Exploratory and Creative Properties of Physical-Modeling-based Musical Instruments

Developing a framework for the development of physical modeling based digital musical instruments, which encourage exploration and creativity

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Exploratory and Creative Properties of Physical-Modeling-based Musical Instruments

Developing a framework for the development of physical modeling based digital musical instruments, which encourage exploration and creativity

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Abstract

Digital musical instruments are developed to enable musicians to find new ways of expressing themselves. The development and evaluation of these instruments can be approached from many different perspectives depending on which capabilities one wants the musicians to have.

This thesis attempts to approach development and evaluation of these instruments with the notion that instruments today are able to facilitate the creative process that is so crucial for creating music. The fundamental question pursued throughout the thesis is how creative work processes of composers of electronic music can be supported and even challenged by the instruments they use. What is it that makes one musical instrument more creatively inspiring than another, and how do we evaluate how well it succeeds?

In order to present answers to these questions, the thesis focusses on the sound synthesis technique of physical modeling. I investigate how various control elements such as explorability, mapping, intuitiveness, perceived causality, physicality, unpredictability, accuracy, connectivity, freedom and constraints can affect the overall creative potential of a physical modeling based musical instrument.

Initially, an interface for creative and exploratory control of physical models is developed leading to the formulation of a framework, that is explored throughout the thesis. This is followed by an investigation into the work process of composers of electronic music with special focus on creativity. Several instruments are then developed in order to concretize and improve the aforementioned framework. Finally, the thesis implements two methods for evaluating musical instruments with a focus on creativity. Both methods emphasize the importance of musical context.

Resumé

For ph.d.-afhandling ved Aalborg Universitet København, Institut for arkitektur, design og medieteknologi af Steven Gelineck:

"Musikinstrumenter baseret på fysisk modelering og deres egenskaber i forhold til udforskning og kreativitet"

Digitale musikinstrumenter bliver udviklet for at gøre musikere i stand til at finde nye måder at udtrykke sig musikalsk. Udvikling og evaluering af disse instrumenter kan gribes an fra mange forskellige perspektiver afhængigt af, hvilke egenskaber man ønsker at videregive til musikeren.

Tilgangen til denne afhandling har været at udvikle og evaluere nye digitale instrumenter med bevidsthed om at instrumenter skal kunne facilitere den kreative proces, der er så afgørende for skabelse af ny musik. Det grundlæggende spørgsmål, der forfølges igennem afhandlingen er, hvordan elektroniske musikeres kreative arbejdsprocesser faciliteres og endda udfordres af de instrumenter, de bruger. Hvad er det der gør et musikinstrument mere kreativt inspirerende end et anden, og hvordan kan vi evaluere, hvor godt instrumentet virker i den henseende?

For at præsentere nogle svar på disse spørgsmål, fokuserer afhandlingen på en specifik lydsyntese-teknik, nemlig fysisk modelering. Jeg undersøger, hvordan forskellige kontrolelementer såsom udforskning, intuitiv mapping, opfattet kausalitet, kropslighed, uforudsigelighed, nøjagtighed, tilslutningsmuligheder, frihed og begrænsninger kan påvirke det samlede kreative potentiale i et musikinstrument, der er baseret på fysisk modelering.

Afhandlingen starter med udviklingen af en fysisk grænseflade for udforskende og kreativ kontrol af fysiske modeller, som ligger til grund for formuleringen af en udviklingsramme, der danner basis for hele afhandlingen. Dette efterfølges af en undersøgelse af elektroniske musikeres arbejdesprocesser med særligt fokus på komposition og kreativitet. Adskillige instrumenter er herefter blevet udviklet med henblik på at konkretisere og forbedre førnævnte udviklingsramme. Endeligt præsenterer jeg to metoder til evaluering af musikinstrumenter med fokus på kreativitet. Metoderne understreger vigtigheden af musikalsk kontekst.

Papers included in the thesis

PAPER I Böttcher, N., S. Gelineck, and S. Serafin. (2007). Physmism: Re-introducing physical models for electronic musical exploration. *In Proceedings of the International Computer Music Conference.* Copenhagen, Denmark

PAPER II Gelineck, S. and S. Serafin. (2010). A practical approach towards an exploratory framework for physical modeling. *Computer Music Journal 34*(2), 51–65.

