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Evaluation of Input Devices for Musical Expression: Borrowing Tools from HCI

The widespread availability of high-performance, affordable personal computers has brought a new wealth of possibilities regarding real-time control of musical parameters. In fact, real-time gestural control of computer music has become a major trend in recent years (e.g., Wanderley and Battier 2000).

Various input devices for musical expression—also called *hardware interfaces*, *control surfaces*, or *(gestural) controllers*—have been proposed (Penny-cook 1985; Roads 1996; Paradiso 1997; Mulder 1998; Bongers 2000, Cook 2001; Piringer 2001). These devices can be roughly classified into several categories: *instrument-like controllers* that try to emulate the control interfaces of existing acoustic instruments; *instrument-inspired controllers* that are basically designed loosely following the characteristics of existing instruments (but that do not necessarily seek an emulation of their counterparts); *extended instruments*, that is, acoustic instruments augmented by the use of several sensors; and *alternate controllers*, whose designs do not follow that of any existing instrument.

A more careful examination reveals two main trends behind these categories: the tendency to design controllers to best fit some already developed motor control ability (the case of the first three categories), or an attempt to deliberately avoid any relationship to gestural vocabularies associated to existing instruments, therefore allowing the use of different movements and postures not traditionally used in music performance. Conversely, *alternate controllers*, *instrument-inspired controllers*, and, to a certain extent, *extended instruments*, have been designed to fit idiosyncratic needs of performers and composers, but as such they have usually remained inextricably tied to their creators.

This situation brings up a number of questions related to the possible use of these interfaces by different performers and musicians. In fact, many times these developments have only been used in very few circumstances, notably at conference demonstrations. Therefore, one needs to find ways to compare the several designs to make sense of the variety of developments. This presents a problem when deciding on which parameters or features of various input devices to use as bases for comparison, particularly when discussing music of varying aesthetic directions. For instance, how do we evaluate an input device without taking into account a specific aesthetic context? That is, if people have only heard one type of music played on the violin, how can they tell if the violin is generally a versatile instrument? What is part of the composition, and what is part of the technology? How can we rate the usability of an input device if the only available tests were done by few—possibly one—expert and motivated performers?

A possible solution to the problem of comparing devices is to turn our attention to existing research in related fields. In this article, we approach the evaluation of input devices for musical expression by drawing parallels to existing research in the field of Human-Computer Interaction (HCI). We extensively review the existing work on the evaluation of input devices in HCI and discuss possible applications of this knowledge to the development of new interfaces for musical expression. We finally suggest and discuss a set of musical tasks to allow the evaluation of existing input devices.

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Human-Computer Interaction

The field of HCI has historically drawn from four complimentary domains—software engineering, software human factors, computer graphics, and cognitive science—that could be grouped into two main foci: methods and software (Carroll 2002). The methods focus became later known as *usability engineering*, while the software focus became known as *user interface software and tools*. In HCI, *interaction* is defined as a process of communication or information transfer from the user to the computer and from the computer to the user. The user starts an interactive process to achieve a given *task* (Dix et al. 1998). The task normally requires the user to monitor the system's status and to manually modify the system's parameters by respectively using output and input devices.

Therefore, the research on input device evaluation plays an important role in HCI, in particular on the definition of the interaction possibilities allowed to the users. These possibilities mainly depend on the interaction metaphor used in each application, the *WIMP* (Windows, Icons, Menus, and Pointers) paradigm being the most common in commercial systems.

Advances in technology, in particular of specialized fields (e.g., video games), seek to introduce new interaction metaphors. Hence, other paradigms have been proposed for expanding the possibilities of WIMP interfaces, which are rather limited if compared to multiple real-time continuous inputs used, for instance, in computer music performances. One such effort has been proposed by Jacob, Deligiannidis, and Morrison (1999) in which the authors define a "post-WIMP" user interface:

> The essence of these interfaces is, then, a set of continuous relationships, some of which are permanent and some of which are engaged and disengaged from time to time. These relationships accept continuous input from the user and typically produce continuous responses or inputs to the system. The actions that engage or disengage them are typically discrete (pressing a mouse button over a widget, grasping an object). (p. 5)

A reader familiar with computer music software will immediately see here an analogy to well-known paradigms such as, for instance, that of Max (Puckette 1988). Another recent interaction model is *instrumental interaction* (Beaudouin-Lafon 2000), that, although still primarily related to the design of graphical user interfaces, expands the possibilities of interaction in post-WIMP interfaces. It takes into account the notion of *instruments*, that is, tools with which the user interacts with domain objects. The instrumental interaction model is based on how we use tools (or instruments) to manipulate objects of interest in the physical world. Objects of interest are called *domain objects* and are manipulated with computer artifacts called *interaction instruments*. This model describes a new interaction style, closer to the case of music performance using gestural controllers, than the traditional WIMP paradigm.

Existing Research in HCI

A substantial amount of material has been published in the HCI literature on the evaluation of existing input devices as well as on the design of new ones. This material includes works on the definition of representative *tasks* to be used in the comparison of different devices (Buxton 1987), the use of *analytical models of aimed movements* (MacKenzie 1992; Guiard, Beaudouin-Lafon, and Mottet 1999; Guiard 2001; Accot and Zhai 1997, 1999, 2001), and the suggestion of various *taxonomies* of input devices (Buxton 1987; Card, Mackinlay, and Robertson 1991).

