bowl of wooden fruit and mimicking the sounds of a guitar player, break dancers that trigger different notes based on where they strike a piece of plywood with their feet, and a percussionist playing a large metal sculpture. These examples leverage artists’ desire to engage with the material world and they also strive towards a playful aesthetic.

Touch & Activate: Adding Interactivity to Existing Objects Using Active Acoustic Sensing by Ono, et al. [19] describes a system that uses a contact mic similar to the Mogees but adds a vibration transducer to the object being sensed. This allows static hand gestures and holding positions to be detected. A sweep signal is sent to the vibration transducer, the microphone signal is spectrally analyzed and sent to a Support Vector Machine (SVM) learning algorithm. The system is designed to measure specific hand positions. In the case of a plastic toy shaped like a cat, the system can identify if it is being touched on the left side, right side, both sides or the top. In the case of a cellphone, the system identifies if the phone is held with the left hand, right hand, either hand using a thumb on the screen, a hand position with two thumbs on the screen or the type of grip characteristic of taking a photo with the phone.

In *Sensing touch force using active acoustic sensing*, by Ono et al.[20] a similar methodology is employed but the pressure with which the object is held or touched is detected as a continuous input parameter. In this case, the spectrum is analyzed and plotted not as discrete events but as a continuous parameter that changes according to hand pressure.

2.4 Nuance

Romain Michon’s *BladeAxe* [16][17] is a musical instrument that is designed to control waveguide physical models of string instruments. The plucking mechanism consists of two piezo film sensors attached to thin pieces of plastic that are individually plucked. One plucking surface controls individual notes and the other controls strummed notes. The piezo sensors are treated as audio signals and routed through a stereo audio interface into the iPad. The iPad software functions as a fretboard for the musician’s left hand allowing them to select and bend notes while simultaneously using the audio signals from the piezos as impulses to the physical modeling synthesis algorithms.

There are a number of interesting elements to the *BladeAxe* but the most intriguing is the use of audio signals as the impulse to the waveguide synthesis method. Waveguide synthesis is a powerful synthesis technique that is capable of great sonic nuance. It can be a challenge, however, for a user to manage and control the number of parameters required to create that nuance. The impulse to the synthesis model has a great effect on the sonic result and focusing on it can result in a wide variety of sonic variation. In the case of the *BladeAxe*, the audio signal will be different for each pluck of the piezo film sensor. Factors such as where along the thin piece of plastic the pluck sensor is struck, how hard it is struck, the use of fingers or plectrum (pick) to pluck the sensor, and the angle of the pluck will all vary the sonic results of the synthesis. Changes in technique will create dramatic changes in the sound produced and this is captured by the high resolution of the audio signal. This creates a level of expressive nuance that is similar to a traditional acoustic instrument. Other examples of using audio signals as an input to waveguide synthesis show corresponding levels of nuance and musicality [9][23][24].

This opportunity for nuance extends past waveguide synthesis and into other compositional and sound design endeavors.

Paisa’s work, “Enhancing the Expressivity of the Sensel Morph via Audio-rate Sensing” [21] uses contact microphones attached to the Sensel Morph to add an additional layer of data to the sound design mapping. The audio data from the sensor provides a sonically rich base that is then modified by the user’s interaction with the touch pad. This extra layer of complexity expands the Sensel into something that was more broad and surprising than a simple x-y grid.

Tomás’ *Tangible Scores* [26] use contact microphones attached to textured scores as a dual-purpose musical score and instrument. The contact microphones and variety of physical materials and textures used in his scores form a creative ecosystem that is tightly coupled both functionally and conceptually.

In Merrill’s [15] *Sound of Touch*, a scraper with a contact microphone is passed over various semi-flat materials and recorded. When the scraper is passed over other materials or the same material again, the new signal becomes the basis for convolution-based sound playback. This allows the nuance of materials to fold back on themselves and create a unique, material-based approach to sound design.

These diverse examples point to unique advantages and affordances of Sound Sensors in NIMES however, each of these examples exists within a complex musical system. Our user study sought to isolate the use of Sound Sensors and look at the specific manner in which they differed from other sensing systems.

3. USER STUDY

Despite our desire to isolate the impact of Sound Sensors, any study that we designed required incorporating the sensing systems into larger digital music systems. We sought to create a system that was as transparent and immediately understandable as possible for our users. To that end, we used simple mapping paradigms, relatively uncomplicated musical examples and simple physical input designs.

