Musical Gesture through the Human Computer Interface: An Investigation using Information Theory

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MUSICAL GESTURE THROUGH THE HUMAN COMPUTER INTERFACE: AN INVESTIGATION USING INFORMATION THEORY

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Music

by

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August 2021
To the benefit of those who may take more delight in the making of meaning and joy through music as a result of these efforts, however small, and to Laurie, Julia, Charlotte, and Ella.
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Survey responses to the question, “How accurately can one continuously control the following sensors at relatively FAST rates of movement?” per sensor.
Abstract

This study applies information theory to investigate human ability to communicate using continuous control sensors with a particular focus on informing the design of digital musical instruments. There is an active practice of building and evaluating such instruments, for instance, in the New Interfaces for Musical Expression (NIME) conference community. The fidelity of the instruments can depend on the included sensors, and although much anecdotal evidence and craft experience informs the use of these sensors, relatively little is known about the ability of humans to control them accurately. This dissertation addresses this issue and related concerns, including continuous control performance in increasing degrees-of-freedom, pursuit tracking in comparison with pointing, and the estimations of musical interface designers and researchers of human performance with continuous control sensors. The methodology used models the human-computer system as an information channel while applying concepts from information theory to performance data collected in studies of human subjects using sensing devices. These studies not only add to knowledge about human abilities, but they also inform on issues in musical mappings, ergonomics, and usability.
Chapter 1. Summary

The expanding availability of inexpensive, mass produced sensors and the further development of flexible, accessible microcontroller platforms have led to diverse, interdisciplinary efforts to explore human-computer interaction in practical and theoretical contexts. It is necessary to understand user performance in controlling sensors. This dissertation is concerned with human performance in continuously controlling sensors that are used in the design of new interfaces. The presented research adds to a relatively small number of studies in human-computer interaction literature about the continuous control task and situates the investigation and findings within the practice of designing interfaces for musical expression. Increased interest in using continuous control sensors within interface designs to enhance performer control of electroacoustic properties has created a need for further understanding of the limits and range of communication made possible through their use. These developments increase the urgency that empirical inquiry in this area be made. Findings from these studies may also be useful toward improved design of demanding continuous control tasks in other applications, such as navigation, machinery operation, robot assisted surgery, etc.

The investigation described here follows a methodology of literature review, observation, analysis, and engagement with practice. The related literature in musical interaction design, human-computer interaction (HCI), and human factors is reviewed. Empirical observation of pursuit tracking tasks is made in a comparison with the well-researched pointing task, in control with multiple degrees-of-freedom, and with various sensors in one degree-of-freedom. An analytical method is advanced and applied within a theoretical model representing the human-computer system and associated noise. These methods are engaged with performance practice using new interfaces. A survey of practitioners of design for such interfaces is also collected to contextualize empirical results alongside craft experience.

Across all of the subject experiments of this dissertation, an analytical method based upon the Shannon-Hartley Theorem is applied to determine the channel capacity of the
human-computer system. Results in bits per second across a range of control bandwidth limits allows comparison of multiple dimensions of human performance and across sensors.

The first subject experiment studied pursuit tracking and pointing gestures with a common interface including a touch strip mounted to a flat screen display, co-locating targets and sensing apparatus. At lower control bandwidth limits, subjects communicated more information by pointing/tapping on discrete targets than by pursuit tracking/following a target curve. At higher control bandwidth limits, subjects communicated more information by pursuit tracking. Overall, subjects performed more accurately with lower bandwidth limit pointing/tapping than higher bandwidth limit pursuit tracking.

Subject experiment II expanded the pursuit tracking task to two dimensions using a trackpad/touchpad interface of a laptop. At lower control bandwidth limits, subjects communicated more information with two degrees-of-freedom than with the one degree-of-freedom touch strip of the former study. In this experiment, subjects completed three successive trials of the control task. Improvement was not shown across the three trials, although there was some evidence that a subset of subjects performing at a higher level improved across trials.

This second experiment was conducted in a lab setting of a class for first-year undergraduate students of music. A hybrid experimental interface and musical composition using the sonification of performer error as a driving synthesis strategy provided the performance setting. Details of this sonification system are shared. The work exhibits an aesthetic featuring characteristics of *glitch* music while providing feedback of performance error and explores agency and the role of the performer of such an interface.

The third subject experiment examined performance within a protocol of successive increase in degrees-of-freedom from one up to four degrees-of-freedom using two joystick interfaces. At very low control bandwidth limits, users communicated more information with each additional degree-of-freedom, monotonically. However, at middling to higher control
bandwidth limits, two degrees-of-freedom afforded higher communication rates, and performance communicated relatively less information in additional degrees-of-freedom.

A comparison of pursuit tracking performance using eleven sensors is the final study described. It found that subjects communicated the most information with position sensors over force and proximity sensors, as groups. Comparison within sensor groups showed that subjects communicated the most information with potentiometer-based sensors within the position sensor group. Among proximity sensors, subjects communicated the most information with an infrared sensor rather than with the capacitive or ultrasonic sensors. A set of reference channel capacities resulted from this study that may be of use to designers of new interfaces.

To situate these results alongside the craft knowledge of designers of new music interfaces, a survey was conducted of the New Interfaces for Musical Expression (NIME) conference community. The results of the survey established the estimations of control by novices, by experts, with slower movements, and with faster movements for a range of sensors. The results broadly correlated with the empirical results, but some differences were evident. Respondents over-estimated the capabilities of control of a capacitive proximity sensor, although this could also be interpreted as evidence of weakness in the capacitive/inductive sensor under investigation. The respondents overestimated control of a force sensing resistor (FSR) at faster rates of movement. There was indication that performance with the load cell sensor was slightly underestimated.

These studies are the first estimations of information transmission in continuous control for the sensors included. The results in a unifying information measure of channel capacity in bits per second significantly contribute to the understanding of human performance of continuous control using sensors in a human-computer interface. Key findings may be summarized as follows:

1. Continuous control may afford higher rates of information transmission than pointing at higher bandwidths of movement.
2. Control with more degrees-of-freedom allows novice performers to communicate more information, but aside from very low control bandwidth limits, more than two degrees-of-freedom has the potential to lower information capacity.

3. Position sensors provide a control advantage over proximity or force sensors and are therefore preferable for more demanding control tasks or parameter mappings.

4. Across all studies where researchers participated in separate trials, expert control exceeded novice performance by large margins, and result should be understood as for the latter group.

5. Practitioners may be overestimating performer control with force sensing resistors and with capacitive sensors, but these estimations require further scrutiny.
Chapter 2. Introduction and Literature Review

Introduction

The design of electronic and computer musical instruments is a growing tradition, one with engagement in dynamic research, performance, and composition activities. The practice of designing such instruments has featured agile adoption of new technologies and the creative application of established ones to new uses in music making. Typically made with a modular approach, an instrument may include an agglomeration of many component technologies that accomplish the various outcomes demanded by the design, from powering the device to diffusing its sound energy. In order for human performers to create music in real time with digital musical instruments, the device must usually include a human-computer interface comprised of sensors that translate detection of physical quantities to signals that may be arranged to control various parameters of sound synthesis and manipulation. Through such sensors, a musician may then perform an instrument using physical movements that are detected by these sensors.


Literature Review

Mapping of these sensor signals to synthesis systems has received considerable research study as it is a central element of instrument design\textsuperscript{4,5,6} Efforts have been made to develop coherent frameworks for mapping and also to connect mapping to broader theories of affordance\textsuperscript{7} summarized briefly by Tanaka\textsuperscript{8} In a critical reflection on the perspective of designing for affordance, Magnusson highlights the perspective of designing constraints\textsuperscript{9} To design for affordances or constraints requires a knowledge of the enabling and limiting factors inherent to ergonomics of a design, mapping decisions, computation speed, signal power, sensor components of a system, capabilities of the performer, noise interference characteristics, to name a few. Some of these material qualities may be known from engineering specification, prior literature on human factors, and others are learned through design experience and reflection. However, the affordances and constraints of these factors where limitations are undefined can only be approached intuitively.

\begin{itemize}
\end{itemize}
Capability Ranges in Design Consideration

Digital musical instrument design requires consideration of the range of player capabilities. Presented as matters of principle, there is acknowledgment of a need to provide a measure of immediate satisfaction to a novice upon first interaction. Perry Cook noted as one of his principles for designing computer music controllers: “Instant music, subtlety later.” Wessel and Wright similarly value this design focus, but reserving some simultaneous consideration of rewarding repeat and practiced interaction, “Low entry fee, with no ceiling on virtuosity.” Sidney Fels and Tina Blaine propose that these design considerations are dependent primarily on context rather than trying to satisfy all in one instrument.

In theoretical writing on interactive instrument design, Pressing speculated as to the capabilities of a super-instrument featuring up to 40 degrees-of-freedom tempering this estimation with assumption of cognitive limitations which would reduce the use of so many dimensions of control. In a realized example of an effort to provide very high control bandwidth, the HIRN instrument included more than eight degrees-of-freedom of continuous control along with as many discrete controls. In reflection, Cook noted that “negative lessons


from the HIRN project indicated that huge control bandwidth is not necessarily a good thing..."[15]

The boundaries of afforded continuous control and the ability to perform or communicate through that control are not well defined. Whether designing for a range of capabilities or for a target sub-range, an understanding of the different capabilities of control could be informative. That a design has been calibrated for a level of expertise is often stated with descriptions of the number of sensors and of the mode of interaction.

**Continuous Control and Enhanced Performance**

There is a growing interest in continuous control as a means of affording additional performance capability through added control bandwidth. Such control may facilitate the provision of acoustic viability[16] to sounds directly from performer control, rather than through complex, informed synthesis techniques. As an advancement of this trend, commercial instrument makers have expanded their use of continuous control sensors in keyboard-like instruments. Products such as the Roli Seaboard[17], the Linnstrument[18], and the Haken Audio Continuum[19] feature continuous control in multiple degrees-of-freedom and provide mappings to continuous timbre, pitch, and amplitude controls.

---


In a recent interview, Roger Linn described benefits of continuous control sensing in recent commercial music controllers.

“You don’t really need much complexity in synthesis when you’ve got expressive control. You can take just a simple oscillator and then you’ve got control over pitch, loudness, and timbre — all in one finger. The beauty is created by your performance more than just adding oscillators, adding envelope fitters, adding LFOs. In point of fact with an expressive controller you don’t need envelope generators or LFOs, because if I want an LFO to do vibrato, I wiggle my finger. if I want an LFO to do tremolo, I vary pressure repeatedly with my finger. if I want to do a pitch bend, I slide my finger from one note to the destination node, and then I vibrato. So synthesis can become remarkably simple under expressive control and yet you still have great beauty.

... It’s the type of thing you have to experience and then once people do, with Linstrument or Seaboard or Continuum, they never go back you just can’t go back to playing music with on/off switches. It just doesn’t work.”

Expressive control here refers to multiple degrees-of-freedom, but also the continuous nature of control in these dimensions.

McPherson documents the introduction and development of continuous control in electronic keyboard instruments and within augmenting devices that detect piano key movements. Also documented there are historical precedents and motivations that led to this practice, including a wish for vibrato and amplitude envelope control and a compensation for the lack of the sensation of touch in discrete electronic keyboard instruments. Moro analyzed the Hammond organ and its performance technique and considers continuous control in keyboard instruments through design experiments and performance studies.

---


Beyond musical application, continuous control gestures are being implemented in authentication systems and researchers are investigating their security potential in information-theoretic terms.\textsuperscript{23} An adaptive text input interface, Dasher, was developed and studied for its capacity to input text with a steering process.\textsuperscript{24} Better understanding of continuous control could inform these applications.

\textit{Gesture: Movement with Meaning}

Originally signifying the carriage of the body, gesture has come to be understood as movement imbued with meaning.\textsuperscript{25} An important topic within studies of musical expression, gesture is of particular importance to studies of the design and use of new interfaces for musical expression. The term was found in a majority of papers in the New Interfaces for Musical Expression conference proceedings, and was even found to be the second most common after \textit{music}.\textsuperscript{26} Beyond this particular research area, the term \textit{gesture} holds many meanings within music research, from conceptual and compositional elements relevant to theoretical music analysis to various types of bodily movements of performers or listeners. There is a broad field of inquiry into these topics, all under the heading of gesture.

\textit{Gesture in Studies of Music}

Communicative gesture is understood to have aspects of \textit{extension}, as physical movement that can be measured through sensing devices, and \textit{intention}, the meaning intended


\textsuperscript{25} “\textit{gesture, n.},” (OED Online, March 2019), accessed March 31, 2019, \url{http://www.oed.com/view/Entry/77985}.

to be carried by the movement.\textsuperscript{27} To avoid a conceptual separation of these aspects, the perspective of embodied cognition is sometimes used to describe gesture as a mental and corporeal category of a perception-action system.\textsuperscript{28}

In some cases, scholars refer to melodic phrases or formal compositional sections of music as \textit{gestures} or \textit{musical gestures}. Since movements may aggregate to and realize these coherently enclosed units, it can be helpful to align these terminologies and describe them as gestures, although the meaning in this case is primarily conceptual and metaphorical. The intention of such a gestural expression in composition is connected to extension as performed movement.

Jensenius provides a thorough summary of how the terminology \textit{gesture} is used in various contexts, making distinction between gesture as communication (as human to human), as control (human to machine), and as mental imagery (metaphorical).\textsuperscript{29}

With regard to physical musical gestures, the qualifying terminologies \textit{music-making gesture} and \textit{music-responding gesture} help to differentiate from conceptually-encoded gestures in music and those made in response to music.\textsuperscript{30} Music making gestures and music responding gestures are investigated separately in some studies, but it can be reasoned that this separation is not distinct in the case of performance with other players and in the sense that there may be common information within these gestures.

In terms of the connection of gesture to sound and instrumental performance, some distinctions may be made. Cadoz distinguishes between sound \textit{producing, modifying,} and


\textsuperscript{28} Ibid., 8.


selecting gestures.\textsuperscript{31,32} The distinction between these gestural modes is often reified by instrumental mappings of sensor control to digital musical instrument design parameters of sound producing, modifying, or selecting aspects of computer synthesis systems. In considering the transmission of performer intent through the interface of an instrument, Cadoz posits a gestural channel.\textsuperscript{33,34}

Overall, gesture is primarily discussed in connection with communicating meaning, either to augment separate communication through musical sound or speech or through movement alone. Communication as control through a gestural channel can more fundamentally be understood as transmission of information.

\textit{Gesture as Information}

In a musical acoustic context, the source information present in a sound can be understood to include aspects of the sound-creating gesture as well as the material property of the instrument and sound diffusion setting. When we hear sounds, we hear within their properties information about the source of the sound and its transmission. Within sound properties, one can discern information about the excitation of the sound, the material modification of the sound (either by transmission of sound energy through material or by change of conditions manipulated by a performer), and aspects of the space of its diffusion. While information about gestures can be gained through direct sensor systems, indirect

\begin{itemize}
\item \textsuperscript{33} Cadoz, “Le Geste Canal de Communication Homme/Machine: La Communication Instrumentale.”
\end{itemize}
acquisition methods through recordings of audio are being developed. The efficacy of early efforts in this domain demonstrate that inferences about gesture information within sound are supportable by informed analysis.