Evaluation Tasks and Methodologies

Buxton (1987) proposed the following tasks as a means to evaluate the match of input devices to applications: *pursuit tracking*, *target acquisition*, *freehand inking*, *tracing and digitizing*, *constrained linear motion*, and *constrained circular motion* (see Figures 1 and 2). Each of the tasks consists of a common user action in HCI with its own

Figure 1. Target acquisition task, after Buxton (1987).

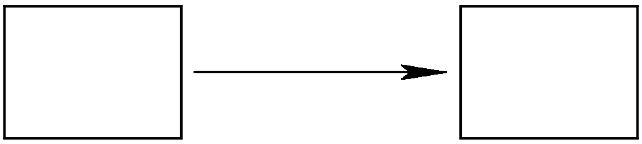
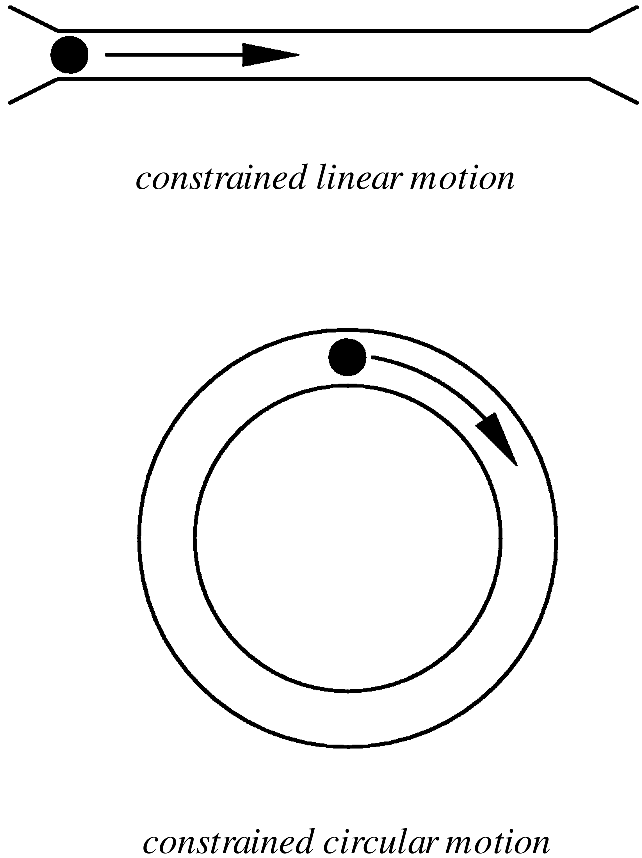


Figure 2. Constrained linear (top) and constrained circular (bottom) motion, adapted from Buxton (1987).



demands, their choice being clearly driven by the application domain—in this case, the development of graphical user interfaces.

The creation of any kind of task implies the problem of quantification of input device performances in each task. Indeed, the existence of an evaluation methodology for *target acquisition*—Fitts's Law—has made it the most widely used among the proposed tasks.

We will here provide a detailed review the various developments concerning evaluation tasks and methodologies in HCI using Fitts's Law as a starting point. Although some of these techniques may initially seem unrelated to musical performance, it will become clear why these are important at later stages of the discussion.

Fitts's Law

Although it was originally proposed for describing movement time when subjects moved a stylus back and forth between two targets as quickly as possible, Fitts's Law has been shown to hold for many other tasks related to aimed movements, such as one-shot movements, throwing darts at a target, underwater movement, object manipulation under a microscope, etc. (Rosenbaum 1991). The first to use Fitts's Law for the evaluation of input devices in HCI were Card, English, and Burr (1978), who compared the performance of a mouse, an isometric joystick, and keys on a text selection task. This study has become the reference for the area of input evaluation, influencing subsequent research.

Fitts's Law, Original Formulation

Fitts (1954) proposed a formal relationship, later known as Fitts's Law, to describe human performance (in terms of a speed–accuracy tradeoff) in aimed movements:

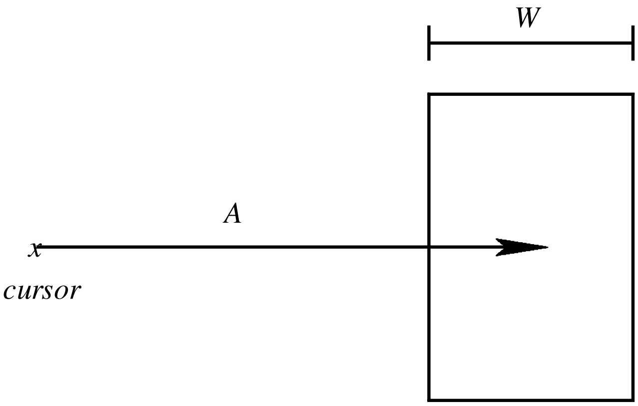
$$T = a + b \log_2(2A/W) \tag{1}$$

Fitts's Law predicts that the time needed to point to a target of width W at a linear distance A away from the initial hand position is T seconds. Constants a and b are empirically determined. The logarithmic term is called the *index of difficulty* (ID, measured in bits), meaning that tasks of greater difficulty present greater IDs. In essence, equation 1 shows that movement time increases linearly with the index of difficulty. The reciprocal of b is called the *index of performance* (IP, measured in bits/sec), representing the human rate of information processing for the movement task under investigation (MacKenzie 1992). Figure 3 shows a discrete target acquisition task.