PAPER III Gelineck, S. and S. Serafin. (2009). A quantitative evaluation of the differences between knobs and sliders. In *Proceedings of the International Conference on New Interfaces for Musical Expression.* Pittsburg, PA.

PAPER IV Gelineck, S. and S. Serafin (2009). From idea to realization - understanding the compositional processes of electronic musicians. In *Proceedings of the Audio Mostly Conference.* Glasgow, Scotland.

PAPER V Gelineck, S. and S. Serafin (2010). Phoxes - modular electronic music instruments based on physical modeling sound synthesis. In *Proceedings of the 7th Sound and Music Computing Conference.* Barcelona, Spain: online under the Creative Commons License.

PAPER VI Gelineck, S. and S. Serafin (2011). Longitudinal Evaluation of the Integration of Digital Musical Instruments into Existing Compositional Work Processes. Submitted for publication in *Journal of New Music Research*.

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Contents

Part I

Introduction

Chapter 1

Physical Modeling and Creatively Inspiring Digital Musical Instruments

Digital synthesis techniques today provide possibilities to explore timbre spaces that traditionally have been fixed by physical constraints in the analogue world. With the processing power of todays computers most of these techniques can be manipulated in realtime rendering them closer to musical instruments than engineered audio algorithms. The musical potential of a given synthesis technique lies in e.g. the overall timbre, sonic quality, sonic range, and temporal structure of the technique itself. However, without providing an appropriate control of those properties the technique will never reach this potential. How can a synthesis technique materialize into useful instruments or tools for musicians and composers in order to be utilized to its true potential? That has been the driving problem throughout this thesis.

Traditionally, when developing new digital musical instruments, the goal has been to merge the best of what traditional acoustic instruments have to offer with the flexible possibilities of the digital (Jordà, 2002; Overholt, 2009; Wessel and Wright, 2002; Cook, 2001). One may look to acoustic instruments to see what hundreds of years of practice has shown to work (playability, expressivity, virtuosity, etc.) trying to make use of existing playing techniques, mimicking interaction paradigms, and so on. One of the greatest advantages of the acoustic instrument is it's balance between completely natural, intuitive affordances (Norman, 1999), and subtle though infinite sonic diversity that on one hand helps novices understand the instrument instantaneously while on the other hand making the instrument interesting enough to make players use all their life exploring and perfecting it.

The major challenge lies within the conceptual differences between the acoustic and the digital instrument. The control mechanism and sound production mechanism are no longer inseparable functions that are interconnected within the instrument. Synthesis algorithms can be controlled in any way the developer sees fit, which gives an unprecedented freedom to create amazing and impressive sonic outcome. What developers of digital musical instruments do with that freedom is the interesting question pursued in this research domain.

While physical modeling sound synthesis has shown a lot of potential for decades, this has not yet resulted in a successful reception within commercial music making[1]. Why not? This has been a highly motivational question asked throughout the thesis. In order to answer this question I have taken a user centered approach, where the goal has been to develop physical modeling based musical instruments that facilitate the needs of the contemporary

[1] Recently though, there has been a small breakthrough within commercial software implementing physical modeling — mostly within virtual MIDI instruments.

electronic musician. The design and development of the instruments has thus been situated in the context of the musician's creative work processes.

1.1 Background

An important aim of the thesis has been to underline the importance of understanding context in which the development of new musical instruments takes place. The role of a musical instrument can change enormously depending on the context in which it is to be used. It will determine what are the main issues or focus points when designing, developing and evaluating such an instrument. For instance developing a musical instrument for teenagers to compose fun ringtones for their mobile phones on the go is completely different from developing an instrument for the trained jazz musician meant for an improvisational jam session.

It is important to note that the context in which this thesis is situated does not as such exclude other possible contexts. As should be apparent throughout the thesis generalization is problematic in this field, and musical approaches are often quite individual. When situating the development of a musical instrument within a musical context it is in most often not a case of 'either or', but more 'to what extent?' (example: a sampler can be used to a large extent when making music in a compositional setting but is also used occasionally in performances.)