Representations of human movement directly obtained via sensor data provide signals that may be analyzed for their information content. Sufficient resolution of sampling rate, circuit fidelity, and sensor precision improve the accuracy of the represented information communicated by the sensed gesture. Further, information transmission in a human-computer system composed of gesture-capturing sensors is measurable and, through the application of information theory concepts, can describe properties of the capability of the system within some limits. Such analytical results have been used in studies of non-musical human-computer systems as measures of human performance and in interface design.

Movement and Gesture in HCI Research

The human-computer interaction (HCI) literature reflects decades of investigation into the pointing gesture for communicating information and into the relationships of target signal characteristics to human capability. Fitts’ Law and extensions within information theory have developed knowledge of the limits of information throughput using a pointing gesture, even informing international standards for pointing devices. Fitts’ Law, with its established relation of time of movement to a target as a ratio of movement and target


width, is a fundamental model influencing human-computer interaction design. Additional choices of target can affect reaction time, and Hick’s law describes a logarithmic relationship of reaction time to the number of options made available.

In contrast, far fewer investigations of pursuit tracking gestures for continuous control have been conducted using information theory. Meanwhile, the ability to convey information through continuous sensors is an essential part of their utility and afforded interaction, especially for music interaction. A quantitative measure of the upper limit of what amount of information may be conveyed through a continuous control sensor is pertinent to musical performance limitations and, further, may be important to the design of its use in this application and in others.

More broadly, an upper limit of 10 bits/sec has been speculated as the maximum for human control communication in one degree-of-freedom. This maximum was affirmed with a study using a stylus although some studies have shown higher information rates. There are sure to be lower maxima for some sensors and modes of movement.


The amplitude of movement has been established to be inversely related to rates of information transmission in pointing\textsuperscript{47} although initial very high throughput results for small movements were later corrected with improved methods\textsuperscript{48} Some sensor use will require larger amplitudes of movement, and others may involve movements that increase motor noise. Certain sensor types may also have noise caused by their design or sensitivity to power source fluctuations that can influence transmission rates. Each of these limitations can decrease throughput below this maximum.

Model

By applying information theory approaches originally designed to calculate communication capacities through equipment in the presence of thermal noise, an estimation of information capacities in continuous control human-computer sensor systems can be made. The model used for experimentation in this study envisions a human-computer system in which a performer intends to communicate an information signal $X(t)$ through a sensor interface, yielding an inevitably different signal $Y(t)$ (see Figure \ref{fig:2.1}).

More formally, the model shown in Figure \ref{fig:2.2} represents an independent noise signal $Z(t)$ causing this difference as well as a gain factor $H_0$ to dampen non-noise elements of performance error\textsuperscript{49}

\begin{thebibliography}{99}
\end{thebibliography}
These approaches are based upon evaluation of the transmission of band-limited Gaussian noise through systems. Through comparison of performed gestures targeting such signals, a signal-to-noise ratio may similarly be calculated.

The Shannon-Hartley Theorem relates mutual information as represented in the signal-to-noise ratio of the performed recording to the channel capacity of the system through an elegant equation. Using the signal-to-noise ratio as calculated in the time domain, the channel capacity may be estimated, combining bandwidth limits $f_X$ of the target signal and the observed accuracy of the gesture performance:

---

\[
\hat{C}(f_X) = f_X \cdot \log_2 \left(1 + S\hat{N}R(f_X)\right);
\]  

(2.1)

The resulting channel capacity denotes an upper bound of the communicative capacity of the system as a whole.

The signal to noise ratio is calculated as follows (as derived by Berdahl\textsuperscript{[51]}):

\[
\frac{S}{N} = \frac{E((h_0X(t))^2)}{E(Z(t)^2)} = \frac{E((h_0X(t))^2)}{E((Y(t) - h_0X(t))^2)} \approx \frac{\text{avg}((h_0X(t))^2)}{\text{avg}((Y(t) - h_0X(t))^2)}.
\]  

(2.2)

The constant \(H_0\) is estimated from the target and performed signal (as derived by Berdahl\textsuperscript{[52]}):

\[
\hat{H}_0 = \frac{\text{avg}(X(t)Y(t))}{\text{avg}(X^2(t))}
\]  

(2.3)

Advantages of Studying the Channel Capacity

An advantage of studying the channel capacity is that many complicating factors are subsumed within the information maximum. The complexities of the human motor control system need not be particularly identified, accounted for and controlled. Noise that detracts from effective control could prove to be exceedingly difficult to isolate. Limitations of sensor use, design, resolution, and calibration are all incorporated into the information model. The


\textsuperscript{52} Ibid.
resulting bit rate serves as an encompassing measurement of an upper bound limitation of the system as an information channel. These limitations may then be related to efficacy of digital musical instruments and their design.

In comparison with traditional acoustic instruments, novel digital musical instruments are often built for a specific composition or even an individual performance.\[53\] The versatility of these instruments may be improved by affording a higher channel capacity and a higher degree of control. Expressive techniques used in the performance of acoustic instruments require continuous control of energy transfer and modification.

Evaluation of control may support the design of digital musical instruments that both are expressive and promise longevity of use. In practice, the concept of evaluation of digital musical instruments includes diverse approaches. Methods of evaluation have included user/performer interviews and surveys, counts of performances using the instrument, and tabulated claims of user adoption. Indeed, more expansive approaches that have evolved in the HCI literature have been suggested for application to evaluation of new musical interfaces. Within this suite of options, there is an opening for a framework for evaluation using direct quantitative methods to develop characterizations, whether evaluative or merely descriptive or categorical in nature.


Methods

In brief, the model described above relating performed gestures of a target signal of the bandwidth limited Gaussian noise yields a signal-to-noise ratio which can be input to the Shannon-Hartley Theorem equation to calculate an estimation of the channel capacity of the human-computer system. The channel capacity represents an upper limit of information that may be conveyed in bits per second.

Target signals of Gaussian noise support an analysis of the channel capacity (see Figure 2.3). It is established that one can communicate more information if power density spectra of target signals have lower power at higher frequencies. The increases found with such an adjustment are significant, but the analytical methods are complicated by calculating signal-to-noise ratios using frequency domain comparisons and calculations involving integration. While those are not exceedingly complex, a simpler model may be of greater use to interdisciplinary researchers engaged in music interface design. A flat or rectangular power density spectrum signal is used in the studies described below.

Presentation of a logarithmic range of frequency bandwidth limits as targets to subjects and subsequent estimation as described explores the range of performance capability with given a system capacity. The approach is adaptable from one to many dimensions and for multiple continuous control sensors.


Figure 2.3. A range of target signals of bandwidth limited Gaussian noise (0.23 Hz, 1.67 Hz, 3.22 Hz, 12 Hz) used in the studies below.

Model and Methods within Human-Computer Interaction Paradigms

The model, methods, and experiment design described below could be viewed as consistent with the first-wave of HCI research\textsuperscript{59,60,61} or with the human factors paradigm\textsuperscript{62} as formulated by Harrison et al. Indeed, they are based in a model of a human-computer system that does not make distinction between human information processing and computational processing. The research motivation is to measure control, or more precisely, communication of control information. The experiments also were conducted in a research setting of a university and includes quantitative measurements of sensor data and analysis with statistical methods to establish generalized knowledge about information rates of user control. There is no intention to disregard or marginalize other contexts by this experimental design. In a


broader view, the results of this investigation may inform more motivation-oriented cognitive research or research into shifts of context. Connected as this study is, deliberately, to the activity of musical performance, there are ready connections to be made in a variety of those contexts.
Pilot Study

As a pilot study\textsuperscript{63} for this research program, an initial experiment was performed to compare four continuous control sensors using a pursuit tracking task. The efficacy of measuring performed gestures to match targets of band-limited, Gaussian noise signals to estimate the channel capacity of a human-computer system was explored with significant results. Four analog sensors were compared: a touch strip (or softpot), a knob potentiometer (or dial), a force sensing resistor (or FSR), and an infrared proximity sensor (see Figure 2.4). 14 undergraduate subjects participated in this study. A brief training preceded each sensor, which was controlled in random order. Bandwidth limits from 0.25 to 2.5 Hz were performed.

The pilot study was informative in several ways. Some assumptions about the model were validated, including independence of the noise and target signals as well as Gaussian distributions of performed signals. The result of the analysis showed that subjects did not perform as well as expected and with somewhat high variance, so there was a need to look for causes.

The visual display was somewhat small and the signal curve representing the performed signal covered the target curve, obscuring the error in post-view. This setup may have biased the recorded gesture signals to be lower, so as not to cover up the target curve. The display strategy was improved in future studies based on this review. The analysis procedure also revealed some need to modify the model to allow for deterministic error on the part of the performer. Having not seen a complete diminishing of the curve at the high-
est subject bandwidth limit of 2.5 Hz, the researchers attempted performance from 0.125 Hz to 8 Hz, with results suggesting that future studies should also include a wider range of bandwidth limits (see Figure 2.6). A common feature of all of the studies conducted in this program was found in the pilot study: that extensive training and repeated attempts yielded much higher channel capacities on the part of the researchers vs. the novice subject participants. Having established an experimental protocol and validated the model, a comparison with pointing (e.g. Fitts' Law) was needed to establish connection to extensive HCI literature.
Chapter 3. Control Information and Musical Information

While the unit of bits per second is of common usage in HCI research, its application to describe control of musical instruments may not be intuitive. A musician controlling an interface is conveying information as throughput of the system. The amount of information communicable through the channel of that control interface may be increased by the number of available control states or in information theory terms, symbols, and by the rate at which those symbols may be selected. A consideration of control in terms of information will show how various limitations within a system may reduce afforded control by reducing communication.

The resolution of a sensor may be very high, but if a performer cannot select with precision from the available values, then the options are effectively reduced. Similarly, if the sensor affords adequate control and the musician can precisely select from available values but only if at a very slow and deliberate rate, then the same total number of control states may not be considered available at higher rates.

As a very simple example, consider a binary switch or key that is changed (or not) once per second, then the throughput of that system during this period would be $\log_2 2 = 1$ bit per second. In a musical context, this could be a simple note on or note off signal.

Throughput values such as this one will not be of a constant value in time, but will exhibit characteristics, such as a maximum, which may be a useful quantity to identify. The channel capacity, however, differs from this maximum, as it represents not only the maximum of a measured throughput, but also the maximum possible throughput of information within the system under consideration for all possible distributions of $X(t)$. To convey more information through a control interface is to wield the potential of relatively more accurate control, and theoretically, the channel capacity provides an upper bound to this quantity.

Information may be encoded as bits to represent symbols as elements of an alphabet. The number of bits required to encode all of the symbols within an alphabet will depend upon the size of the alphabet, which for a sensor system will be an available set of control
states. The size of the alphabet of control states afforded by a sensor system will depend on several factors. Limitations of resolution and accessibility are two significant groups of factors that will reduce the number of control states.

One group of resolution reductions are due to computation. The bit depth of analog to digital conversion renders a finite set of symbols and sets a resolution of these discrete values assigned from detected analog voltages, thus reducing the number of control values available and therefore the alphabet. There may also be limitations of bit depth in the communication channel from a microcontroller to a sound synthesis system, effecting a reduction in the alphabet of control states. Further, calculations to map or fuse sensor values on the microcontroller may introduce reductions of resolution due to limited precision of operator calculations.

However, it is possible that these technological reductions may not ultimately cause an effective reduction of the final control alphabet as they may be subsumed by greater reductions of resolution due to human factors. Physiological or psychological limitations of ability to discern, select, hold, or intend incremental differences of control states may reduce the alphabet of control values beyond these computational reductions. The range of movement between incremental control states is at some resolution too fine to accurately select and hold a particular symbol. The degree of perception is at some level too blunt to accurately notice a difference between adjacent symbols in a highly precise and therefore larger alphabet.

Some reductions may not uniformly transform the alphabet. For instance, these latter effects may not be evenly distributed across a sensor. Some sensors may have non-linear relationships between physical space and sensed voltages that are converted to digital control states. This situation is similar to the very high pitch ranges of a violin string, where limitations of finger size and performance precision may affect control of the instrument more than at lower pitch ranges on the string.
However distributed, where exceedingly fine changes of pressure or of movement may be necessary to use control states within a range of the sensor, blocks of control states may be considered as one equivalent state if they cannot be discretely used in control. This blocking or merging of symbols is in effect a reduction of the alphabet.

Physical accessibility can also reduce the number of symbols in the alphabet. A multi-sensor system will likely have some theoretically possible combinations of control states that are not possible in practice due to limitations of physical accessibility. It may not physically be possible to simultaneously operate specific parts of each sensor (individual subsets of the alphabet) due to the placement or orientation of the sensors. Just as certain combinations of pitches may not be simultaneously played on traditional instruments (for instance, due to keys exceeding the reach of the hands), certain parts of sensors may not be used if they cannot be reached simultaneously by the performer. As symbols of information, those combinations are not part of the alphabet of system control states.

Other physiological limitations affect the communication of information. Cognitive difficulty in simultaneously envisioning targets and controlling multiple sensors (or selecting a composite symbol in information terms), will reduce successive control states as degrees-of-freedom are added to a system. Also, as mentioned above, studies of the amplitude of control movements have found that performance of control tasks using the arm communicates less information than performance with movements of the wrist and fingers. Depending on the relationship of a sensor to the movement of the body in terms of scale or placement, control states may not be reliably accessible by such movement. This imprecision of movement is exacerbated by an increased rate of movement, reducing the attainable alphabet further.

Indeed, communication of information as a rate in time introduces a more complex consideration of control state to control state limitations. It is not only that specific symbols (or combinations of symbols) may be eliminated from the alphabet, but that symbols or

their combination may not be selected at a desired rate. For instance, human motor noise can reduce control performance and introduce a variability in the gesture signal. Particular symbols of the alphabet may be available in the sensing system, but like the limits of non-noticeable difference discussed above, motor noise introduces a time-dependent merging of adjacent symbols within the alphabet. Simple limitations of human movement in physical distance can also reduce control state to control state possibilities.

As a matter of evaluation of a system, some of these reductions of possible information throughput are calculable, such as analog conversion and serial communication bit depths. It is plausible that studies of just noticeable differences may be adapted or such perceptive quantities could be determined for particular sensors through empirical study in order to determine reductions of control state resolution. Examination of fineness of selection with various sensors and reductions that merge but do not eliminate particular control states (individual symbols or combinations of symbols) could potentially be formalized. Taken together, the complexity of theoretically predicting throughput for a sensor control system is high and experimental evaluation of throughput is difficult to isolate on particular factors among these effects.