Fitts's Law, Shannon Formulation

Various refinements in the original model have been presented. For instance, MacKenzie (1992) pro-

Figure 3. A discrete target acquisition task using a cursor, adapted from MacKenzie (1992).



posed another version of the original Fitts's Law formulation that always gives a positive rating for the index of difficulty.

$$T = a + b \log_2(A/W + 1) \tag{2}$$

This new form is known as the *Shannon Formulation* and is the most commonly used formulation of Fitts's Law in HCI today.

Interest and Applicability of Fitts's Law

The main interest of Fitts's Law is that it allows the translation of the performance scores from different devices into indexes of performance. These indexes are assumed to be independent from the experimental conditions used in the various tests, allowing the direct comparison of the performances of different devices.

Concerning the applicability of Fitts's Law to HCI, more than just its formulation has been subject to improvements through the years. Also, the meaning of independent variations in A and W have been recently challenged. According to Guiard (2001), there are only two variables that can be manipulated independently in a Fitts's task experiment: relative movement amplitude, or *movement difficulty* A/W, and absolute movement amplitude, or *movement scale* A. He showed that A and W cannot work as independent factors (both alter the index of difficulty), because varying W with constant A involves movement difficulty, and varying A with constant W involves co-variation of movement difficulty and scale.

Extensions of Fitts's Law

Fitts's Law originally concerned one-dimensional movements. Mackenzie and Buxton (1992) proposed an extension to two-dimensional tasks by using the Shannon formulation and considering an alternative interpretation of target width for two dimensions.

Guiard, Beaudouin-Lafon, and Mottet (1999) attempted to extend Fitts's Law to navigation. Navigation is defined as the metaphor of movement inside a complex environment that is only partially accessible to the senses. Guiard et al. have shown that the Fitts model applies to a variety of navigation tasks that can be considered as a pointing movement over a huge distance, or a *multiscale* pointing. According to Guiard et al., pointing and navigation movements—although involving quite different motor activities—can be equivalently tackled by the proposed model, even when presenting different coordinate systems. This is true because both pointing and navigation can be treated as moves in task space, i.e., the space that incorporates both the target and the cursor, using the coordinate system that is most appropriate to Fitts's Law.

Meyer's Law

Meyer et al. (Rosenbaum 1991) proposed a relationship describing aimed movements composed of sub-movements:

$$T = a + b\, n\, (A/W)^{1/n} \tag{3}$$

where n is the number of sub-movements performed to reach a target of size W, at a distance A from the hand's initial position, and a and b are constants.

This relationship has been called *Meyer's Law*. Fitts's law can be derived from Meyer's law when n approaches infinity, which represents the case when subjects can make as many sub-movements as they wish.

Steering Law

Recently a model describing user performance in *constrained movement* tasks was introduced. Accot and Zhai (1997) developed a technique for the evaluation of trajectory movement tasks based on constrained motion for different path shapes.

The *steering law* for a generic curved path can be represented by the following equation:

$$T_C = a + b \int_C \frac{1}{W(s)}\, ds \qquad (4)$$

where T_C is the time to move through a curved path C, an arbitrary nonlinear path of variable width $W(s)$; s is the curvilinear abscissa (the integration variable); and a and b are constants. The total index of difficulty for steering through such a path is therefore the integral of the elementary indexes of difficulty.

Selection of Input Devices

Apart from the evaluation of device suitability for a certain task using direct quantitative measures of user performance, other approaches for device comparison/selection have been suggested in the HCI literature. Examples of two such approaches are the comparison of input devices based on their mechanical characteristics and comparisons based on their match to the perceptual structure of a given task.

Taxonomies of Input Devices

The idea behind the proposal of input device taxonomies is to suggest ways of comparing devices according to their basic characteristics. Buxton (1987) proposed a taxonomy of continuous, manually operated input devices. The main characteristics analyzed are the physical variables being sensed (position, motion, or pressure) and the number of dimensions sensed for each variable.

An improvement on Buxton's taxonomy was proposed by Card, Mackinlay, and Robertson (1991). It shows each independent physical variable being sensed instead of the whole device. This taxonomy uses two basic variables (position or force) and their derivatives in each of the six possible degrees of freedom—that is, translation and rotation in the three directions. Furthermore, it includes the resolution of each variable—from discrete to infinite values—as the horizontal position of the variable in each column and the possible combination between the variables (e.g., *merge*, *layout*, or *connect*) indicated by the type of line connecting the variables.

Integrality Versus Separability of Input Devices

It has been suggested that the evaluation of existing input devices should be shifted from the analysis of their mechanical structure to the evaluation of their fitness to the perceptual structure of the task to be performed (Jacob et al. 1994). Multidimensional objects are characterized by their attributes. Attributes that are perceived as combined are considered *integral*, while those that remain distinct are considered *separable*. Jacob et al. have shown that devices whose control structures match the perceptual structure of the task will allow better user performances.