3.1 Methodology

Participants were asked to control a single parameter within nine different musical examples in an Ableton Live session. The first three examples controlled the volume of a given track (Piano, Kick Drum or Synth), the second three examples controlled the resonant frequency of an audio filter (Low-pass filter on Bass and Kick/Snare and a High-pass filter on Strings), the final three examples controlled the wet/dry mix of reverb (Kick Drum, Guitar, or in one example the entire mix)

Figure 1: Wooden Box Construction

For each of the three types of audio parameters (volume, filter, reverb), the participants used one of three sensor systems (Section 3.4):

- **Slider**: a single slider on a Korg nanoKONTROL 2.
- **Touch Sensor**: a Sensel Morph touchpad with no silicon overlay applied.
- **Sound Sensor**: a wooden box with a piezoelectric contact-microphone attached to one of the two thin-plywood faces.

3.2 Musical Examples

The focus of the user study was the physical interaction with the three sensing systems. Simple mappings and musical examples were used, in order to maintain that focus and ensure that users who were unfamiliar with computer-based music creation, were not distracted by unnecessary complexity. One-to-one mappings of sensor values to individual parameter values allowed users to quickly understand the effect that their physical choices had on the musical outcomes.

Each of the nine musical examples was between 30 seconds and one minute long. The examples were kept relatively simple, with no more than five tracks making up a single example. A variety of musical styles was employed in an effort to appeal to the widest range of musical tastes. The users were given an opportunity to listen to the example and experiment with controlling the given parameter for as long as they liked with the individual track and with the entire mix playing. When they were familiar with the tracks and controls and we had made any adjustments necessary, we recorded the automation data for one full loop of the musical example.

Within each parameter type (volume, filter or reverb), the order of the three tracks and which controller was used to control that parameter were randomized. This was done to avoid inadvertently biasing users in case one of the musical examples was especially appealing to users. The order of the controllers used was also randomized to again avoid biasing the users.

3.3 Participants

Participants from a wide range of musical backgrounds were recruited. Of the twenty-four participants, five had no musical training or limited musical training as children and did not consider themselves musical. Six participants were accomplished acoustic musicians, three were accomplished electronic musicians and ten participants had significant experience in both electronic and acoustic music.

Musical experience was determined by asking a series of questions about the length of time participants had played acoustic instruments and/or created music using electronics or computers. They were then asked to summarize their musical experience in 1 to 4 sentences.

All participants were adults and were recruited by a mixture of online publicity and extensive paper flyers throughout academic institutions and music venues in Wellington, New Zealand.

3.4 Sensor Systems

3.4.1 Sound Sensor

In preliminary discussions of study design, several potential participants expressed anxiety about being asked to make sound. The act of making sounds with their voice or an object that had too many similarities to a musical instrument made them feel vulnerable and open to judgement. Sensing sound requires making sound which can be intimidating for many people, including some trained musicians who might not feel comfortable being put on the spot and “tested” and even more so for people who do not consider themselves musicians. We wanted the gestures being sensed to be unassociated with traditional music making because we wanted to avoid any association between the gestures being sensed and musical skill. However, we still needed there to be an audible sound being made that could be detected by the participant in order for the user to have a clear understanding of what was being sensed, even if they did not understand the technology behind it. We were hopeful that this would give them the tools to form a mental model [8][22] of the sensing system.

We decided to use a hollow wooden box that would allow users to generate sound via actions such as scratching, tapping, or stroking. We built the box to be roughly the size of an Apple iPad because that is a physical dimension with which contemporary technology users are familiar. While tapping movements could be rhythmic, and indeed that was a feature that some users enjoyed, the control was not dependent on any type of fundamentally musical gesture and stroking or scratching worked just as well as more rhythmic actions. The loudness of the contact microphone signal was analyzed over a window of samples in Max/MSP and a corresponding MIDI CC message was sent to Ableton Live where it was mapped to the appropriate automation parameters.

3.4.2 Slider Sensor

In order to compare the participants’ use of the Sound Sensor to their use of a more traditional physical control for an automation parameter, we chose to use a commercial controller with a vertical slider. We chose a Korg nanoKONTROL 2 for ease of portability because the study was conducted at a number of locations. We hoped that the slider would function as a standard base against which to compare other sensing protocols.