The channel capacity as a maximum possible throughput encompasses all of the various noise influences on the information communication throughput of a system. By estimating channel capacities for human control of single and multiple sensor systems, there is then no need to identify the particular limitations that reduce the number of control states that may be effectively used. The effect of their summed influence has been made on that value.

Knowing the channel capacity of a system may assist in evaluating the applicability of the system to a particular musical use. The alphabet of musical instructions or intentions may exceed that of a sensor system. Consider a mapping of a sensor to an equally segmented chromatic pitch range of two octaves, with no algorithms to assist in selection of any particular pitches or patterns of pitches. The musical information would have an alphabet of
24 options (excluding rest) and therefore require $\log_2 24 = 4.59$ bits per note of information to be controlled reliably. A sensor system design that has a lower channel capacity than this value in bits per second should be assumed to be difficult to perform with at one note per second. A reduction of available pitches or other adjustment to assist in encoding or decoding the control signal would be necessary to realize such an intention.

Conversely, one could calculate from a known channel capacity of a system an upper bound of control states available per second and design a mapping accordingly to ensure reliable performance. A system with a channel capacity of 6 bits/sec would afford a maximum availability of $2^6 = 64$ control states per second.

The channel capacity provides a powerful value in an easily compared unit of bits/sec. It can also be estimated with a straightforward method based on a simple model that conforms to the Shannon formulation. Through application of such a model in experimentation, a method is developed in experimentation described below.
Chapter 4. Subject Experiment I: An Estimation and Comparison of Human Abilities to Communicate Information through Pursuit Tracking vs. Pointing on a Single Axis

Introduction

As described above, the communication of control at discrete target locations with a pointing gesture has been thoroughly examined in human-computer-interaction (HCI) research. This experiment was designed in order to establish a comparison of continuous control in pursuit tracking gestures to such pointing gestures using a common interface, common target signal sources, and cohesive analyses based on the Shannon-Hartley Theorem.

Apparatus

An experimental apparatus was assembled in order to compare pursuit tracking and pointing gestures using a common interface to match a co-located target signal (see Figure 4.1). The apparatus was comprised of a flat screen high-definition monitor of 30 cm by 47.3 cm, a Spectra Symbol 200 mm soft potentiometer (also known as a touch strip), an Arduino Micro microcontroller, and a 5V power adapter (for reference voltage). As shown in Figure 4.1, the touch strip was mounted to the display surface and placed 11 cm from one short side and centered evenly between the long sides of the display.

To achieve a higher accuracy of microcontroller sampling of the sensor output, an external reference voltage was maintained through a 5V adapter connected to the reference pin of the Arduino Micro.

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A program realized in the Cycling ’74 Max application assembled and displayed the target signals onto the display and recorded the performed gesture data from the sensor as audio file data at 4410 samples per second. The application also provided instructions and control to progress through phases of the experiment.

Figure 4.1. An experimental apparatus provides a display with co-located 200 mm touch strip sensor for target performance.
Stimuli

Target signals were generated as bandwidth-limited Gaussian noise in two modes: pursuit tracking and pointing. For pursuit tracking gesture targets, a continuous curve with a length of 20 sec at 4410 samples per second formed the target shape (see Figure 4.2). For pointing gesture targets, diamond shapes of 13 mm diagonal width were oriented as diamonds to be presented at values sampled from the pursuit tracking curve. The signal was sampled at twice the frequency of the bandwidth limit in an evenly spaced time interval (see Figure 4.3). Sampling at twice the frequency bandwidth serves to meet the requirements of the Nyquist frequency sampling rate for reproducing the original signal.

These Gaussian target signals were generated for 12 frequency limits that were spaced logarithmically from 0.12 Hz to 12 Hz. Two signals were prepared for each limited band and in the two forms of pursuit tracking and pointing. Therefore, the number of target gestures for each participant totalled 48 gestures.

Procedure

Participants were seated in a chair of appropriate height to allow comfortable movement and free range of motion to interact with the interface. The apparatus was laid upon a work-station surface with display and attached sensor facing up, oriented with the side closest to the sensor immediately before the subject. Subject participants used an interface on the laptop device to navigate the study options and continue through its phases. There, they were directed to follow target signals of 20 second duration on the sensor apparatus.

In presentation, the two types of signals moved at the same rate from the top to the bottom of the screen to approach and travel below the sensor, crossing its axis. Targets moved at a rate of 23.6 cm per second with a total preview visibility of 2.94 seconds and post-view visibility of 0.97 seconds. The range of display for the target gesture amplitude was 190 mm from a maximum value of +1.0 at the left to a minimum value at the right of -1.0.
Figure 4.2. A pursuit tracking gesture waveform moves down the display toward a 200mm touch strip for the subject to press their finger along the sensor in synchrony.

In order to ensure a measurement of the channel capacity for participants familiar with the interface, a training phase introduced the types of gestures to the subjects in three escalating levels of difficulty. Subjects were offered the opportunity to repeat gestures in
Figure 4.3. A series of targets as diamond shapes move down the display toward a 200mm touch strip for the subjects to press their finger on the sensor location in synchrony. Targets were sampled from Gaussian targets at $2f_x$ Hz, where $f_x$ is the bandwidth limit.

training and also to request additional gestures until they felt satisfied with their command of and familiarity with the interface.
Instructions were provided to describe the type of movements and to characterize the training difficulty levels. Three levels were provided in training for both pursuit tracking and pointing/tapping. The 0.7 Hz, 1.5 Hz, and 7 Hz bandwidth limits were presented as easy, medium, and difficult levels, respectively. For the difficult level, subjects were encouraged to make their best effort to perform the target gestures with as much accuracy as possible.

During the recorded portion of the study, the order of the 48 gestures was randomized throughout the trial in order to avoid factors that may result from learned agility or developed fatigue of participants. Participants were given the opportunity to rest, if requested.

Upon completion of each gesture, the guiding interface presented the option of retrying the completed gesture in case the subject felt that they could improve their performance. The gesture could be repeated an unlimited number of times. When satisfied with their performance, the subject would then elect the option to accept the last performed gesture and continue to the next one.

The duration of subject trials was 35 to 40 minutes of continuous participation.

**Analysis**

Before conducting analysis using an information theoretical approach, some adjustments to the data were made. First, in instances where a participant was not touching the control strip, either due to error in their use of the sensor or due to exceeding its effective sensor area, a value of -1.0 was recorded by the sensor apparatus (its rest value). Where these cases were found, a scalar of 0 was multiplied prior to analysis in order to avoid a distortion of the signal-to-noise ratio calculation due to the rest state at a peak amplitude. Second, to compensate for errors of anticipation or delay while pointing in relation to the single, instantaneous target sample, the beginning and ending sample values for each sensed pointing instance were identified and extended to midpoints between the neighboring pointing instances. Third, to account for instances where subjects were consistently late or early in the performance of the gestures, an iterative calculation of the mean-squared-error from
-200 milliseconds to 200 milliseconds was conducted in relation to the target signal at 1 millisecond intervals. In the interest of finding maximum channel capacities, the most favorable delay interval within the resolution described above was tabulated and accepted as the representative value for a subject’s performed gesture. With these adjustments, a best representation of the performed gesture is prepared for the channel capacity calculation.

Using the signal-to-noise ratio as calculated in the time domain, the channel capacity may be calculated, utilizing the bandwidth limits and the limits of human performance speeds as observed in this study. The bandwidth of the signal in the case of the human-computer system is limited not only by the target design, but also the capability of movement in time by the human participant. Where the target signal exceeded this capacity of movement, the upper limit is applied within the bandwidth component to calculate the channel capacity.

To wit, upon analysis of pursuit tracking results using the Fast Fourier Transform (FFT), the highest sustained frequency rate of movement observed was 5.6 Hz. An upper limit of 5.6 Hz was therefore applied as input to the bandwidth of the Shannon Hartley equation for the 7 Hz and 12 Hz target results for pursuit tracking gestures. For pointing gestures, a maximum of 7.0 Hz was observed for a sustained pointing movement rate. Accordingly, a maximum of 7.0 Hz was applied to the channel capacity calculation for the 12 Hz target results for pointing.

Results

Eight subjects participated in the study. All subjects were musicians enrolled in either undergraduate or graduate music study at LSU. Subjects performed gestures with their dominant hand.

As shown in Figure 4.4, the mean observed channel capacity for pointing attained levels as high as 6 bits per second, representing the highest overall capacity for the subject pool. This peak channel capacity for pointing was at bandwidth limit 1.0 Hz, following a
steady curve to that level and descending to the next highest capacity found near that level at 1.5 Hz.

The channel capacity of pursuit tracking similarly followed a discernible curve, clearly exceeding that of pointing capacities at 2.9 Hz and higher. Peak channel capacity for pursuit tracking was around 4 bits per second on average at bandwidth limit 2.3 Hz.

Analysis using Welch’s t-test with Bonferroni correction identified any significance of differences across bandwidths between the two gesture types. It appears from these results that, with subjects having a very minimal amount of training, pointing at a lower frequency of movement allows communication of more information than pursuit tracking at such rates of movement. At 1.0 Hz, a mean of 2.6 bits/sec more information was communicated than with pursuit tracking (95% CI:1.53, 3.65; p < 0.01).

Under these conditions, at higher rates of movement, pursuit tracking appears to offer a higher capacity to communicate information. At 3.5 Hz, 2.4 bits/sec more information was communicated than with pointing (95% CI:1.8, 2.99, p < 0.01).

A varying delay was observed for all subjects. There are several factors that could contribute to this delay. Screen refresh rates in relation to the recording of input gestures
present information to the subject later than the recording. Simple visibility of the target beneath the transparent sensor and estimation of its position under the opaque portion of the sensor could lead to some inaccuracy either before or after the recording moment. The delay of reaction to the previewed signal and delayed contact after the impulse to follow or touch the signal target point is a likely contributor to this observed delay as well.

A slackening of movement intensity was observed at the higher bandwidth limits for most participants, despite instructions of encouragement to try to follow as closely as possible or touch as many targets as possible. The seeming impossibility of following such a complex target or touching so many shapes at the rate presented was perhaps dispiriting. Fatigue could also be a factor here.

Figure 4.5. Researchers’ data: Estimated channel capacity across bandwidth limits $f_x$ of target signals for pursuit tracking and pointing gestures.

Two researchers also participated in the study. Their data was treated separately as they had considerably more training gained during preparation of the study and apparatus design, although not as a controlled condition to prove a performance plateau. They also repeated their trials more frequently, in order to try to achieve even higher capacities. Their data is shown in Figure 4.5 Overall, these two researchers were able to achieve higher capacities both for pointing and for pursuit tracking. The additional training appeared to
provide more benefit for the pursuit tracking condition, under which the researchers almost managed to catch up with their maximum channel capacities for pointing (see Figure 4.5).

**Training and Performance Learning**

In general, even with a training session component to the study design, the subjects performed as novice users compared to the researchers in using the interface. Therefore, the channel capacity results should be considered maxima only for such a class of users. A more intensive training protocol, perhaps combined with a competition paradigm, could improve results and demonstrate a higher channel capacity for an advanced performer with significant practice on the interface.

Factors that could differentiate the novice from the experienced user could include a residual uncertainty due to novelty, inattentiveness during the session, and a lack of learned adaptive behavior that would assist with anticipating movement. These latter could include strategic thinking about how to best perform high frequency signal components.

**Conclusions**

In summary, a comparison of pursuit tracking and pointing gestures was observed on a single analog sensor interface that was co-located with visual target stimuli. Application analysis based in information theory shows a straightforward means for evaluation of subject performance using the interface in these two ways.

In utilizing systems for applications that require higher throughput rates, composer/designers or performers can ensure that capacity is available by arranging their gestures to include pointing at a rate of 2.0 Hz to 3 Hz. Conversely, where movement of 5 Hz to 10 Hz is desired, it is clear that a higher throughput is available via a continuous control movement than via pointing.

Further investigation along these lines should include more ambitious training with interface use by subjects to seek limits beyond the novice level. Indeed, analysis of perfor-
mances after memorization of the target gestures as would be the case with the performance of a composed musical work would be informative. Virtuosic levels of pointing or pursuit tracking may differ from the results found here. No feedback other than the benefits of co-location with the target stimuli were provided. Investigation of haptic, sonic, or visual feedback on the performance accuracy for subjects may demonstrate that higher capacities are possible when such information is incorporated into the human-computer system.
Chapter 5. Subject Experiment II: An Estimation of Human Abilities to Communicate Information Through Pursuit Tracking in Two Degrees-of-Freedom using a Trackpad

Extending the Model to Multiple Dimensions

Music interfaces commonly include many degrees-of-freedom to afford additional control of music and sound parameters. It is also common for the built-in interfaces of the laptop computer to be used in compositions for laptop orchestra. This subject experiment was developed to further advance the evaluative model discussed here in light of these practices. The study described in this chapter involves the use of the trackpad interface with two degrees-of-freedom. Further experimentation with greater than two degrees-of-freedom is described in chapters below.

Trackpad as Performance Interface

Macbook Pro computers (13 in. models released in 2012) with a glass “no-button” trackpad (also referred to as a touchpad) were used for this study. The trackpad is not square, so the range of target movement was constrained to 74.5mm square in accordance with the maximum of the vertical dimension. A sound interface connected to a hemisphere speaker under a standing-height adjustable performance table completed the performance setup.

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system. Participants all stood and used their preferred hand to perform input gestures that were generated according to the evaluation model.

A composition entitled *Pursuit Variations* was prepared for this experiment and was based upon error differentials between the cursor position and the presented target. These differentials correspond to error calculated within the evaluative model discussed here. Further discussion of the sonification of error within this experiment is provided in the following chapter. Aural feedback of performance was thereby provided in real time to the musicians.

That the experimental stimuli were provided as a composition also cast the experiment as an ensemble performance. Providing such sonic feedback may contribute to a performance improvement. While this study did not isolate feedback as a factor for comparison, feedback should be acknowledged as a dynamic within the system of the experiment.

A secondary goal of this study was to provide the student subjects with an experience of ensemble performance in a laptop orchestra. The composition included three movements which varied by how the segments were conducted. The group was first conducted by the experiment supervisor to begin the performance of each of the experimental stimulus gestures simultaneously. The second movement allowed participants to begin and proceed from one gesture to another at the time of their own choosing. The third movement was performed as in a chamber performance, where participants cue one another to begin together.

**Studies of Control Performance in Two Dimensions**

Mackenzie and Buxton extended the Fitts’ Law paradigm to examine target gestures in two dimensions using a mouse. More recently, Mackenzie investigated control using a touchscreen on a mobile phone in both one and two degrees-of-freedom. Interestingly, higher throughput was measured for one degree-of-freedom than two, although, as the device was a touchscreen controlled with the finger, occlusion occurred at unavoidable moments. Viviani

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and Campadelli studied visuo-manual pursuit tracking in two dimensions, but focused on human factors of delay lag and strategies rather than information throughput or capacity. The trackpad does not allow co-located target presentation, but it is a highly refined, responsive interface in wide distribution and use.