Interactive Computer Music

Interactive computer music can be seen as a highly specialized field of HCI, where the interaction between a performer and a computing system engages several complex cognitive and motor skills. An important characteristic of interactive computer music systems is that the goal of the interaction (the performance) is part of the bi-directional communication between the performer and the computer. The performer's gestures are both a part of the choreography and the input for the system; the system's audio output is heard both by the audience and by the performer, who can use it to extract information on the system's status. These peculiarities imply that interactive computer music demands highly skilled users. It therefore departs significantly from the current WIMP model and presents inherent demands. According to Hunt and Kirk (2000),

> In stark contrast to the commonly accepted choice-based nature of many computer interfaces are the control interfaces for musical instruments and vehicles, in which the human

> operator is totally in charge of the action. Many parameters are controlled simultaneously and the human operator has an overall view of what the system is doing. Feedback is gained not by on-screen prompts, but by experiencing the moment-by-moment effect of each action with the whole body. (p. 232)

Live performance with computers deals with such specific topics as simultaneous multiparametric control, timing and rhythm, and training. The relevance of timing and rhythm is another peculiarity of music with respect to typical HCI contexts.

Compared to the commonly accepted approach to the design of input devices in HCI, the design of input devices for musical control—most often referred to as gestural controllers—has traditionally been marked by an idiosyncratic approach. Although various controllers have been proposed, they have usually been developed in response to precise artistic demands. As Buxton notes, it is probably for this reason that the design of controllers for computer music benefits from an unusually high amount of creativity, in particular if compared to better-structured fields where the tendency to follow guidelines may inhibit the appearance of innovative designs (Wanderley and Battier 2000). The counterpart of this creativity is the lack of commonly accepted methodologies for evaluating existing developments, which hinders the comparison of different controllers and the evaluation of their performances in different musical contexts. This in turn inhibits the widespread use of such devices.

Applications of HCI Results to Music

Regarding the comparison of existing gestural controllers and the design of new ones, only a very few attempts have benefited from existing knowledge of HCI.

Navigation in a Multidimensional Space

Vertegaal and Eaglestone (1996) proposed the comparison of several input devices in a timbral navigation task. In this study, three devices were used to navigate in a four-dimensional timbre space. Users were asked to reach a given timbre with each device. An evaluation of users' movement time and errors was carried out.

Taxonomy of Gestural Controllers

Another direct application of HCI methodologies is presented in Figure 4 (Wanderley and Depalle 1999; Wanderley 2001), which shows a comparison of gestural controllers using the taxonomy presented by Card, Mackinlay, and Robertson (1991). Six controllers are compared, with respect to their degrees of freedom, the physical variables sensed, and their resolution.

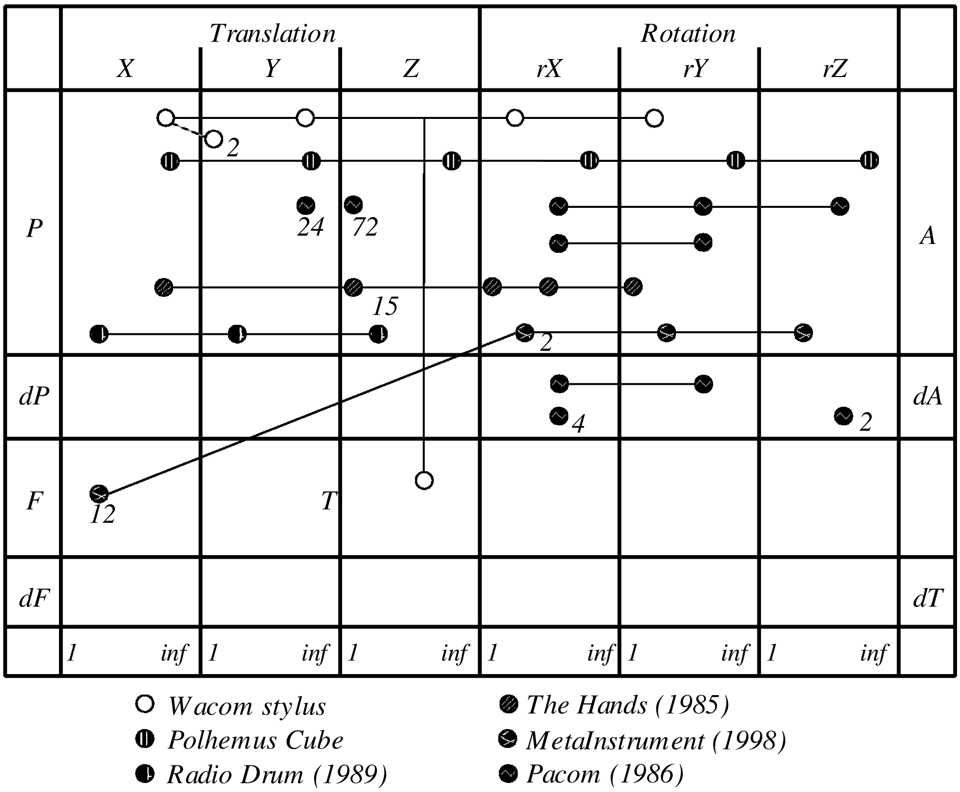
Although presenting important information at a glance, this taxonomy cannot be easily applied to all the controllers that have been developed for interactive music, many of which use more complex interactions than translations and rotation. For instance, controllers that capture the shape of the body or of a body part, like the interface developed by Nicola Orio that is controlled by the internal geometry of the mouth (Orio 1997), do not give a clear concept of translation and rotation. The same could be said about controllers based on the recognition of patterns of facial expression (Lyons and Tetsutani 2001).