3.4.3 Touch Sensor and Dynamic Input

In initial mockups of the study, it became apparent that in addition to the difference in sensor technology between the Slider and Sound Sensor, there was a crucial difference in the interaction paradigm that, as far as we know, has not been articulated. The Sound Sensor measured a fundamentally temporal signal which required constant input to register any value.

For the purposes of this paper, we will call this a Dynamic Sensing system. Oxford University Press defines Dynamic as: “(of a process or system) characterized by constant change, activity, or progress” [27]. The word dynamic has distinct connotations in both the musical and engineering realms so it is not an ideal choice, however it will have to suffice until we find a more appropriate term. Identifying sensing systems as dynamic is distinct from categorizing them as continuous or discrete in that what is being looked at is not the range of data being sensed but whether the sensor needs constant input in order to maintain a value. Dynamic sensing is closer to the disfluent design strategy described by Bin et al. [3] however the “instability over time” described in the disfluent system is an intrinsic part of the dynamic system and not an element that is intentionally mapped into the design strategy.

The need for constant physical involvement when interacting with the Sound Sensor was so different from the use of the slider that we decided an intermediary sensing system was needed – one that required constant input to register a value but was not built on the sensing of an audio signal.

We decided to use Sensel Morph because participants could use moving gestures that were similar to those made on the wooden box of the Sound Sensor. In Max/MSP, we analyzed the distance that the users' finger or fingers travelled over time on the Morph. We ignored the multi-touch and the pressure sensitive aspects of the device.

3.5 User Customization

For all three parameters, the range of control could be adjusted. In the case of the Slider, we could adjust the range of the parameters to which the slider was mapped. In the case of the Sound Sensor, we could control the pre-amplifier sensitivity on the audio interface that connected the contact microphone to the computer. For both the Sound Sensor and the Touch Sensor, we could alter the window of time over which the signal was measured and averaged. Shorter windows led to faster attack and decay times but also a need for a more constant input.

At the beginning of each user study, we explained the system to the users, allowed them to experiment with a visual representation of the data that was being produced in Max/MSP, and then showed them how they or we could change the sensitivity to suit their preferences. Throughout the study, we checked in with the user to make sure that they were happy with the settings for the various controllers.

3.6 Data and Questionnaires

Results for the study were recorded in three ways:

1) We recorded the automation data for each of the musical examples and that was eventually exported as text files via Max/MSP.
2) We filmed the users' interactions with the controllers.
3) After the nine examples were completed, users were asked to fill out an eleven-point questionnaire. For each controller, they were asked what they most and least liked and if they were to re-design the controller, what would they do. Then they were asked if there were musical possibilities they would like to explore with the controllers.

4. USER RESULTS

4.1 Individualized Physical Approaches

One of the most interesting outcomes of the user study was the wide variation of physical techniques that users developed when interacting with the Sound Sensor system. Users frequently developed an individualized ergonomic approach that was unique to their own experience of the physical world.

Four distinct examples highlight this physical difference:

- A former Feldenkrais movement instructor asked that the contact microphones preamplifier be turned up to 75% of its maximum amplification. Her movements were never more than 5 cm in diameter.
- A classical violinist asked that the preamplifier be turned up to almost 100% and her movements rarely exceeded 3 cm in diameter.
- A former rock musician who now makes Noise Music using analog gear controlled by Ableton Live enthusiastically stated that he appreciated knowing that he could kick the sound controller. He preferred to hit and tap the wooden box and quickly abandoned any type of stroking or scratching movement. The possibility of translating intense physical energy into the system without the fear of breaking a delicate music controller excited him.
- A former puppeteer and percussionist who had struggled with severe, career-altering tendonitis, placed the wooden box on its edge and experimented with using different sides of the box and angles of approach.

Not all users were as individualized in their interactions with the Sound Sensor – some were content with the settings that they were given. Likewise, there was variation in the musical and physical gesture choices of the users when operating the Sensel touch sensor and the Korg nanoKONTROL slider. Users brought their own musical styles, experience and taste to bear on their choices. However, their physical movements were mostly similar. No user asked to physically reposition or place the nanoKONTROL or Sensel controllers in a different orientation. Each tool remained flat on the desk and the user conformed their movements to the prescribed technology. At the beginning of the study, the users were told that they could change the sensitivity and range of all three sensing systems. As the test progressed, the users were repeatedly questioned to make sure that they were happy with the settings. No user asked for an extremely different level of sensitivity or range in these sensing systems.