**Experimental Procedure**

Subject participants were members of a laboratory course for early career undergraduate students of Music at LSU. Twenty-nine (29) subjects participated in the study. In groups ranging from 5 to 8 subjects, subjects performed the composition while performance data were recorded on the laptops.

For each bandwidth limit two gestures were prepared as stimuli. Target signals were generated for bandwidth limits spaced in eight steps logarithmically from 0.4 Hz to 5.0 Hz. Two targets were generated for each limit. Each of these target gestures included two independent target stimuli of 20 seconds duration to be presented together as representations in two dimensions on the laptop screen.

A diamond shape centered on a target point represented the current samples (as x and y coordinates) in playback, along with a curve representing a preview of one second of samples of future movement of that target point (see Figure 5.1). The display interface was developed in the Jitter software package of Cycling 74’s Max.

The subjects controlled the default arrow cursor of the operating system as the representation of their position on the trackpad. The position of this cursor is not an absolute mapping of the touchpad position, but a position determined relative to the original engagement of a digit with the touchpad surface commanding the cursor from its last location. Participants were advised to begin gestures with their preferred digit in a location on the physical trackpad analogous with the initial target location on the screen, such that future movement would not run off of the trackpad surface.
Figure 5.1. A target is represented as a diamond shape and one second of preview is elided and represented as a curve, presented for pursuit tracking in two dimensions using a trackpad.

The laptops were configured to the highest cursor speed available in the operating system preferences for consistent comparison. Additional control gestures of the trackpad preferences (swiping controls, tapping selection, etc.) were disabled to prevent unintended disruptions of the experimental system. It is worth noting that the operating system applies an acceleration of the cursor movement dependent on the rate of input movement. This aspect of the operating system was not disabled.
Analysis

It may be derived that the estimated channel capacities of independent signals in a given system may be summed to estimate a joint channel capacity of that system. Accordingly, an additional step was added to the analysis for this experiment. Calculation of the channel capacity was made separately for each degree-of-freedom and then summed to estimate the system channel capacity. The three performances of each subject from each study session were included equivalently in the summary analysis.

Before estimating the channel capacity, a best time offset value to maximize correlation between the target and performed signals was calculated for both degrees-of-freedom, separately. The larger of the two offset values was used for estimation of the channel capacity for each independent dimension using calculations as described in prior chapters.

Results

It was apparent upon completion of this study that lower bandwidth limits should perhaps have been included. The mean channel capacity at the lowest bandwidth limit of 0.40 Hz is not very far off from the maximum mean channel capacity at 0.82 Hz.

As shown in Figure 5.2, the mean channel capacity approached 5 bits per second at limits 0.82 Hz (4.97 bits/sec) and 1.69 Hz (4.92 bits/sec). The mean at 1.18 Hz between these bandwidth limits was slightly lower at 4.33 bits/sec. Beyond 1.69 Hz, the channel capacity diminishes linearly to 0.80 bits/sec.

A comparison of the information rates from this experiment and the prior co-located touch strip pursuit tracking task may be informative. While operating a touch strip in one degree-of-freedom and operating a trackpad in two degrees-of-freedom are not directly

7. A proof of the efficacy of this additive estimation of joint channel capacity was made by Prof. Edgar Berdahl in personal communication with the author in February 2019.

Figure 5.2. Estimated joint channel capacity across bandwidth limits up to 5 Hz for pursuit tracking in two degrees-of-freedom using a trackpad.

comparable control tasks, they are similar in manual orientation and range of motion. Their difference as sensors also challenges comparison. The resolution of trackpad movement was quantized at 800 pixels in each dimension vs. the touch strip’s 1024 values, possibly reducing target/performance resolution.

Compared to the touch strip, the observed channel capacity, within some ranges of equivalent rates of movement, increased. For instance, at 0.4 Hz the estimated channel capacity for pursuit tracking with the touch strip was found to be 1.69 bits/sec (from Figure 4.4), whereas with the laptop trackpad it was found to be 4.08 bits. This could be assumed to largely result from the addition of one more degree-of-freedom.

Other factors that may contribute to this increase include the considerably smaller sustained pressure required to control the trackpad in comparison with the touch strip. The range of movement is slightly lower in each dimension of the trackpad, possibly allowing for faster rates of movement (relative to the target gesture range).
This relative increase of the channel capacity of the trackpad does not hold for higher rates of movement. At 3.5 Hz and at 5.0 Hz, subjects performed higher with the touch strip (3.8 and 2.0 bits/sec, respectively) than with the two dimensions of the trackpad (2.7 and 0.8 bits/sec).

Figure 5.3. Estimated joint channel capacity across bandwidth limits up to 5 Hz for pursuit tracking in two degrees-of-freedom using a trackpad, shown by trial sequence number.

While it was not a primary goal of this study to investigate improvement across repetitions, it is interesting that improvement is not evident within this series of trials (see Figure 5.3). The maxima at the medium bandwidth limits do increase from trial to trial, indicating a possible improvement among a subset of subjects.

Discussion

The author was able to reliably register over 10 bits/sec channel capacity with this model laptop and trackpad (and even exceeding 14 bits/sec with another model), which is surely dependent upon many practice trials in development of the software and analysis

9. The touch strip was measured at 3.48 Hz
components of this experiment. While participants may have had many hours of experience with trackpads from their own laptop use, one must regard that the pursuit tracking mode of use for this interface is not a common one. It should therefore be considered that the results of this study represent that of novice users for this control task. Their inexperience with the software interface and with the task of continuously controlling the trackpad may be the cause for a reduced performance capability, as a group.

It is apparent that additional degrees-of-freedom can potentially afford a higher channel capacity, yet it appears that the upper bounding limitations related to higher bandwidths affect these additional degrees of control in comparison with one degree-of-freedom with a similar interaction at those levels. A subject experiment with joysticks, described below, extends this experimentation to further degrees-of-freedom.
Chapter 6. Sonic Feedback of Performance Error while Controlling a Laptop Touchpad as Laptop Orchestra Chamber Music

Introduction

Musical performance often involves goal-oriented movement to achieve desired acoustic outcomes. Such goals may be those set by a composer, with some room left widely or narrowly to engage with a performer’s intuition, choice, or limits of capability. Interpretation and thoughtful deviation from the prescriptive encoding of musical intentions may often be considered welcome or perhaps even essential to the vibrancy and richness of expression in music. Nonetheless, precision and agility in control imbue performance with elements of vibrancy and richness alike. Precision in control is gained through mastery of the instrument, and high levels of information would be needed to encode a representation of the precise movements of an expert musician. In this still-early phase of composition for and design of digital musical instruments (DMI), we can engage performers in the pursuit and attainment of high precision and agile musical control using sensing devices. Understanding the limits of control of such devices may assist in bringing the precision and agility of traditional instrument performance to the realization of sounds through DMIs alike, affording greater opportunity for expression through these media.

Continuous control sensors are commonly used in digital DMI or New Interfaces for Musical Expression (NIME) design to afford performers with gestural control of computed values for music making. Subsets of human-computer-interface (HCI) research involve experimentation with human subjects to identify information throughput during certain performance tasks using sensing equipment. Pointing tasks have been extensively researched,

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When investigating the ability to perform time-series, goal gestures with continuous control sensors, quantities of training time and repetition of performance movements can emerge as determining factors in the results of accuracy measurements in cases where experimental subject participant time and incentives are significantly constrained. Given the well-established, practical design goal to tailor instrument design to novice performers\footnote{Crossman, “The Information-Capacity of the Human Motor-System in Pursuit Tracking”} there could be much value in determining the performance capability of such a class of users. However, in service to a design goal that aspires to the long-term viability of a DMI\footnote{Cook, “Principles for Designing Computer Music Controllers”} acquiring an understanding of well-practiced performer accuracy is desirable.

Securing additional practice time and opportunities to repeatedly perform goal gestures should reasonably be expected to improve performance results and a better understanding of human capacities to control sensors for DMI design. Further, real-time feedback beyond visual tracking during performance of the pursuit-tracking task could also improve results in accuracy measurements. Sonification of performance error as a musical performance in an ensemble setting could provide better results through corrective measures and motivations inherent to the musical performance dynamic. To support better performance

\begin{enumerate}
\item Soukoreff and MacKenzie, “Towards a Standard for Pointing Device Evaluation, Perspectives on 27 Years of Fitts’ Law Research in HCI”
\item Crossman, “The Information-Capacity of the Human Motor-System in Pursuit Tracking”
\item Cook, “Principles for Designing Computer Music Controllers”
\item Morreale and McPherson, “Design for Longevity: Ongoing Use of Instruments from NIME 2010-
\end{enumerate}
and to situate this experiment in a concert performance and rehearsal context, a sonification of the experimental data of the human subject performance in real time was prepared. Research into the sonification of error for motor performance improvement has shown mixed results\textsuperscript{[6]} but in a musical setting and in performance as a musical task, the sonic feedback should be considered more directly relevant to those trained in a chamber ensemble.

Laptop orchestras have been established in several research university music programs since their inception in 2005 with the Princeton Laptop Orchestra.\textsuperscript{[7]} Experimentation in new performance structures and interactions has been a feature of this movement. However, the current study appears to be the first instance of research using a laptop orchestra piece as a human subjects experiment for better understanding human factors/HCI.

In laptop orchestra contexts, there is an established practice of composition for the laptop to be performed as a DMI.\textsuperscript{[8]} The laptop offers reliable, standardized display interface components and input sensing components, including a keyboard, some form of pointing sensor apparatus, and an integrated microphone and camera. Sometimes provided with a nub-style joystick but more often recently with a touchpad, the ability to follow an intended path in two dimensions with the operating system cursor is a core element of a laptop system. Laptops in a musical performance may be used with an audio interface and external speakers or used to control additional systems, depending on the performance setting.

Given the utility of the standard laptop interface for musical performance, an empirical understanding of the capacity for expression through the laptop input components should


\textsuperscript{8} Fiebrink, Wang, and Cook, “Don’t Forget the Laptop: Using Native Input Capabilities for Expressive Musical Control”
be gained. The trackpad in particular is a continuous control interface in two dimensions, affording two degrees-of-freedom of movement.

**Experimental Context**

To support investigation of continuous control sensors using an information theory approach, target signals of Gaussian band-limited noise are presented visually (see Figure 6.1) to performers as a diamond shape representing the current coordinate. A two-dimensional curve showing one second of preview is displayed to show the path the diamond target shape will follow, in order to prepare the performer's pursuit tracking movement. The performer is to follow the target shape using the laptop cursor as best as they can while the system records their performance and excites the sonification model based on their error. Later analysis of the recorded performance data using the Shannon-Hartley theorem within a human-computer system model developed in prior research will establish an upper bound of information communication capacity in two dimensions using the touchpad.

The experimental design and subject pool criteria were reviewed by the appropriate governing institutional review board and received approval before experimentation start. Six participants rehearsed this piece as members of a laptop orchestra and performed the work at a concert to complete the subject study.

**Composition**

Driven by the experimental design, a work *Pursuit Variations* proceeds through a succession of sixteen 20 second pursuit tracking gestures for a group of 4-8 performers. These time-series goal targets were prepared in an exponential spacing of bandwidth limits of Gaussian noise from 0.4 Hz to 5.0 Hz, progressing from least to most difficult. This signal type supports the aforementioned information theory analysis model. As a formal

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consideration, the pauses inherent to completing one 20 sec. gesture and moving on to another one as a group are jarring, so the performers are instructed to proceed at their own pace in continuing from gesture to gesture. This adjustment allows the work to feature continuous sound and blurs the transition from less to more difficult gestures in performance. This procedural and creative adjustment is expected to do little harm to the experimental procedure or resulting data.

As an ensemble performance, the sonification of each performer’s variance from the target movement is heard alongside that of the other performers. This presentation is made within the context of other performers and their respective variance. At times, the emergence of sections of higher volume resulting from performer movements away from the target of the score can resemble phrases and interactions between performer “phrases.” As the piece progresses and the goal gestures require higher rates of movement, the uniformity of sound
levels and characteristics increases, creating a more cohesive unity among the ensemble and its participants.

**Sonification Synthesis and Aesthetic Considerations**

Error as a digital media aesthetic has roots in both the digital art and computer music traditions. Consistent with the research goal of this experiment and engaging with performer perceptions, the synthesis within this sonification design is intended to convey a sense of erroneous or glitch results of audio signals.

Cycling74’s Max software was used to realize the sonification system. The experimental interface is drawn with Jitter from target signals generated in the *numpy* Python

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scripting library. The position of the cursor as controlled by the touchpad is polled for comparison to the simultaneous target coordinate.

Preliminary analysis of correlation between the horizontal and vertical performance error has shown that these values are independent of one another yet are comparable in magnitude. Using these error values independently for sonification rather than combining them into a single vector magnitude is of little difference in application and provides two values with which to drive the sonification parameters. Accordingly, two distances from the target in these dimensions are calculated, considering the target as an origin in motion.

To provide a direct emergent value of error, the horizontal distance value is directly applied as a control of the amplitude of a synthesis wavetable model. A higher distance of error results in an attendant increase in amplitude level, therefore sonifying the error as a direct and notable increase in sound pressure. One can discern mistakes and corrective movements that performers enact as a result of this mapping.

The vertical distance value is scaled and applied to the frequency parameter control of a sawtooth wavetable signal generator for insertion into a blank wavetable buffer in memory. The vertical error distance value is also separately scaled and applied as a frequency parameter control of a phasor wavetable oscillator that reads through the aforementioned buffer for playback. The resulting pitch and texture of the content of the work is therefore derived directly from the performer error in this dimension. The pitch and texture are thus more complex than a primary oscillator value, adding some refinement of the discernment of movement within the amplitude value from the horizontal error.

Some fixed elements of the synthesis design are independent of the error in performance, affecting the character of the synthesis and of the piece in general. The lookup system that plays back from the written buffer according to the phasor control indexing includes a moving offset value that effectively limits the buffer size dynamically in a repeating small to large pattern. This design introduces a repeating structural pattern and also some discontinuities resulting from looped buffer playback immediately from end values to beginning
values. These signal discontinuities sound like audio errors, contributing to the aesthetic of error. The sawtooth signal generator mentioned above also contributes some sonic patterning that, while affected by the performer error, is not directly attributable in its texture and characteristics to their movements. Aside from these exceptions, the sonic content of the
piece is derived directly from the relationship between the performed gesture and the target signal. Indeed, if the performer perfectly matched the target signals (an impossible task no doubt), there would be no sound issued by the synthesis system.

The effectiveness of the sonification design is best exemplified by the responsiveness of the sonic interface to the error values. Sounds of similar timbral characteristics are introduced by error, but are not identical, creating a comparable but not overly repetitive or identical result. Very small values of error are noticeable and correctable through adjustment.