Design Methodologies

Concerning the design of new controllers and the applicability of results from other fields, again only a few attempts have been proposed (Pressing 1990), and these were not necessarily related to the application of HCI methodologies.

Vertegaal, Ungvary, and Kieslinger (1996) presented a methodology to match transducer technologies to musical functions, taking into account the types of feedback available with each technology. They proposed diagrams where transducer technologies are rated with respect to their suitability to perform a certain musical function and their intrinsic feedback properties. The implications of such research are significant. In fact, if it can be shown that the proposed match holds true, then a designer would benefit from already existing directions on

Figure 4. An application of the taxonomy of Card, Mackinlay, and Robertson (1991) to various gestural controllers and a three-dimensional tracker.



which sensor to use for each musical task and the type and amount of feedback that will be available for a certain choice. The question remains how to evaluate the methodology proposed by Vertegaal, Ungvary, and Kieslinger, because the authors have not presented empirical evidence of its validity. How can one ascertain that what has been proposed will surely apply in every circumstance?

As an attempt to answer this question, Wanderley et al. (2000) presented exploratory data analysis of user performance on specially defined musical tasks. Although it consisted of a qualitative evaluation (users were asked to rank the different sensors according to six discrete levels from "excellent" to "null"), some hints on possible preferences of sensors to perform certain musical functions have been found. For instance, the isometric force sensor ranked best when compared to the linear displacement sensor when performing a relatively dynamic musical function (e.g., modulation of the frequency of a continuous tone).

But apart from the question related to the validity of the relationship itself, perhaps the most interesting problem raised in this work was the definition of the musical task to be evaluated. As seen before, in HCI a series of basic tests are used as indicators of the usability of input devices. But how "basic" can a test be when it refers to musical tasks? As mentioned before, interactive computer music is related to the simultaneous control of multiple parameters and includes questions related to timing, rhythm, and training that are not usually present in HCI. Therefore, is pointing alone an interesting musical task? If so, in which circumstance? How far can one simplify the musical context to isolate few—possibly one—variables of interest? Moreover, what is the role of qualitative versus quantitative measurements in the evaluation of musical tasks? To approach the above questions, let us first put into perspective the various contexts related to interactive computer music.

Contexts in Interactive Computer Music

We believe results from HCI can suggest methodologies for evaluating controllers, provided the context of interaction is well defined. The contexts—sometimes called "metaphors for musical control" (Wessel and Wright 2002)—in which interactive computer music systems are used and for which they are designed can vary enormously. These different contexts are the result of the evolution of technology, allowing, for instance, the same input device to be used in different situations, for instance to generate tones or to control the temporal evolution of a set of pre-recorded sequences. Although these two example contexts traditionally corresponded to two separate roles in music (those of the performer and the conductor, respectively), the differences between these two roles today have been minimized. Moreover, new contexts derived from metaphors created in HCI are now current in music. In fact, in some of these contexts, the primary goal of the interaction may radically differ, and sound production may just be a secondary channel of communication.

We present below a list of contexts commonly found in interactive computer music, from the most traditional to the most recent:

1. *Note-level control*, or *musical instrument manipulation* (performer-instrument interaction), i.e., the real-time gestural control of sound synthesis parameters, which may affect basic sound features as pitch, loudness and timbre.
2. *Score-level control*, for instance, a conductor's baton used to control features to be applied to a previously defined—possibly computer generated—sequence.
3. *Sound processing control*, or *post-production activities*, where digital audio effects or sound spatialization of a live performance are controlled in real time, typically with live-electronics.
4. *Contexts related to traditional HCI*, such as *drag and drop*, *scrubbing* (Wessel and Wright 2001) or *navigation*; some of these contexts can also be part of other metaphors, such as timbre control in a musical instrument manipulation—a sort of navigation in a multidimensional space.
5. *Interaction in multimedia installations*, where one person's or many people's actions are sensed to provide input values for an audio/visual/haptic generating system. This context differs from the above ones because it does not require a skilled user who knows precisely how to interact, hence the primary goal of the interaction is not necessarily the expression of some information, but may for instance be the exploration of a physical space.

To this list we can also add other metaphors, keeping in mind that in the following cases the generation of sound is not necessarily the primary goal of the interaction (Wanderley, Orio, and Schnell 2000):

6. *Interaction in the context of dance/music interfaces*, where the main focus may be on the choreography of dancers' movements, which are typically sensed through ultrasound devices or cameras; here, music is often a secondary channel of communication with the audience, and hence sound generation may not be the main goal of interaction.
7. *Control of computer games*, that is, the manipulation of a computer game input device, although in this case the primary goal of the interaction is amusement rather than performance.