The uniqueness of each user's interaction with the Sound Sensing device suggests an individualized idiomatic quality to the interactions, a personal style that is intrinsic to each user.

4.2 User Forms

There were a number of clear trends in the qualitative user feedback forms. A summary of common descriptors can be found in Figure 2. Unsurprisingly, the slider on the Korg nanoKONTROL was praised for its predictability and ease of use but it was also frequently described as boring. The Sound Sensor was described as fun and varied but the background noise of touching the box and the effort required to keep a steady value was criticized.

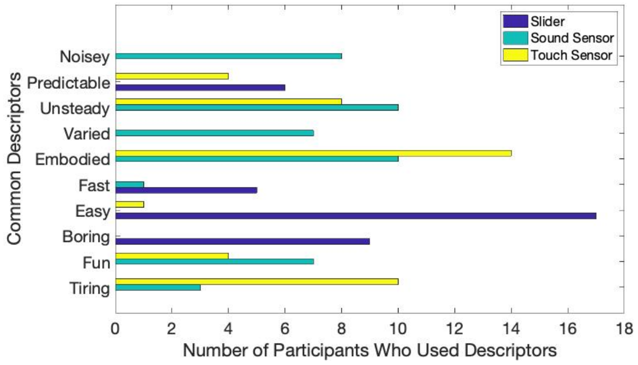

Figure 2: Common Descriptors, Extracted From Qu

4.2.1 Surprising , Unpredictable, Fun

Surprising and fun but unpredictable was a common summary of the users' feedback about the Sound Sensor. Users that had experience with electronic music expressed a desire to explore the system in greater depth and with more freedom than a restrictive user study could provide. One user wrote, " Yes. I want to jam with it at home. Attach it to a bunch of plugins, filters, whatever. It's tactile and fun to interact with."

This was in contrast to the Slider, which often was described as more predictable but also less fun. "It took the excitement and sense of play out of the task." The control that the slider provided, however, allowed some users to more accurately reach their musical goals: "I like the ability to have fine control and find the sweet spot."

4.2.2 Embodied

The physicality of the Sound Sensor was one of the most remarked upon advantages: "The embodied interaction. It was very open in interaction in that I had to find multiple ways of imparting energy into the system to control it. It was more like an instrument in interaction."

One user wrote about the possibilities that this embodiment offered for people of different abilities: "A much more embodied to the control of midi data. Elements of randomness due to lack of ability to control specificity. Allows for multiple interpretations of how to use the device. Could be used in different ways by people with different ability requirements."

The materiality of the Sound Sensor provided some users welcome tactile feedback: "The wood texture made it easy to feel how hard I was inputting sound and texturally it helped my senses to know what I was doing."

4.2.3 Noisy

A large number of users remarked on the noise of the Sound Sensor itself (the touching and tapping the wooden box) and the distraction that this provided. In the case of the examples that were discussed in Section 2, most of the devices were not producing as much acoustic noise and if they were, it was fundamentally more musical. In an effort to make sure that users were quickly developing an accurate mental model, we created a noisy, resonant box. This level of noise would not occur in most DMIs.

4.3 Effort and Dynamic Sensing

The Touch Sensor and the Sound Sensor were both criticized for requiring too much effort. One user wrote about the two sensors that they, "required some more physical effort, which I may not feel like doing, only sometimes.(sic)"

This brings up interesting questions of user engagement within digital music. It is only in the electronic age that we have become accustomed to sonic systems that do not require continual physical energy being placed into the system. Pianos, flutes, drums etc. all require repeated effort.

There was also a frequent cognitive conflict between a user's perception of effort and the actual action being performed. In the case of the Touch Sensor, some users felt like they were moving very fast when they quickly switched directions of their finger back and forth. An engineer said, "I thought that you were measuring speed, but you are just measuring distance travelled over time." This dissonance was sometimes perceived as the device not working properly.

4.4 Slider Gestures Influenced

Initially, we hoped to use the slider as a control subject, a baseline for common control techniques. Instead, we were surprised to find that users were often influenced by the Dynamic sensors to use the Slider in a more active manner.