**Interactivity**

With such a responsive system, the participants are able to identify their own performance error in real time. The immediate feedback allows for some corrective actions to be taken. In the rehearsal context, some performers experimented with deliberate error, exciting more sound energy as a result. An inverse motivation to perform poorly could thus be identified, although the performance as an ensemble is somewhat dependent on norms of realizing composer intent. Performer/participants are also motivated by supporting a strong experimental result.

Further, the immediacy of the error sonification feedback loop provides an additional level of interest for the concert performance aspect of this project. As performers engage with the experimental target prompts in their performance, their perception of error is shared with the audience. Hearing these interactions is an important component of the compositional design.

**Agency**

In *Pursuit Variations*, the performer does not determine the intended path of their movements. In many cases, musical scores may very precisely fix certain musical parameters to realize a composition and, by extension, determine the movements of a performer to accomplish this intention. Here, the movement itself is specified without any description of
or direct connection to the musical parameters other than that related to the matching of the movement and avoidance of error.

Secondary elements of motivation and attentiveness to their performance are matters of will and capacity as performers. The performer holds agency in engagement with the performance task and with the experimental outcome. Their creative agency, however, is limited by the experimental design.

If one performs less well than the other performers, there is a sense of standing out amongst the group, with possible attendant emotions of embarrassment, guilt, or anxiety. Avoiding these negative feelings and wishing to fulfill the goals of the performance are motivations for better pursuit tracking of the target. Inevitably, the more difficult targets will generate a significant volume level and texture resulting from the presence of error in the measurements.

**Investigative/Creative Endeavors**

The motivations involved in experimentation with human subjects and in musical composition and performance may differ significantly, complicating the conjoining of these activities in one project. In the case of the effort described here, several aspects of the composition design were restricted in order to preserve the integrity of experimental research findings. The score as presented to the performers consisted of generated paths that conformed to and approach of analysis using information theory to analyze the channel capacity of a system. This limitation does not necessarily pose a conflict because such a design is consistent with the traditions of composition utilizing chance or other randomized generation processes.

Uniformity of score paths supports consistent comparison across subject performances, but prevents definition of multiple, characteristic voices and diversification across the frequency spectrum or across other parameter spaces. As mentioned above, a progression as an ensemble through 16 segments of 20 seconds each with a pause between each would be
too disruptive a formal design, sounding more like an experiment than a composition. The participants are allowed to start successive segments at their own rate. Randomizing the difficulty of the segments was also explored, but the formal design and progression of the piece is better supported by a successive increase in difficulty from segment to segment.

**Conclusions**

Sonification of performance error can be designed in an aesthetic way to engage creative ends alongside scientific observation goals. The results of the experimental aspect of this study should inform understanding of practiced instrumental training and learning progress across the rehearsal and performance phases of a chamber orchestra’s use of a digital musical instrument. The interactive sonification within this design is a key component of motivating performers to contribute to the forthcoming results and to engage musical practice and performance dynamics. To wit, laptop orchestras may provide a setting where performance using digital musical instruments can be investigated systematically.
Chapter 7. Subject Experiment III: An Estimation and Comparison of Human Abilities to Communicate Information Through Pursuit Tracking in Increasing Degrees-of-Freedom with Joysticks

Introduction

Many types of musical instruments require simultaneous, continuous control of multiple component materials for their use. Within digital musical instruments, such control may be provided through an arrangement of sensors, allowing for gestural control of musical parameters. With each additional sensor, an additional means of control and accompanying information signal are added. However, additional control movements also add to cognitive load, which can potentially hinder precise performance.

Indeed, various bottlenecks of information processing affect how precisely humans can continually control sensors. One limitation involves working memory. From experimental psychology, it is clear that for various tasks, a certain maximum number of items may be maintained in working memory. Researchers continue to refine this understanding, but numbers such as seven (plus or minus two) or four items have been posited as maxima, with more complex refinement alongside these reductive numbers. Working memory and its

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limitations affect musical tasks in various ways, including movement in gestures of musical control.

While additional control and communicative capacity may be desirable for designing richly expressive instruments, a limit may be exceeded If one cannot effectively control the full range of sensors and their associated mappings to musical parameters, then the instrument may be too difficult to learn or, worse, may not be very playable.

The present study of human subjects was designed to investigate the ability to independently control multiple sensors. It also explores the control of two joystick devices — first one joystick with one hand and then two joysticks bimanually. Laptop orchestra compositions exist for joystick controllers. Alongside new and experimental interfaces, laptop orchestras often make use of readily available controllers for music making. Of course, the laptop itself as an interface figures large in these endeavors but golf game controllers enhanced faders MIDI-enabled controllers, and various game controllers are creative interfaces in ensembles for live musical performance.

**Extending the Model**

In the study described here, essentially four systems are considered, each with additional degrees-of-freedom using joysticks. Channel capacities of each individual degree-of-


freedom are summed to form a representative value for that control mode. The channel capacities across the different rates of movement and degrees-of-freedom are then prepared for evaluative comparison.

**Experimental Procedure**

Eleven subjects participated in the study. Each was either an undergraduate or graduate music student at LSU. Subjects were seated before a table on which were placed the control and display apparatus. The study was conducted in compliance with the framework of institutional oversight as maintained by the university’s institutional review board.

Increasing from one degree-of-freedom to four degrees-of-freedom, participants first controlled one joystick with their dominant hand, then two joysticks simultaneously. The first phase observed control of front and back movement of the joystick. Eight targets of bandwidth-limited Gaussian noise were presented in a logarithmic spacing with cutoff frequencies from 0.11 Hz. to 2.29 Hz. The second phase observed left, right, front and back movement of the single joystick with additional signals of the same bandwidth limits. The third phase added control of the second joystick in front/back movement, following additional signals, and the fourth added the left/right movement with a final set of additional signals.

**Apparatus**

Four identical Logitech Extreme 3D Pro model joysticks were used to allow two simultaneous participant trials. This joystick device includes a mechanism that returns the joystick to center, requiring force to maintain any non-centered position. Cycling74’s Max software was used to present and record target and performed gestures.

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10. Cover and Thomas, *Elements Of Information Theory*
Visual Presentation of Targets

The display software operated in a division of the screen into right and left halves in order to facilitate association of target signals and user controlled signals with the right and left joysticks. The design also prevented any overlap or confusion of target or performed signals associated with the separate devices. Different visual configurations were used for the different cases of one degree-of-freedom, two degrees-of-freedom, three degrees-of-freedom, and four degrees-of-freedom.
For example, consider the display used for testing three degrees-of-freedom as shown in Figure 7.2. A bar shape spanning the left half of the screen (corresponding to the left joystick) was shown to represent a target restricted to only vertical movement. The participant’s joystick location was represented by an identically shaped bar, but with a lighter color. Matching the target would precisely obscure the participant-controlled bar cursor. Additionally, a thin curve presented a preview of one second of future movement to guide the participant. Although the bar target moved only vertically, the preview line presented two dimensions of movement in order to indicate the rate of vertical movement and to avoid obscuring the preview of vertical direction changes due to overlap of the line with itself. For the other two degrees-of-freedom, a display was configured on the right half of Figure 7.2. There, a diamond shape represented targets and their movement in two degrees-of-freedom. Similar to the bar target and cursor, the participant’s joystick location was represented in an identically shaped diamond, but with a lighter color than the target. Matching the target would precisely obscure the participant’s diamond cursor. Again, a one-second preview was provided using a thin curve leading from the target diamond. In this way as shown in Figure 7.2, the tests in three degrees-of-freedom were conducted. For the other cases of one, two and four degrees-of-freedom, the setup was accordingly adjusted.

**Training**

A training session presented easy (low cutoff frequency), medium (midrange cutoff frequency), and difficult (higher cutoff frequency) versions of the four modes of control prior to the observational trial. Roughly 5 minutes of training was provided to briefly familiarize participants with the interface, with the progression of movement modes, and with the experimental environment. Adjustable desk chairs allowed for bodily comfort, and throughout the training period, encouragement to seek comfortable control positions was provided to participants.
Figure 7.2. The interface of the subject trial during the three degrees-of-freedom phase. Shapes elided with the preview line are targets, and free shapes are the cursor position of the associated joystick. Note: Image color has been inverted for better visibility.

Following the training session, the proper study began with the sequential progression of increasing difficulty from 0.11 to 2.29 Hz for the four modes: vertical in one joystick, vertical and horizontal in one joystick, vertical in one joystick with vertical and horizontal in the other (e.g. see Figure 7.2), and vertical and horizontal in both joysticks.

Results

As a general observation, the range of variance in performance grew as bandwidth limits increased, tempering evidence found in the mean channel capacity comparisons. For example, with one degree-of-freedom at bandwidth limits above 0.62 Hz, the variance of performance grows such that there is no significant difference in comparison with even the lowest bandwidth limit, despite a relatively large difference in mean capacities.

At the lowest two bandwidth limits, as degrees-of-freedom increase, the channel capacity increases monotonically. In tests of significance at these levels, the difference between
means of two and three degrees-of-freedom were not significant. At 0.11 Hz, the channel capacity of four degrees-of-freedom significantly exceeded that of two (p < .01). At low rates of movement, there appears to be a benefit to increasing degrees-of-freedom to four to afford higher throughput.

More broadly, two degrees-of-freedom provides the most consistent difference beyond one degree-of-freedom. Indeed, the highest mean channel capacity was found to be 4.48 bits/sec controlling in two degrees-of-freedom in one joystick at 0.96 Hz. Two degrees-of-freedom in one joystick also significantly outperformed one degree-of-freedom (p < .05) for all bandwidth limits, with the exception of the comparison at bandwidth limit 0.62 Hz. At the highest bandwidth limit, 2.29 Hz, only two degrees-of-freedom could be said to have a higher channel capacity than one degree-of-freedom with statistical significance.

With the one exception at 0.11 Hz between two and four degrees-of-freedom, pairwise t-tests with Bonferroni correction do not establish that comparisons between the greater degrees-of-freedom (greater than one) are significant. While means suggest that channel capacities are higher for four degrees-of-freedom up to 0.40 Hz, the high variance of partic-
ipant performance prevents any conclusion of significance. It appears that, for novice users of these devices, additional degrees-of-freedom beyond two may not be generally assumed to provide a higher throughput above 0.11 Hz.

Discussion

With the limited time available to participants in training and in completion of the tasks, these results should be considered commensurate with novice performance. Additional practice would likely yield better control, reduced error, and therefore higher estimated channel capacities.

While the results suggest that the addition of more than two degrees-of-freedom using joysticks would not generally provide a higher potential throughput, this conclusion is complicated by the apparent difficulty of perceiving multiple target signals.

The control modes that included three and four degrees-of-freedom presented more than one target object. The visual perception challenge of following two objects could have reduced information throughput more significantly than any additional throughput afforded by the additional degrees-of-freedom. Participants verbally reported difficulty with viewing both targets and some offered description of strategies that they employed, such as using peripheral vision, attempting a general focus or a specific focus in alternation, and/or concentrating favorably on one target versus the other.
Chapter 8. Subject Experiment IV: An Estimation and Comparison of Human Abilities to Communicate Information Through Pursuit Tracking with Various Continuous Control Sensors in One Degree-of-Freedom

Overview

A comparison of performance with several different continuous control sensors with one degree-of-freedom may reveal significantly different capabilities of musical control afforded to performers by each sensor. A resulting common unit rate of bits/sec across sensors and across rates of movement could facilitate comparison of sensors using values well established in HCI research and would enable consideration of affordance for a musical context with an approximate maximum information rate.

Apparatus

An apparatus was constructed to include an array of sensors in one experimental device which could be connected to one laptop. Included were eleven inexpensive continuous control sensors for comparison (see Figure 8). These included a knob potentiometer (dial), a slide potentiometer (fader), an infrared proximity sensor, an ultrasonic proximity sensor, a capacitive/inductive proximity sensor, an inertial measurement unit (IMU or Magnetometer/Accelerometer/Gyroscope-MARG) sensor, a force sensing resistor (FSR), a load cell (bar 500 g), a soft potentiometer (100 mm touch strip), a small joystick, and a flex sensor. A laser-cut plywood enclosure housed the sensor and microcontroller components, and provided a tabletop control surface for the sensors that require one. Descriptive information about the sensors is available in Table 8.1.

Three Arduino Micro microcontrollers collected data from the sensors, separated as required by modified firmware. One microcontroller collected data from several analog sensors through its analog input pins. A second microcontroller collected data from two of the digital sensors: the inertial measurement unit and ultrasonic sensor. The infrared sensor
Figure 8.1. A sensor apparatus, including eleven continuous control sensors (infrared and ultrasonic sensor mounted at right). NB: A removable flex sensor is embedded within the index finger sleeve of the glove, and the interface surface of the load cell was covered with electrical tape (not shown above) during the trial to prevent contact interference.
input was also collected on this microcontroller in order to isolate noise effects from this sensor on other analog sensor voltages. The third microcontroller’s counter/timer system was used to accumulate changing values from the oscillator of a capacitive/inductive sensor circuit. External reference voltages were provided by two 5V power adapters connected to a conditioned power supply.

Table 8.1. Sensors included in an apparatus for comparing performance in one degree-of-freedom.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Model (if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARG</td>
<td>Bosch BNO055</td>
</tr>
<tr>
<td>Flex</td>
<td>SpectraSymbol 115mm</td>
</tr>
<tr>
<td>FSR</td>
<td>Interlink 402</td>
</tr>
<tr>
<td>Load Cell</td>
<td>HT Sensor TAL221</td>
</tr>
<tr>
<td>Capacitive/Inductive</td>
<td>Custom</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>ElecFreaks HC - SR04</td>
</tr>
<tr>
<td>Infrared</td>
<td>Sharp GP2Y0A21YK</td>
</tr>
<tr>
<td>Fader</td>
<td>Bourns PTB 100mm Slide Potentiometer</td>
</tr>
<tr>
<td>Dial</td>
<td>Bourns PDB18 100K Rotary Potentiometer</td>
</tr>
<tr>
<td>Touch strip</td>
<td>SpectraSymbol 100mm SoftPot</td>
</tr>
<tr>
<td>Joystick</td>
<td>Adafruit Mini-Joystick (10K)</td>
</tr>
</tbody>
</table>

Each sensor was measured in a calibration procedure to model its input characteristics and establish a common numerical range with an approximately linear curve through function mapping and signal conditioning. To reduce noise in the capacitive and ultrasonic sensor signals, banks of one-pole low pass filters in series were applied with limits of 6 and 12 Hz
respectively. As a consequence, a discernible delay of sensed movement was introduced to these sensors’ signals.