It should be clear that the above list of contexts is intended to aid in the analysis of different devices and is not a fixed classification. In fact, some devices cannot easily be classified into any of the above metaphors. Examples of devices not easily classifiable include the Global String (Tanaka 2000) and the Jam-O-Drum (Blaine and Perkis 2000).

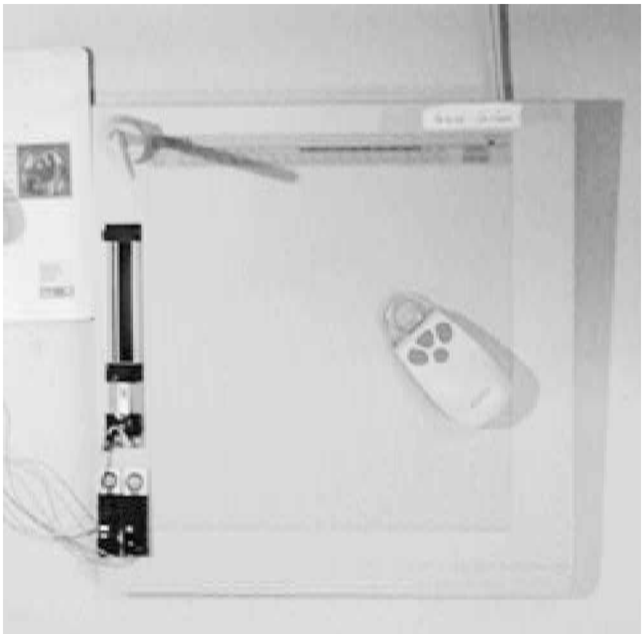


Figure 5. The graphical tablet and extra sensors used for the experiments described by Wanderley et al. (2000).

Different Contexts, Same Device

As an example of the use of the same input device in different contexts, consider the case of a graphical drawing tablet. Apart from the pioneering use of graphics tablets as part of the compositional systems SSSP (Buxton et al. 1979) and UPIC (Raczinski and Marino 1988; Roads 1996), more recent tablet models have been used with the "drag and drop" metaphor as the input device of a sort of gesturally controlled sequencer (Wright, Wessel, and Freed 1997). The graphics tables has also been used in the more traditional musical instrument manipulation metaphor, either part of the simulation of an acoustic instrument (Serafin et al. 1999) or as an input device for the prototype system used for the evaluation of user performance mentioned above (Wanderley et al. 2000; see Figure 5).

Therefore, to analyze and evaluate interactive systems, we must clarify the metaphor in which the system is being used. How did the above tablet behave in the three cases? Was it more suitable for one metaphor or another?

Perhaps the most obvious metaphor of interaction in music is the manipulation of a musical instrument by a performer (the first context mentioned above). Viewing a computer as a musical instrument provides access to a large range of resources of musical literature and traditions for the evaluation of controllers, even if many existing applications reproduce a situation that is closer to the interaction between a conductor and an orchestra (i.e., score-level control). This leads to different constraints and observations.

We will focus on the instrument-manipulation context owing to the limitations of space in this article. Specifically, we will consider the case of digital musical instrument manipulation, in which a human performer and a computer system interact to generate the sound. In this scenario, one or more input devices translate a performer's actions into input variables that control the system.

Evaluation of Interactive Music Systems

Once the context is chosen, it is necessary to find a suitable approach for the evaluation of interactive music systems. We decided here to focus on *musical tasks*. Musical tasks are already part of the evaluation process of acoustic musical instruments, because musicians and composers seldom choose an instrument without extensively testing how specific musical gestures can be performed. For well-known musical instruments, this task is facilitated thanks to the vast music literature available. This is not the case of interactive music instruments that have a limited, or even nonexistent, literature. Hence, it seems natural to extend the concept of musical tasks to controllers.

Research in HCI shows that tasks, to be effective, should allow performances to be measured. The question here is whether this measurement must necessarily be quantitative, as in the case of HCI. In music, it must be noted that controllers cannot be evaluated without taking into account subjective impressions of performers, ruled by personal and aesthetic considerations. In fact, when skilled performers try a new instrument, rarely is a quantitative measurement of the instrument's characteristics the initial goal.

From HCI research, it appears that musical tasks should in general strive for maximal simplicity.

Even though it may seem entirely non-musical, the use of a few simple tasks may help in a first step in evaluating controllers.

Usability of Controllers

With the goal of highlighting the most suitable musical tasks, we believe that some features are particularly relevant for the usability of a controller and can be used as guidelines for the development of musical tasks. These features are mostly related to digital instrument manipulation, but they could be extended to other metaphors such as the control at score-level and the activities of post-production.

"Learnability"

It is essential to take into account the time needed to learn how to control a performance with a given controller. Lehmann (1997) proposed that a musician needs more than ten years to master a musical instrument, a time far too long for any kind of measurement in the world of controllers. Nevertheless, learning to play a second instrument takes less time, because the acquisition of musical ability is not only kinesthetic, but also tonal and rhythmic (Shuter-Dyson 1999). Musical tasks thus should account for the time needed to learn how to replicate simple musical gestures by experienced musicians.