There are different approaches to understanding context and context can be defined on different levels. For instance, Abowd and Mynatt (2000) present a minimum set of elements that can be used to form the context; *who, what, where, when*, and *why*. Dey and Abowd (2000) present a very good overview of context (including various definitions) while focussing on the field of context awareness in interactive applications within ubiquitous computing. They end up defining context as being:

> *"any information that can be used to characterize the situation of an entity, where an entity can be a person, place, or object."*

This definition leaves room for approaching context at different levels of detail. The context throughout this thesis has been concerned with the user (contemporary experimental electronic musician), the activity of the user (creative use in composition), and the role of the instrument in that activity. These are described in greater detail in the following.

The user

A large part of the initial motivation of this thesis was to try to understand why physical modeling was not more broadly used in contemporary (and commercial) electronic music. The great potential of the technique seemed to mainly be exploited in academia where most of the instruments were developed for specific integration into one specific performance or project (Janer, 2005; Van Stiefel and Cook, 2004; Kojs and Serafin, 2003; Kojs, 2007; Gluck et al., 2007). The aim here has instead been to focus on contemporary, commercial electronic musicians. By understanding their musical skills, work practices, experiences with existing instruments, approaches to music making, etc., it is possible to understand how to develop for certain types of musical interaction.

Throughout the thesis contemporary musicians from the Danish electronic music scene have been used both to inform the development of the design framework and in evaluation. I have intentionally sought out musicians with an experimental approach in their music making. This means that while they might have very fixed ideas of genre, sound, aesthetics and so on, they have an openness to new musical instruments, tools or environments. This also means that they for instance have a larger focus on timbre than on established musical structure (linear progression, ABABCB, ...).

The electronic musicians targeted here can be largely distinguished from other types of musicians within Western music culture (orchestral, jazz, pop, etc.) in the way that they consistently act as both composers and musicians. The traditional distinction between a musician and composer, where the composer writes a piece of music using some form of notation for other musicians to play on a certain instruments doesn't apply. There tends to be an interplay between different activities, where the electronic musician plays many roles almost simultaneously (Jensenius, 2007). As is stated by Drummond (2009):

> *"Interactive systems blur these traditional distinctions between composing, instrument building, systems design and performance."*

This makes it difficult to regard the electronic musician as a musician in the traditional sense. O′Modhrain (2011) also emphasizes the difficulties resulting from the fact that;

> *"Performers are often the composers of the music they play and may also be the designers of their instruments".*

Especially within commercial electronic music, it is rare to find one single solo instrument, that is studied for decades, as seen in other genres. Rather, musicians work years on developing a certain musical speciality, working with a certain setup or working with a certain approach to music making.

Throughout this thesis a distinction between the activities associated with performance and activities associated with composition has been made—although the activities to a large extent influence each other. While acknowledging that the electronic musicians can take on many simultaneous roles, the focus has been on the compositional setting of making music in the studio. The following section will go more into depth with this compositional setting.

The exploratory compositional setting

Focussing on the compositional setting means targeting a specific way of interacting with an instrument. The interaction involved when contemporary electronic musicians compose a pieces of music differs a great deal from when they express themselves during a performance. In the compositional setting the user can play the instrument in many different ways and may have many different approaches as of how to gain from using the instrument. Often instruments are used in unintended ways by for instance connecting them to other instruments or musical tools, sampling only microsounds or using them to generate sound that can be used as a basis for something else (for example additive/subtractive/granular synthesis).

Sarath (1996) regards composition and improvisation to be:

> *"the same process undertaken at different speeds."*

The same sort of interaction takes place, however in the compositional activity the composer can revisit any section of the composition at anytime, letting choices regarding future events influence former ones, re-order events, edit already recorded events and so on and so forth. This is particularly true for the experimental electronic musician as the composition is often constructed using a form of audio sketching, where compositions are built up not using pen and paper and traditional notation, but by recording sound that undergoes an iterative series of refinement, re-definement, and perhaps complete transformation before ending up turning into the actual piece. Notation seems to be used quite rarely, as musical ideas are typically organized either as audio files (either directly in a DAW, or in a hierarchical audio file system), or as notes, sketches or scribbles on paper. The resulting piece is thus formed together with the composition.