Some of the sensors hold a persistent value other than a resting state at the maximum or minimum end of a range without user interaction. These include the fader, knob, and joystick sensors. The MARG sensor was affixed to a small wood block and the sensor continuously reports orientation. The flex sensor, due to its affixing within a glove, was persistently in a state of interaction with the subject while worn. The touch strip, load cell, FSR, ultrasonic, infrared, and capacitive sensors have a steady return state that is represented when disengaged either purposely or accidentally. Such return values disrupt analysis, so instruction and assistance were provided to prevent accidental disengagement with the sensors.

To assist participants in remaining engaged in continuous control with the touch strip sensor while looking at the display, a halved wooden dowel was affixed beside that sensor to provide a reference anchor which would be felt while operating the sensor in the correct position. Horizontal centering springs were removed from the joystick sensor; however, the vertical spring was left to in place to retain placement along the axis of the measurement degree-of-freedom. Finally, the capacitive/inductive sensor was a custom circuit based upon a prior design.¹

**Subject Pool**

Fourteen subjects participated in the study. Each participant was either an undergraduate or graduate student at LSU. A small monetary incentive (20 USD) was offered to each participant with no requirement of study completion to receive the incentive. All subjects completed the study in full.

Experimental Procedure

Subjects were seated before a table holding the apparatus and the laptop which presented the visual interface on a 391 mm (diagonal) display. The target stimuli included eighty-eight target signals of twenty second duration. These signals were generated as waveforms of Gaussian distributed noise, low-pass filtered at eight bandwidth limits spaced in logarithmic scale from 0.12 Hz to 12 Hz for randomization across the eleven sensors. Each signal was presented as a curve which descended across the screen from top to bottom with 2.5 seconds of preview visible before interfacing with the level of the cursor. A diamond-shaped cursor symbol’s position represented the current status of the sensor’s output for matching to the target curve.

Subjects performed in eleven segments, one for each sensor, controlling with their preferred hand. The order of sensors was randomized for each participant trial. To begin each sensor segment, a training presented three twenty-second signals of low (0.23 Hz), medium (1.67 Hz), then high (6.22 Hz) bandwidth limits for performance. Following the training, eight twenty-second target signals corresponding to each of the bandwidth limits were presented in random order for performance and recording with the sensor. Subjects were allowed to retry performances if they felt that one could be improved with an additional attempt. The full duration of a study trial ranged from 1 to 1.5 hours, dependent upon the extent of retrying and upon adjustment or configuration of the sensors.

Because the study was conducted during a period of pandemic conditions, participants and researchers wore masks for the duration of the study and disinfecting protocols were carried out within the duration of trials. No indications of discomfort or distraction resulting from these health and safety requirements were made.

Analysis

The mean channel capacity at each bandwidth limit was calculated for each sensor. Before calculating the channel capacity, a constant time offset of maximum correlation was
identified to best match the recorded gesture signal to the target signal in time. The touch strip sensor data required conditioning that assigned an amplitude value of 0 where the touch strip sensor was at rest (due to running off of the sensing area or applying insufficient pressure and yielding a value of -1.0).

Results

Two-way analysis of variance (ANOVA) indicated that the bandwidth limit, the individual sensors, and sensor groups had a statistically significant effect overall (p < 0.01). Paired t-tests (with Bonferroni correction) were also conducted for each bandwidth limit to compare if different sensors resulted in different channel capacities. Of the 440 comparisons, 163 were statistically significant (p-value of 0.05). Similarly, a comparison with paired t-tests was made for each sensor across changing bandwidth limits. Of those 308 comparisons, 146 were significant.

Sensors Compared in Groups

The sensors may be grouped according to the mechanics of their operation, and their results may be compared in these groups. Three groups are compared here: proximity, position, and force sensors. The proximity sensors include the infrared, ultrasonic, and capacitive/inductive sensors. The position sensors include the dial, fader, touch strip, flex, MARG, and joystick sensors. Because the MARG sensor was measured in one degree-of-freedom as Z-axis rotation, it is included in the position sensor group. The force sensors include the FSR and load cell sensors. Mean channel capacities for sensors in groups are plotted in Figure 8.2

Across all bandwidth limits, the mean channel capacities of the position sensor group significantly exceeded that of the proximity and force sensor groups, with a greatest difference of maximum means of 2.34 bits/sec at 1.67 Hz (95% CI:2.01, 2.67; p < 0.01). Between those latter groups, the proximity and force sensor group mean channel capacities do not
Figure 8.2. Main subject pool: Estimated channel capacity across bandwidth limits up to 12 Hz for groups of sensors categorized by their mechanics.

significantly differ across all bandwidths, with the exception of 3.22 Hz (95% CI:0.30, 0.85; p < 0.01) and 6.22 Hz (95% CI:0.22, 0.63; p<0.01) where proximity means were higher.

**Force Sensors**

The highest mean channel capacity within the force sensor group was found to be 1.60 bits/sec with the load cell sensor at the 1.67 Hz bandwidth limit (see Figure 8.3). The load cell and FSR were not found to differ significantly at like bandwidth limits within the broader comparison of all sensors in pairwise t-tests and the application of Bonferroni correction. There is evidence of some non-normality and skew at some bandwidth levels. The higher means and higher maxima of the load cell, particularly at medium range bandwidth limits, suggests that for non-novice users, the load cell might potentially afford higher communication throughput, although a significant difference cannot be claimed based upon these results.
Figure 8.3. Main subject pool: Estimated channel capacity across bandwidth limits up to 12 Hz for control with force sensors.

Figure 8.4. Main subject pool: Estimated channel capacity across bandwidth limits up to 12 Hz for control with proximity sensors.
Proximity Sensors

The highest mean channel capacity of the proximity sensors (see Figure 8.4) was shown to be with the infrared sensor, reaching 2.43 bits/sec at 1.67 Hz. Among the proximity sensors, the infrared sensor was found to have a statistically-significantly higher channel capacity than the capacitive sensor at all bandwidth limits below 6.22 Hz, with the exception of 0.23 Hz and 0.86 Hz.

The ultrasonic sensor observations had higher variance than the infrared sensor, including high enough values such that there was no significant difference of means at like bandwidths from the infrared sensor. The ultrasonic and capacitive sensors were not found to have a statistically significant difference at like bandwidths.

It should be noted that the ultrasonic and capacitive sensors exhibited delay in response to movement as well as noise resulting from their design. The ultrasonic sensor’s 40 Hz sampling rate and the significant filtering necessary to de-noise the capacitive sensor may have caused poorer performance, resulting in a lower channel capacity. These sensors also exhibited significant noise characteristics, although it should be noted that the infrared sensor also was noisy in comparison to the potentiometer-based sensors.

Position Sensors

The highest mean channel capacity of the position sensor group — indeed, of any group — was observed to be 4.53 bits/sec with the fader sensor at the 1.67 Hz bandwidth limit (see Figure 8.5).

Within the group of position sensors, the flex and touch strip sensors deviated below the other position sensors across a few bandwidths. For instance, at very low rates, performance with the flex sensor was significantly lower than the dial and fader sensors, and at 3.22 Hz, its observed channel capacity was significantly below the fader and joystick sensors. At 0.44 Hz and 1.67 Hz, the mean channel capacity of the touch strip is significantly below that of the fader. Otherwise, this group of sensors could not be considered to differ significantly.
The maximum touch strip sensor mean channel capacity of 2.37 bits/sec at 3.22 Hz is lower than the mean of 3.98 bits/sec at 2.9 Hz of the related experimental trial with co-located target signal and sensor. This could possibly be attributed to the separation of the presentation of the target signal from the sensor interface. The visual focus on the target signal prevents stable interfacing with the sensor. Also, the provided guide rail was perhaps too low for some finger positions. Several participants adjusted the angle of their finger and struggled to remain engaged effectively with the sensor. It is also possible that at least some of the difference in this sensor’s channel capacity between these studies could be attributed to the shorter length of the 100 mm touch strip vs. the 200 mm touch strip of the prior study.

*Researchers’ Performance*

In order to have a reference of more practiced and experienced performance to compare with the result of the participants, the researchers completed one experimental trial in the same format. Experience in developing the apparatus, the software, and the broader
research program as well as familiarity with the sensors from other projects could contribute to improved performance.

![Graph showing channel capacity across bandwidth limits](image)

Figure 8.6. Researchers’ data: Estimated channel capacity across bandwidth limits up to 12 Hz for groups of sensors categorized by their mechanics.

As with the other studies discussed here where researcher data is shown, the channel capacities for this more experienced group is higher. Some comparisons between sensor groups for this pool reinforce the findings of the subject study. Here again, the position group of sensors allowed higher information capacities than the other sensors, across all bandwidth limits.

Mean channel capacities of the proximity group similarly exceed those of the force sensor group in the lower to middle bandwidth limits of 0.86 Hz and 1.67 Hz; however the researchers performed better with the force sensors than with the proximity sensors at higher bandwidth limits at 3.22 Hz and 12 Hz. Their maximum mean channel capacity with the force sensors was shifted to the higher bandwidth of 3.22 Hz, where the subjects’ highest force sensor mean was at 1.67 Hz. Experience and practice seems to have enhanced performance with the force sensor group more than performance with the proximity sensor group.
Figure 8.7. Researchers’ data: Estimated channel capacity across bandwidth limits up to 12 Hz for control with force sensors.

Within the force sensor group, the researchers performed better with the load cell than with the force sensing resistor at all bandwidth limits, where performance by the subjects was better with the FSR at higher limits. That the differences were not significant for subject performance between these two sensors, due to high variance, it appears that experience and practice improves performance with the load cell more than the FSR, revealing a possible higher channel capacity for that class of sensor.

Proximity sensor performance by the researchers was higher with the ultrasonic sensor at lower to middle bandwidth limits, exceeding the infrared sensor at those levels. The subjects performance means were higher with the infrared sensor at these levels; however, the difference was not found to be significant due partly to high variance with the ultrasonic sensor.

Researcher performance results with the position sensors mostly reinforce the comparative relationships in the performance results of the subject pool. Some heightened performance with the touch strip is evident in the middle range of bandwidth limits. This could partly be due to less ‘running off’ of the sensing area of the sensor. Performance with
Figure 8.8. Researchers’ data: Estimated channel capacity across bandwidth limits up to 12 Hz for control with proximity sensors.

Figure 8.9. Researchers’ data: Estimated channel capacity across bandwidth limits up to 12 Hz for control with position sensors.
the fader sensor is also relatively higher at the middle to high bandwidth limits than other sensors, but more data would be necessary to assert any significance of difference.

**Conclusions**

There are many considerations that can lead to the choice of a particular sensor in a musical application, such as ergonomic relationships, appearance, power limitations, enclosure limitations, prior experience, etc. User control of the sensor would sensibly be a primary factor, and the results shown in this study may inform such considerations. Position sensors were found to afford a higher information throughput than proximity or force sensors, as a group. These may be preferable for application to more demanding continuous control parameters. Further, the channel capacity findings for each sensor here may be consulted to support design for a range of control parameter mapping contexts.

With the limited time made available to participants in training and in completion of the tasks, these results should be considered commensurate with novice performance. The values and inter-relationships found in these results may best serve a context where an instrument is presented to non-musicians or in a passing engagement, such as that of a gallery or conference installation setting.

Additional practice would likely yield better control, reduced error, and therefore higher estimated channel capacities. The practice and familiarity that comes from designing and testing the sensor apparatus led to considerably higher channel capacities achieved by the authors. A thorough study including extensive training should yield results more appropriate to support instrument design for a musical stage performance context.
Chapter 9. A Survey of Experience with Continuous Control Sensors

To facilitate a comparison of craft experience and the empirical results of a comparison study of one degree-of-freedom sensors, a questionnaire was developed to solicit responses regarding various aspects of individual sensors and their usability.

Survey Design

The sensors chosen for inclusion in the survey matched those planned for the original design of the subject experiment of the previous chapter. However, during development of the comparison subject experiment (which took place at a later date than the survey administration) the myosensor was removed from that study. Responses on this sensor remain in the survey results displayed below.

Generic terminologies were used for the sensors, with the exception of the load cell. It is further specified as a 550 g capacity load cell, as these sensors can measure a quite large range of force. No particular sensor model is specified in the questionnaire. One sensor type in the questionnaire, a generic accelerometer sensor, was not measured in the empirical study, because a MARG/IMU sensor with sensor fusion was selected as a result of some of the descriptive responses in the survey results. The responses on the accelerometer sensor should therefore not be considered directly comparable to the MARG/IMU sensor evaluated in the subject study.

To align responses with the methods of the experiments, questions were developed to ascertain estimations of performance at slow or fast rates of movement and by novice or expert performers. The results of the studies reveal relationships of bandwidth limits that can correspond with interpretations of movement rates. There are also results, in some cases, of researchers’ performance, which could inform or at least contextualize respondents’ estimations of expert performance.
Free text descriptive responses were requested to identify preferred sensors and sensor mapping preferences. The preferred sensors section was intended to ensure that the empirical study included sensors used in the NIME community as well as to have descriptive commentary to relate with estimations of performance. Sensor mapping preferences were solicited in order to relate possible musical information rates to empirical results.

The full survey instrument is shown in Appendix E.

Subject Pool

The survey was distributed to the community of the New Interfaces for Musical Expression (NIME) conference community through its email distribution system.

26 Respondents identified themselves (with multiple identity selection allowed) as an Instrument Builder/Designer (24), a Human Computer Interaction Researcher (13), a Digital Musical Instrument Performer (17), and/or a Composer for Digital Musical Instruments (15). Respondents reported a mean time of involvement with new music interfaces of 13.82 years with a range from 2 years to 40 years.

Results

Acknowledging that the intervals of an ordinal scale may not be assumed to be uniform, means from the combined responses across the range of sensors are provided along with stacked bar chart results representing tabulation of the ordinal responses. The results shown below include only the opinions of those respondents with experience with a sensor. Those responses indicating no experience with the sensor were removed, causing varying group sizes for each sensor.

Results are aggregated by type as with the empirical study comparing one degree-of-freedom sensors and also listed by sensor.
Responses Regarding Control by Novice Users

Figure 9.1. Survey responses to the question, “How easy are the following sensors to control by a novice user?” grouped by controller type.

Figure 9.2. Survey responses to the question, “How easy are the following sensors to control by a novice user?” per sensor.

Responses regarding the ease with which novices could control the listed sensors favored position sensors as a group (see Figure 9.1). This result corresponds well to the results of the empirical study. Responses for proximity sensors and force sensors suggest a middling to low estimation of ease of control for novices, also in keeping with the empirical results by group.
The rankings of individual sensors for novice control mostly track the results of the empirical study, although with some differences regarding force sensors. The somewhat large difference in mean rating for the novice dimension between the FSR and load cell estimation is perhaps not supported by the channel capacity value comparison between these force sensors. Indeed the FSR empirical results show that it had the lowest maximum mean channel capacity of all the sensors at 1.12 bits/sec (at the 1.67 Hz bandwidth limit, see Figure 8.3), although tests of significance did not show a significant difference from the load cell’s highest mean result of 1.59 bits/sec at at the same bandwidth limit.