"Explorability"

A characteristic of interest is the possibility of exploring the capabilities of the controller, that is the number of different gestures and gestural nuances that can be applied and recognized (Orio 1999). Explorability is then related to controller features (e.g., precision and range) and also to the adopted mapping strategy. Musical tasks may be then based on the use of sound examples that the performer is asked to replicate.

Feature Controllability

A musical performance is based on the continuous changes of sound parameters. Accordingly, it is important to account for how the user perceives the relationship between gestures and changes in the performance features and the level at which these features can be controlled. The accuracy, resolution, and range of perceived features should be determined by musical tasks. It is important to stress that the focus is on what the user perceives rather than on the actual values of the control parameters. It may happen that a controller will appear totally inadequate for some musical tasks (for instance, due to a reduced accuracy in pitch control) and perfectly fit for others (for instance, when the same device is used to control timbral features), owing to the inherent functioning of our perceptual system.

Timing Controllability

A characteristic of music that differentiates it from the classical HCI context is the central role of time. The classical evaluation used in HCI (i.e., Fitts's Law) takes into account the time needed to perform a given task. On the other hand, a great part of a musician's skill consists of performing a given task with very precise timing (Gabrielsson 1999). Time becomes a constraint rather than a variable to be measured. This means that musical tasks should also allow measuring of the temporal precision at which the musician can control the performance and its relationship to tempo.

Proposed Musical Tasks

Given the guidelines introduced in the previous section, we can highlight a number of potential musical tasks. It is clearly impossible to cover all the features of a controller unless an unbearable number of musical tasks is considered. We think that performances of musical tasks should help give a general description of a controller without completely avoiding the need to directly use and try it. To this end, it is possible to consider musical tasks as a way to create a sort of benchmark. Knowing the capabilities of a controller in a musical context, however simplified it may be, should be more useful than—or at least complementary to—knowing quantitative data about single features regarding the output rate, the number of voices, or the precision in detecting gestures.

Musical Instrument Manipulation Metaphor

Tasks can be related to the control of pitch, including *isolated tones*, at a number of different frequencies and with different loudness; *basic musical gestures*, like glissandi, trills, vibrato, and grace notes; and *musical phrases*, from scales and arpeggios to more complex contours with different speeds and articulations. Tasks could be extended to include continuous timbral changes for a given note (or phrase) at a given loudness. Moreover, because time is a central feature in music, musical tasks should also cover performances of different rhythms with increasing tempo and precision in synchronization with external signals.

For each of these tasks, a measure indicating the degree of polyphony is to be added. The controller performances for these tasks can be based on the performer's—and possibly the audience's—perceptions represented on a subjective scale, for instance from "very easy" to "almost impossible." To consider the difficulty in learning to use a new controller, we can envisage including a measurement of the amount of practice time that preceded performance with the controller.

Other Metaphors

Although we focus on the manipulation of digital musical instruments, we also present here a short list of tasks possible for some other metaphors. Considering that control at the score-level metaphor is related to the conductor-orchestra interaction, corresponding tasks could include *triggering of sequences*, indicating how many simultaneous sequences can be controlled; *continuous feature modulation*, regarding timing and amplitude envelopes of sequences; and *synchronization of processes*, when two or more sequences may start at different moments and, for example, finish together. These tasks may also be extended to control of sound processing, where the control of post-processing audio effects can be substituted for the triggering of sequences mentioned above.

Considering HCI-related metaphors, a more direct application of the methods and measurements previously reviewed in this article is possible. In fact, the quantitative measurements of a user's performance (movement time and accuracy) in the timbre space navigation task performed by Vertegaal and Eaglestone (1996) was very similar to traditional measurements in HCI, because the task could be considered a target-acquisition task in a four-dimensional space.