One participant wrote about the Slider, "I would normally have moved it less, but the nature of the test somehow made me move around more." While he was the only person to make a note of this in his evaluation, this change in behavior was apparent with a significant majority of the participants. Participants rarely left the slider in a static position but instead moved it up and down and tried to sync the changes to the music even when doing so was a slightly odd choice musically – for example the rapid and extreme changes to the wet/dry mix of the reverb. Additionally, the small size of the nanoKONTROL slider meant that there was a tendency to move the slider to the two extremes of its range.

4.5 Touch Sensor– Divided Opinion

The Sensel Touch Sensor elicited the most divided responses. For both the Slider and the Sound Sensor, most users articulated positive and negative attributes about the interactions. In the case of the touch sensor, user response was largely one sided. Sixteen participants were overwhelmingly positive, five were overwhelmingly negative and only three provided a less decisive response. In contrast, the feedback given to both the Sound Sensor and the Slider were more nuanced with people providing a mixture of both positive and negative remarks with 3 and 2 users respectively giving only positive remarks.

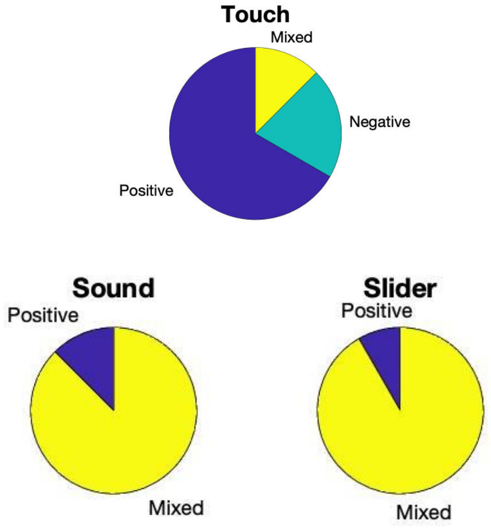

Figure 3: User Opinions of Sensors

Additionally, the people who appreciated the touch sensor interaction used words such as fluid, smooth, intuitive, and natural. They said that the interaction felt more artistic and made them feel like musicians. This is particularly interesting because, as seen in Figure 2, the touch sensor also had the highest number of people say that they found using it to be tiring and require a significant amount of physical exertion.

It is possible that some of the negative reactions could be from the conflict between how a touchpad is typically used and how we were asking the users to use the Sensel. Users of contemporary technology are accustomed to dealing with a two-dimensional touch surface analyzed in an X-Y pattern. There was a cognitive dissonance between that expectation and the analysis of dynamic movement that was felt by users, even when they enjoyed the interaction. One user who particularly enjoyed the touch sensor suggested that an improvement to the device would be adding grid markings. It is possible that he meant adding a layer of analysis that looked at movement location, but he verbally described it as a way for a user to go back to the same section of the control space that they had enjoyed previously. It was as though he somehow over-laid his expectations of a position-based touch sensor onto his experience with this dynamic controller and wanted those two interaction models to exist simultaneously.

4.6 Summary and Future Work

These user test results largely mirror what we might have expected from the use of Sound Sensors – they are more flexible and open-ended and simultaneously more difficult to control and replicate. The range of responses to dynamic sensing and user effort was intriguing and points to one of the many ways that digital music making has departed from acoustic music.

Several of the electronic musicians who participated in the user study expressed a great interest in using the Sound Sensor system in the own work. The authors hope to work with these musicians to fine tune and further customize the system towards their particular creative practice. Many of these musicians had excellent suggestions, such as adding textures and zones within the resonant box to illicit different results. We look forward to working with some of these musicians and developing collaborations that are more musically mature and focused.

5. CONCLUSION

While most readers of this paper are familiar with sound-based sensors, this paper has examined their unique advantages and limitations. We have analyzed examples of NIMEs created with sound-based sensors and presented a user study that highlights and confirms the unique qualities of sound-based sensing systems.

We have shown that Sound Sensors and Dynamic Sensing systems are compelling ways of adding nuance, playfulness and embodiment into new musical devices. Not every NIME would benefit from the addition of these paradigms. But there are a great number of interactions and gestures that can be sensed through audio. Sound Sensors are capable of considerable nuance and complexity and there is often something clarifying and intuitive about the use of Sound Sensor data within the design of DMIs and other musical interactions. Sound Sensors present unique capabilities that set them apart from other sensing modalities.

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