The touch strip sensor performance results are relatively lower than these ratings expectations may indicate. Finally, the accelerometer estimation, as noted above, should not be considered comparable to the MARG/IMU sensor channel capacity values. In the empirical study, subjects performed with higher mean channel capacities using that sensor than with the infrared sensor. Had a simple accelerometer without sensor fusion been studied, the results may be very different and more in keeping with these estimations.
Responses Regarding Control by Expert Performers

Figure 9.3. Survey responses to the question, “To what extent do the following sensors afford control at a virtuosic level by an expert performer?” grouped by sensor type.

Figure 9.4. Survey responses to the question, “To what extent do the following sensors afford control at a virtuosic level by an expert performer?” per sensor.

The formal experimental comparison did not include expert performers, but the researchers’ data may provide some points of comparison.

A very large difference is shown between the survey respondents’ estimation of capacitive proximity control and the empirical result. The sensor with which capacitive/inductive sensing was measured was not as sophisticated as a commercial Theremin and showed noise
characteristics which required significant filtering. A study of the more complex device for continuous control using the methods described above could yield results for better comparison. The Theremin has a long history of regard as a particularly expressive new electronic music interface. However, the proximity sensors in general did not afford information channel capacities as high as position sensors. Resolving this difference could be useful and informative.

The FSR was also overestimated to some extent. Among the results across the researchers’ data for all bandwidths (see Figure 8.7), the FSR had the second lowest maximum channel capacity mean of 2.8 bits/sec at 3.22 Hz, only after the capacitive/inductive sensor’s maximum mean of 2.73 bits/sec at 1.67 Hz.
Figure 9.5. Survey responses to the question, “How accurately can one continuously control the following sensors at relatively SLOW rates of movement?” grouped by sensor type.

Figure 9.6. Survey responses to the question, “How accurately can one continuously control the following sensors at relatively SLOW rates of movement?” per sensor.

Among the experimental results, the force sensor and proximity sensor groups were not found to be significantly different at low bandwidth limits. The middling estimations of the respondents seem in keeping with this result with perhaps an underestimation of the force sensing group. It seems here again that the load cell sensor is considered not to be accurately controlled.
Responses Regarding Control with Fast Rates of Movement

Figure 9.7. Survey responses to the question, “How accurately can one continuously control the following sensors at relatively FAST rates of movement?” grouped by sensor type.

Figure 9.8. Survey responses to the question, “How accurately can one continuously control the following sensors at relatively FAST rates of movement?” per sensor.

At higher bandwidth limits, the infrared sensor channel capacity means were higher than these average estimations may indicate. Its subject performance channel capacity mean at 3.22 Hz of 1.76 bits/sec significantly exceeded (p < 0.01) that of the load cell (0.62 bits/sec) and FSR (0.67 bits/sec). As these comparisons of survey results and empirical results are inexact, it is difficult to assert that there is a significance to this underestimation, but it is
fair to say that the infrared sensor affords more control than the FSR and load cell given the channel capacity values at higher rates. The respondents nonetheless favored the FSR over the infrared sensor for this consideration of control at fast rates of movement.

While there are some broad consistencies between the estimations represented in these survey results and the experimental findings, those findings do reveal some possible biases for or against particular sensors. The load cell and infrared sensors may be underestimated, and the capacitive/inductive proximity sensor may be overestimated in some contexts. These discrepancies indicate that the experimental results in the case of these sensors may inform reconsideration and adaptation of their use.
Chapter 10. Discussion Across Studies

Some brief observations across these studies become salient. The studies in some cases have common sensors or sensors of the same form, but with different sizes and force characteristics. Comparison of the channel capacity estimations from the experimental results raises possible areas of further inquiry.

The touch strip was included in the pilot study, the experiment comparing with pointing with pursuit tracking, and in the experiment comparing various one degree-of-freedom sensors. The channel capacity estimations of performance with these touch strips vary in ways that may relate to the variations in study design and differences in the experimental apparatuses. The highest performance among these was the study that also included co-location of the target signal display and the sensor interface (see Figure 4.4).

Further, that study’s sensor was twice the length of the sensor of the other two studies. While the amplitude of movement might be expected to reduce communication of information, the co-location assists in maintaining contact with the control surface and with the basic pursuit tracking task of matching the target. Instruments that provide co-located reference assistance, either through adaptive lighting or pixel displays or through form-molded or inscribed reference shapes, may afford better control through such target highlighting.

Performance with the smaller joystick in the comparison of one degree-of-freedom sensors was higher than that of the first (one degree-of-freedom) stage of the increasing degrees-of-freedom study. The scale of movement required to control the larger joystick seems to have reduced performance, which is consistent with prior research findings on the amplitude of movement. The much smaller movements with the mini-joystick allowed for finer control using the fingers, which may have contributed to a performance gain.

There are other differences between these studies that could also contribute to differing results. The direction of movement was vertical in the case of the larger joystick and horizontal with the smaller. Spring centering was active on the larger joystick and was
removed from the smaller joystick. Finally, differences in visual interface design, such as a large bar cursor with the larger joystick in one degree-of-freedom and the small diamond with the smaller joystick could also have contributed to differing results.
Chapter 11. Conclusion

Summary of Primary Conclusions

The conclusive evidence from this dissertation includes the following key findings as determined from the results of experimentation and the development of a model for measuring the channel capacity of a human computer system when performing a pursuit tracking task.

Continuous Control vs. Pointing

It appears that continuous control may afford higher rates of information transmission than pointing at higher rates of movement, especially with training/experience.

More degrees-of-freedom may add and also reduce control

Higher channel capacities were shown in the trackpad and joystick study for additional degrees-of-freedom, but there was a limit to the significance beyond two for novice users. This finding is complicated by the difficulty in perceiving multiple target signals, though.

Sensor types have control advantages

Sensors that measure displacement of position have allowed for greater control than force and proximity sensors and should perhaps be favored for demanding control applications.

Clear difference in novice vs. expert control

In every study, researchers who were involved in the design of the apparatus and the development of the control software communicated at much higher rates of information in bits per second. This is understandable, even obvious, but the results of sensor comparison and degrees-of-freedom in these studies must be understood to represent novice users. The
applicability of these results may not be as strong for instrument design for a highly expressive instrument or for demanding, expert control tasks in other contexts. Further investigation with longer term committed participants who practice and train with apparatus would be very interesting.

Established Reference Values

Reference values providing channel capacity estimations for a range of sensors are now available to researchers and designers.

Limitations

As is shown in the reviews of Fitts’ law research, there can be great variation in the experimental results of different research studies following similar approaches. The efficacy of generalizing the results shared in this dissertation may be similarly limited or in need of validation and comparison. Limitations have been expressed through the discussion of the experiments, but it may be worth repeating a few here.

The sensor instrumentation in some cases exhibited noise and time delay that could result from the deliberate selection of inexpensive, common components or by circuit design in building the experimental instruments. Particularly, the capacitive/inductive sensor included both noise and time delay due to de-noising filter effects. The ultrasonic sensor’s slower polling rate may have introduced delay affecting the channel capacity estimation vs. what may have been measured for other sensors of that type.

Visual perception is a key element of every experiment described above, and many choices were made about how to represent preview, from what shape to how much time should be seen. These choices were optimized in development, but each decision could affect performer’s ability to perceive the target signal of the model. The study most affected by visual presentation seems to have been the study of successively increasing degrees-of-
freedom while controlling joystick sensors. These influences should be noted in interpreting the results shown.

As the first estimations of their type for many of these devices, it should be expected that they can be improved and refined. From these investigations, there are clear indications of what should be beneficial lines of inquiry in future research.

**Future Study**

A clear candidate for informative application of this model would be a systematic investigation program that includes significant training and consistent practice schedules to measure performance plateaus as would be appropriate for an instrument one spends time practicing. An attempt was made to investigate the effects of practice as an extension of the trackpad study, but the rehearsal program was too inconsistent to yield firm results.

Applying this model to investigate amplitude of movement in pursuit tracking tasks with like sensors and effects on the channel capacity could be very informative, especially in relation to instrument design goals of providing small scale control and improvement of touch in instrument interfaces.

Addition of different modes of performance feedback beyond visual and the limited sonic feedback provided in these students could be done in a controlled way to study effects on performance. Some musicians asserted that presentation of target data in auditory display would improve their performance.

As a final suggestion from what could be a much longer list, relating performer perceptions of sensor control satisfaction or instrument performance satisfaction for an instrument designed to a certain channel capacity could relate affordance/constraints of information throughput to expressiveness or other musical goals.

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In Closing

As interdisciplinary research, this dissertation may find interest from scholars of more or less distinct fields of inquiry. There is a rich nexus for the synthesis of advancements from various contributing areas to inform and improve new music interface designs. Some of these may incorporate, reconsider, or revise the conclusions of this dissertation. The rapid development of literature around this practice from scientific to creative to humanistic is astounding and will surely continue to expand and inform the making of musical meaning in the human computer interface.
Appendix A. Documentation of Institutional Oversight of Experimentation with Human Subjects

Approval Documents
ACTION ON EXEMPTION APPROVAL REQUEST

TO: Edgar Berdahl
Music and CCT

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: November 19, 2018

RE: IRB# E11376

TITLE: Continuous Control Versus Pointing for Human Control of a User Interface


Review Date: 11/19/2018

Approved X Disapproved

Approval Date: 11/19/2018 Approval Expiration Date: 11/18/2021

Exemption Category/Paragraph: 2a

Signed Consent Waived?: Yes

Re-review frequency: (three years unless otherwise stated)

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman [Signature]

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –

Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU’s Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
8. SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc. Approvals will automatically be closed by the IRB on the expiration date unless the PI requests a continuation.

* All investigators and support staff have access to copies of the Belmont Report, LSU’s Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb
TO: Edgar Berdahl  
Music and CCT  
FROM: Dennis Landin  
Chair, Institutional Review Board  
DATE: January 22, 2019  
RE: IRB# E11376  
TITLE: Continuous Control Versus Pointing for Human Control of a User Interface  

New Protocol/Modification/Continuation: Modification  

Brief Modification Description: Record how many of the test subjects were female and how many of them were right handed from memory.  

Review date: 1/22/2019  

Approved X Disapproved _____________  

Approval Date: 1/22/2019 Approval Expiration Date: 11/18/2021  

Re-review frequency: (three years unless otherwise stated)  

LSU Proposal Number (if applicable):  

By: Dennis Landin, Chairman  

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING – Continuing approval is CONDITIONAL on:  

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU’s Assurance of Compliance with DHHS regulations for the protection of human subjects*  
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*All investigators and support staff have access to copies of the Belmont Report, LSU’s Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb
ACTION ON EXEMPTION APPROVAL REQUEST

TO: Michael Blandino
Music

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: April 8, 2019

RE: IRB# E11661

TITLE: Continuous Control of a Two Dimensional Interface in Musical Performance


Review Date: 4/8/2019

Approved X Disapproved

Approval Date: 4/8/2019 Approval Expiration Date: 4/7/2022

Exemption Category/Paragraph: 2a

Signed Consent Waived?: No

Re-review frequency: (three years unless otherwise stated)

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING – Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
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* All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb
ACTION ON EXEMPTION APPROVAL REQUEST

TO: Michael Blandino  
Music

FROM: Dennis Landin  
Chair, Institutional Review Board

DATE: December 2, 2019

RE: IRB# E12026

TITLE: Continuous Simultaneous Control of Multiple Sensors (Joysticks)


Review Date: 12/2/2019

Approved X Disapproved

Approval Date: 12/2/2019 Approval Expiration Date: 12/1/2022

Exemption Category/Paragraph: 3a

Signed Consent Waived?: No

Re-review frequency: Three years

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING – Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
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* All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb

Institutional Review Board  
Dr. Dennis Landin, Chair  
130 David Boyd Hall  
Baton Rouge, LA 70803  
P: 225.578.8692  
F: 225.578.5983  
irb@lsu.edu  
lsu.edu/research
TO: Berdahl, Edgar Joseph
LSUAM | HNRS College | Dean's Office
FROM: Alex Cohen
Chair, Institutional Review Board
DATE: 17-Nov-2020
RE: IRBAM-20-0534
TITLE: A Comparison of the Channel Capacity of Several Continuous Control Sensors with Application to Designing Musical Instruments
SUBMISSION TYPE: Initial Application
Review Type: Exempt
Risk Factor: Minimal
Review Date: 16-Nov-2020
Status: Approved
Approval Date: 16-Nov-2020
Approval Expiration Date: 15-Nov-2023
Re-review frequency: Three Years
Number of subjects approved: 20
LSU Proposal Number:

By: Alex Cohen, Chairman

Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU’s Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.

8. **SPECIAL NOTE:** When emailing more than one recipient, make sure you use bcc. Approvals will automatically be closed by the IRB on the expiration date unless the PI requests a continuation.

*All investigators and support staff have access to copies of the Belmont Report, LSU’s Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at [http://www.lsu.edu/research](http://www.lsu.edu/research)*

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Louisiana State University  
131 David Boyd Hall  
Baton Rouge, LA 70803  
O 225-578-5833  
F 225-578-5983  
http://www.lsu.edu/research
Hi,
The IRB chair reviewed your application, A Survey of the Usage of Continuous Control Sensors in Digital Musical Instruments, and determined IRB approval for this specific application (IRB# E12152) is not needed. There is no manipulation of, nor intervention with, human subjects. Should you subsequently devise a project which does involve the use of human subjects, then IRB review and approval will be needed. Please include in your recruiting statements or intro to your survey, the IRB looked at the project and determined it did not need a formal review.

You can still conduct your study. It falls under a certain category that does not need IRB approval.

Elizabeth

---

Elizabeth Cadarette
Compliance Specialist
Office of Research and Economic Development
Louisiana State University
131 David Boyd Hall, Baton Rouge, LA 70803
office 225-578-8692 | fax 225-578-5983
eantol1@lsu.edu | lsu.edu | www.lsu.edu/research

LSU Research - The Constant Pursuit of Discovery
Consent Forms
Form for Participants

1. Study Title: *Continuous Control Versus Pointing for Human Control of a User Interface*

2. Performance Site: The Media Lab MDA 244 or the FabLab DMC 1065

3. Investigators: The principal investigator is available for questions about this study, M-F 9AM-5PM
Dr. Edgar Berdahl (650) 492-0211 edgarberdahl@lsu.edu

4. Overview: People commonly operate user interfaces to point. For example, one can point with a mouse, and one can point with a touchscreen. However, in computer music and gaming, continuous control is also important – for example, consider controlling a video game with a steering wheel. This study investigates how accurately human participants can point with versus continuously control a touch strip.

5. Purpose of the Study: This study investigates how accurately human participants can point with versus continuously control a touch strip.

6. Subject Inclusion: To participate in this study you must meet the requirements of the inclusion criteria (must be a student in MUS 4745 or a student, faculty or staff member in the School of Music) and exclusion criteria (cannot be 17 years of age or younger).