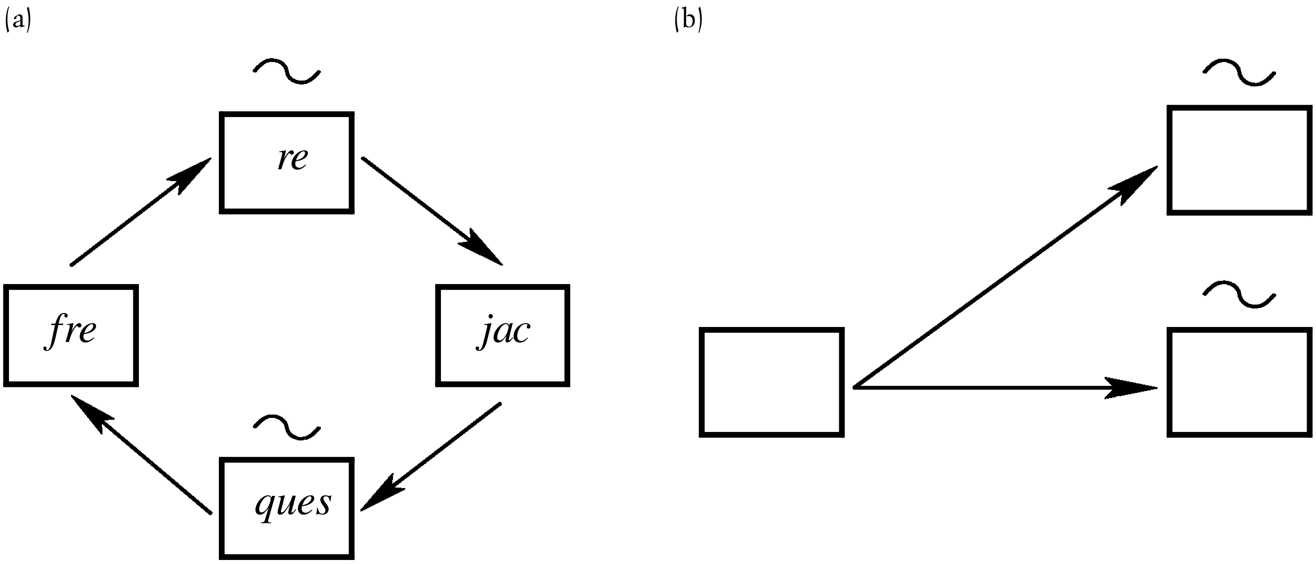
Example: Combination of Simple Tasks

The basic tasks suggested above can be helpful tools in discussing the usability of a controller. In addition, simple combinations of basic tasks can improve the musicality of the final task without necessarily giving up possibilities related to measurements.

An example of a combination of two basic tasks has been presented in Wanderley et al. (2000a), where subjects were asked to perform different musical tasks by moving a stylus on the graphical tablet shown in Figure 5. The definition of the musical tasks was a major topic of the experiments. In fact, different tasks have been proposed and tested. These varied from the use of a piano keyboard mapped onto the tablet's surface (from which the subjects had to select the correct pitch from a melody) to the use of circular paths (see Figure 6a) to reduce the cognitive demands on the user, and finally to a target acquisition task (see Figure 6b). These initial tasks were followed by supplementary actions applied to specific notes, specifically the absolute and relative movements needed for the subject to reach a particular note.

The task finally selected and evaluated was a simple continuous feature modulation task that was performed after the user had generated a transition between two isolated tones. In other words, considering Figure 6b, the total task consisted of first moving the tablet stylus from one rectangle (discrete tone) to another (another discrete tone)—a target acquisition task—and only then performing the continuous feature modulation task. The feature modulation task was actually the only one to be evaluated; no evaluation of the movement be-

Figure 6. Suggestions of musical tasks used for the evaluation of the match of transducer technologies and musical functions. (a) A circular task. (b) The task finally selected and evaluated by Wanderley et al. (2000).



tween the two tones was performed. This methodology was loosely inspired by the real situation faced by string instrument players when performing a vibrato. Usually, an absolute musical function is first performed (i.e., selecting a position on the string), and only then a relative function (i.e., the vibrato) is executed. In this case, the total task was closer to the bending of a note in a guitar than to the vibrato performed in a violin, because the modulation just added frequency to the basic note. This total task can be regarded as the imposition of an initial musical condition to the final basic task to be evaluated.

Comparison with HCI Research

One can draw a parallel between some musical tasks and the tasks discussed in the HCI literature. In particular, target acquisition may be similar to the performance of single tones (acquiring a given pitch as well as a given loudness or timbre), while constrained motion may be similar to the performance of specific phrase contours. Other musical tasks are peculiar to music; for instance, those related to timing and rhythm have no parallel in classical HCI. We believe that in this case it is possible to pinpoint general laws, for instance related to the learning time or the maximum speed allowed by a given controller, that could be useful for future designs. Extensive research may help in the definition of such laws.

The use of musical tasks may also aid in the evaluation of existing controllers by defining the set of musical gestures a controller can perform, together with an indication of the ones each controller performs best. Of course, the evaluation of controllers extends beyond the mere comparison of different devices. Such evaluation may help artists and performers carefully choose and reuse existing technologies for the realization of new works.

The definition of a "chart of controllers" that summarizes the main characteristics of available controllers can be a step towards a more systematic approach to the design and use of controllers in music. Nevertheless, we believe that the charting of well-defined musical tasks is more suitable for musical aims. This is mainly because of the crucial roles of mapping (Hunt, Wanderley, and Kirk 2000) and sound synthesis in the overall performances of a controller that cannot be only analyzed in terms of mechanical characteristics. Controllers can only be evaluated by assuming the user's point of view.

Conclusions

In this article, we have presented a review of various methodologies for the evaluation of input devices from HCI and discussed their applications to the musical domain. A particular focus has been given to the use of specific tasks that are used in HCI to measure the performance of an input device. This approach suggests applying a similar methodology for the evaluation of controllers in the context of interactive music. The concept of musical tasks has been proposed as an initial step to this end.

The presence of an evaluation methodology can be useful both for designers, who can take advantage of previous results, and for composers and performers, who can have a reference of how and what can be done with a given controller. Moreover, we believe that the great creativity that characterizes the field of interactive music will not suffer from a more formalized approach.

Finally, we believe that a bidirectional flow of knowledge between classical HCI research on input devices (dealing mostly with pointing and dragging material on graphical interfaces) and the design of new digital musical instruments can lead to substantial improvements in both fields.

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