7. Number of subjects: 4 to 25

8. Study Procedures: The study begins with a training phase, in which you will learn how to record gestures using a touch strip. For recording, you will view a "target gesture" (see Figure 2a,b above) on a graphical user interface and are asked to use the touch strip to control a live signal, which should match the target gesture as accurately as possible. Your experience...
will somewhat resemble playing a video game in which the goal is to follow a target path or hitting a series of targets (e.g. pointing).

During the testing phase, you will try to record gestures with continuous control or pointing at various speeds. For any given trial, you may choose to record the gesture over and over again until you are satisfied with the recording.

8. Benefits: The study may yield new information on how humans are able to control computer interfaces and electronic musical instruments.

9. Risks: This study presents no more than minimal risk. No sensitive information will be collected during the study, and all data will be made anonymous.

10. Right to Refuse: You may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which you might otherwise be entitled.

11. Privacy: All data will be made anonymous. Results of the study may be published, but no names or identifying information will be included in the publication. Your identity will remain confidential unless disclosure is required by law.

12. If I have questions about subjects’ rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, or www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the researchers’ obligation to provide me with a copy of this form.
Consent Form for Participants

1. Study Title: Continuous Control of a Two-Dimensional Interface in Musical Performance

2. Purpose: In computer music and gaming, continuous control is important – for example, consider controlling a video game with a steering wheel. This study investigates how accurately human participants can continuously control a trackpad in two dimensions. The investigation is made while participants perform gestures on computers that create musical sounds as an ensemble.

   Procedure: The study will start with a verbal description of the performance computer program, and a rehearsal to learn how to follow a target using the trackpad. Your experience will resemble playing a video game in which the goal is to follow a target path. Following this rehearsal, two additional performances will be completed simultaneously with other performers (up to 8), in which you should match the target gestures as accurately as possible. The session will take place over 50 minutes.

3. Risks: This study presents no more than minimal risk. No sensitive information will be collected during the study, and all data will be made anonymous.

4. Benefits: The study may yield new information on how humans are able to control computer interfaces and electronic musical instruments. Participants will gain an experience of performing music with a laptop.

5. Alternatives: Student participants may gain similar experience through enrollment in a laptop orchestra ensemble course.

6. Investigators: The principal investigators for this study are available for questions about this study, M-F 9AM-5PM Michael Blandino mblandi@lsu.edu (225) 405-5322 and Assistant Professor Edgar Berdahl (650) 492-0211 edgarberdahl@lsu.edu.

7. Performance Site: 304 School of Music

8. Number of Subjects: 30 – 60

9. Subject Inclusion: To participate in this study you must meet the requirements of the inclusion criteria (must be a student in MUS 2700 or a student, faculty or staff member...
in the School of Music) and exclusion criteria (cannot be 17 years of age or younger).

10. Right to Refuse: You may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which you might otherwise be entitled.

11. Privacy: All data will be made anonymous. Results of the study may be published, but no names or identifying information will be included in the publication. Your identity will remain confidential unless disclosure is required by law.

12. If I have questions about subjects’ rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, or www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the researchers’ obligation to provide me with a copy of this form.

13. Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. For injury or illness, call your physician, or the Student Health Center if you are an LSU student. If I have questions about subjects’ rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, or www.lsu.edu/research. I agree to participate in the study described above and acknowledge the investigator’s obligation to provide me with a signed copy of this consent form.

Subject Signature: __________________________________ Date: ________________

The study subject has indicated to me that he/she is unable to read. I certify that I have read this consent form to the subject and explained that by completing the signature line above, the subject has agreed to participate.

Signature of Reader: ______________________________ Date: _______________
Consent Form for Participants

1. Study Title: Continuous Simultaneous Control of Multiple Sensors

2. Purpose: In computer music and gaming, continuous control is important – for example, consider controlling a video game with a steering wheel. This study investigates how accurately human participants can continuously control multiple two joystick devices. The investigation is made while participants perform gestures on sensors that display values on a laptop screen.

Procedure: The study will begin with a verbal description of the performance tracking computer program. A training protocol will run to allow participants to learn how to follow a target using the joy sticks. Your experience will resemble playing a video game in which the goal is to follow a target path. Following this training, target points will move in two dimensions on the laptop screen. You should match the target gestures as accurately as possible using one joystick in one degree of freedom (up and down), in two degrees of freedom (adding left and right), three degrees of freedom (adding the left joystick’s up and down movement), then four directions with two joysticks.

3. Risks: This study presents no more than minimal risk. No sensitive information will be collected during the study, and all data will be made anonymous upon storage.

4. Benefits: The study may yield new information on how humans are able to control computer interfaces and electronic musical instruments. You will gain an experience of controlling a joystick sensor and following up to four target movements.

5. Alternatives: Student participants may gain similar experience through playing a video game with continuous control sensors.

6. Investigators: The principal investigators for this study are available for questions about this study, M-F 9AM-5PM Michael Blandino mblandi@lsu.edu (225) 405-5322 and Assistant Professor Edgar Berdahl (650) 492-0211 edgarberdahl@lsu.edu.

7. Performance Site: LSU campus

8. Number of Subjects: 5-60

9. Subject Inclusion: To participate in this study one must meet the requirements of the inclusion criteria (must be an undergraduate or graduate student) and exclusion criteria.
10. Right to Refuse: You may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which you might otherwise be entitled.

11. Privacy: All data will be made anonymous. Results of the study may be published, but no names or identifying information will be included in the publication. Your identity will remain confidential unless disclosure is required by law.

12. Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. For injury or illness, call your physician, or the Student Health Center if you are an LSU student. If I have questions about subjects’ rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, or www.lsu.edu/research. I agree to participate in the study described above and acknowledge the investigator’s obligation to provide me with a signed copy of this consent form.

Subject Signature: _______________________________   Date: ________________
Consent Form for Participants

1. Study Title: A Comparison of the Channel Capacity of Several Continuous Control Sensors with Application to Designing Musical Instruments

2. Purpose and Procedure: In computer music and gaming, continuous control is important – for example, consider controlling a video game with a steering wheel. This study investigates how accurately human participants can continuously control various sensors. The investigation is made while participants perform gestures on sensors that display values on a computer display screen.

The study will start with a verbal description of the performance computer program. A training protocol will run to allow participants to learn how to follow a target using a sensor. Your experience will resemble playing a video game in which the goal is to follow a target path. Following this training, target curves will move down the laptop screen. You should match the target gestures as accurately as possible using each successive sensor.

3. Risks: This study presents no more than minimal risk. No sensitive information will be collected during the study, and all data will be made anonymous upon saving.

4. Benefits: The study may yield new information on how humans are able to control computer interfaces and electronic musical instruments. Participants will gain an experience of controlling sensors that measures physical pressure or proximity.

5. Alternatives: Student participants may gain similar experience through playing a video game with continuous control sensors.

6. Investigators: The principal investigators for this study are available for questions about this study, M-F 9AM-5PM Michael Blandino mblandi@lsu.edu (225) 405-5322 and Assistant Professor Edgar Berdahl (650) 492-0211 edgarberdahl@lsu.edu.

7. Performance Site: Louisiana State University and Agricultural and Mechanical College in Baton Rouge

8. Number of Subjects: 2-20
9. Inclusion Criteria: To participate in this study you must meet the requirements of the inclusion criteria (must be an undergraduate or graduate student or member of the LSU faculty or staff) and exclusion criteria (cannot be 17 years of age or younger).

10. Exclusion Criteria: Individuals 17 years of age or younger or those unaffiliated with the University as student, faculty, or staff will be excluded from participation in this study.

11. Financial Information: This study provides an incentive of $20 for up to 20 participants. Compensation for participants will be distributed through LSU financial systems administration following participation and allowing for administrative processing time of up to three weeks.

12. Right to Refuse: You may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which you might otherwise be entitled.

13. Privacy: All data will be made anonymous. Results of the study may be published, but no names or identifying information will be included in the publication. Your identity will remain confidential unless disclosure is required by law.

14. Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. For injury or illness, call your physician, or the Student Health Center if you are an LSU student. If I have questions about subjects’ rights or other concerns, I can contact Alex Cohen, Institutional Review Board, (225) 578-8692, irb@lsu.edu, or www.lsu.edu/research. I agree to participate in the study described above and acknowledge the investigator’s obligation to provide me with a signed copy of this consent form.

Subject Signature: _______________________________   Date: ________________
Appendix B. Musical Parameters as Information

A relationship from musical parameters to an information rate in bits/sec may assist in relating the results of this study to a context of musical goals. Upon defining a set of musical parameter limitations, an information rate per symbol may be developed across the ranges of those parameters. As a simple example, if a digital musical instrument provides a range of one octave of discrete diatonic pitch values, there would be 7 available pitches. Assuming all pitch probabilities are equal (leaving aside that they likely are not), the maximum information rate is $\log_2 n$ bits per symbol.

If a score for such an instrument calls for a tempo of 60 beats per minute with an expectation of pitch transitions no shorter than half a beat apart and allowing for any available pitch value per note, then it shall require no more than approximately $2\log_2 7 \approx 5.6$ bits/sec of information to fully control the pitch parameter for such a monophonic performance.

The information rate demands of the pitch parameter may be lower, perhaps significantly lower, by reduction of probable pitches and extension of durations appropriate to a style or harmonic space. Design for these lower rates is certainly possible, but such a reduction may constrain, eliminating possibilities.

---

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<td>Licensed Content Author</td>
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Baton Rouge, LA 70803
United States
Attn: Mr. Michael Blandino

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Appendix D. Permission to Reprint “Sonic Feedback of Performance Error while Controlling a Laptop Touchpad as Laptop Orchestra Chamber Music”
Appendix E. A Survey of the Usage of Continuous Control Sensors in Digital Musical Instruments
A Survey of the Usage of Continuous Control Sensors in Digital Musical Instruments

Start of Block: Introduction

1. Study Title: Usage of Continuous Control Sensors in Digital Musical Instruments
2. The purpose of this research project is to determine rates of usage for several continuous control sensors as well as informed intuition about the ability to control them. The study will be conducted online through Qualtrics and you will spend approximately 20 minutes completing one questionnaire about continuous control sensors.
3. Inclusion criteria: You are eligible to participate if you are aged 18 or older and are interested in electronic musical instrument design.
4. Exclusion criteria: You are ineligible to participate if you are under the age of 18.
5. There are no risks involved in participating in the study.
6. The principal investigator of this research program is Michael Blandino (mblandi@lsu.edu, +1 (225) 578-8845) and the supervising professor is Dr. Edgar Berdahl (edgarberdahl@lsu.edu).
7. Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled.
8. Results of the study may be published, but no names or identifying information will be included in the publication, as they are not collected.
9. This study was determined by the Institutional Review Board (IRB) to not require formal review. Participants may contact Dr. Dennis Landin, Chair of the LSU Institutional Review Board at +1 (225) 578-8692, irb@lsu.edu, or www.lsu.edu/research.
10. By continuing to this survey, you are giving consent to participate in this study.

End of Block: Introduction

Start of Block: Default Question Block
With which roles do you identify?

- [ ] Instrument Builder/Designer (1)
- [ ] Human Computer Interaction (HCI) Researcher (2)
- [ ] Digital Musical Instrument (DMI) Performer (3)
- [ ] Composer for Digital Musical Instruments (DMIs) (4)

For how many years have you been involved with new musical interfaces (not necessarily in a formal role)?

________________________________________________________________

End of Block: Default Question Block
### Estimations of Sensor Control

How accurately can one continuously control the following sensors at relatively SLOW rates of movement? (0=no experience, 1=not at all accurately, 5=completely accurately)

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How accurately can one continuously control the following sensors at relatively FAST rates of movement? (0=no experience, 1=not at all accurately, 5=completely accurately)

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<th>Sensor</th>
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How easy are the following sensors to control by a novice user? (0=no experience, 1=not easy, 5=very easy)

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</table>
To what extent do the following sensors afford control at a virtuosic level by an expert performer? (0=no experience, 1=very little, 5=approaching virtuosic)

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touchstrip ()</td>
<td></td>
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<tr>
<td>Force sensing resistor (FSR) ()</td>
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<tr>
<td>Load Cell (500g) ()</td>
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<tr>
<td>Infrared Distance (IR) ()</td>
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<tr>
<td>Ultrasound Distance ()</td>
<td></td>
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<tr>
<td>Fader (slider) ()</td>
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<tr>
<td>Flex sensor ()</td>
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<tr>
<td>Myo (muscle) sensor ()</td>
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<tr>
<td>Joystick ()</td>
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<tr>
<td>Accelerometer ()</td>
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<tr>
<td>Potentiometer (knob) ()</td>
<td></td>
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<tr>
<td>Capacitive Distance Sensor (e.g. Theremin)</td>
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</tbody>
</table>

End of Block: Estimations of Sensor Control
Start of Block: Sensor Mappings

What music or sound parameters are suitable for control with a touchstrip?

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What music or sound parameters are suitable for control with a force sensing resistor?

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What music or sound parameters are suitable for control with a load cell (500g)?

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What music or sound parameters are suitable for control with an infrared distance sensor?

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What music or sound parameters are suitable for control with an ultrasound distance sensor?

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What music or sound parameters are suitable for control with a fader (slider)?

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What music or sound parameters are suitable for control with a flex sensor?

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What music or sound parameters are suitable for control with a myo (muscle) sensor?

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What music or sound parameters are suitable for control with a joystick (non-stationary)?

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What music or sound parameters are suitable for control with an accelerometer?

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What music or sound parameters are suitable for control with a potentiometer (knob)?

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End of Block: Sensor Mappings
Start of Block: Sensor Preferences

What sensors do you prefer to use when building new interfaces for musical expression (NIME)?

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Describe why you like using these sensors

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List sensors that you think are easy to control

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List sensors that you think are difficult to control

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End of Block: Sensor Preferences
Start of Block: Block 5
Bibliography


Miller, George A. “The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information.” Psychological Review 63, no. 2 (1956): 81–97.


Vita

Michael Blandino offers his digital art music from Baton Rouge, LA and intends to graduate with a Ph.D. in Music with a concentration in Experimental Music and Digital Media from LSU in August 2021. He serves as Assistant Dean of that university’s Ogden Honors College, and his Bachelor’s degree in Philosophy and Master’s degree in Music Theory are from LSU. Blandino’s works have been presented at the International Computer Music Conference, the New York City Electroacoustic Music Festival (NYCEMF), the Korean Electro-Acoustic Music Society Academic Conference (KEAMSAC), the Electric LaTex Festival, the Electronic Music Midwest festival, the Ebb and Flow Festival, the New Orleans Film Festival, and in a supplement to The Csound Book (MIT Press). Active in experimental music and human computer interaction (HCI) research, he has contributed to the study of continuous control/analog sensors, of the meaning and environmental impacts of digital music performance and practice, and of the auditory display of environmental risk data in augmented reality.