Compositional processes have been studied from many perspectives. Eaglestone et al. (2001) presents a nice review of various methodological issues associated with the study of compositional processes with focus on how tools can support the creative activity of composition. Polfreman (1999) analyzes compositional processes in order to inform the design of a new software user interface, the goal being to understand the various tasks the composer works on while composing a piece of music, using a task analysis technique from Johnson (1992). Collins (2005) studied a composer over a period of 3 years in order to develop a process model that involved several recursive stages or "richly context-driven solution spaces". Nuhn et al. (2002) studied composers using a multi-dimensional approach similar to that of Collins (2005) including observation, a compositional task, verbalization, interviews, and gathering of computer data. They emphasize that composers often engage in convergent/divergent activities in a "voyage of discovery"-like manner. Bertelsen et al. (2009) interviewed two composers of electronic music, which lead to the argumentation that the creative activity of using music software can not be merely be considered as simple mediation, but rather as chains of complex mediation. Creative music software needs to be moldable, to be connected to each other, to be able to extend its own limitations, the goal being both to create and play new *instruments* but also to find creative inspiration, leading to reconfigurations, new connections, unpredictable use and new *instruments*. The overall activity thus involves a much more complex relationship between user (subject), music (object), and software (tool).

Where composition can be regarded as the overall activity of interest throughout this thesis, I have been more specifically interested in how musical instruments are used within this setting. The compositional setting entails that the user does not necessarily need to strive for virtuosity when developing skills playing a new instrument. With todays technology it is possible to explore an instrument, extracting meaningful sonic potential from the instrument without being an expert player. Consider the novice guitar player not being able to play more than a few chords. In a compositional setting this user can record multiple takes of few chords - cut them up, re-arrange them (even at the micro-/granular level), transpose them, play them backwards, etc. Here the creative potential of the guitar is totally transformed because the potential is formed in a great deal by how the instrument interacts with the existing environment. This does not mean that the notion of control vanishes into the background. It is more transformed, as the control helps determine which sounds are achievable in the first place, and how those can spark creative ideas in the mind of the user[2].

Understanding the compositional environment becomes important when trying to understand the interaction that occurs between user, instrument and existing musical tools. In other words the ways in which the instrument being developed may interact with the whole compositional environment becomes a key design element.

Throughout the thesis the focus has been on the creative, exploratory approach to composition, where the musician explores various ideas, methods, tools, etc. in order to form the composition in an exploratory manner. This is opposite to the approach where the musician starts out by having a concrete idea or goal, and then uses tools at hand to realize the idea (Manning, 2004). In other word the process is not problem/goal driven, but more opportunity driven. In practice both approaches are often used in some iterative

[2] Of course, if the user is an experienced and skilled guitar player the possibilities for interaction increases.

manner, however (as argued throughout the thesis), it can be beneficial to design for one or the other. This involves investigating processes associated with creative exploration, with the development and embodiment of creative ideas, how musical instruments or tools play a role in those processes, and finally how the creative processes can be supported by the instrument.

The musical instrument

Traditionally acoustical instruments are built by having mechanical systems that produce sounds when a person manipulates certain parts of the system. The possible sounds of an instrument are directly coupled to its physical form and to how the person physically acts upon it. This coupling between the manipulation of the instrument and the sound it produces is fixed. The controller (the part of the instrument that the user can manipulate) and the sound generation mechanism are the same. With the advent of computer-based digital synthesis techniques, sounds could be generated by a computer instead of a mechanical system, the control of which can now be facilitated using a separate controller. In other words the controller and the sound generator have been separated[3].

This separation comes with great advantages which in turn poses great challenges. One is no longer bound by the constraints of the physical world making it possible to establish connections between the control layer and the sound production layer for creating and controlling timbres that are unprecedented. The connecting layer is normally referred to as the *mapping* layer. As presented later in this thesis, mapping strategies are a central part in the development of new digital musical instruments. The challenges of establishing a meaningful mapping layer present themselves on several levels. Firstly, one can not simply remove physical constraints on the system level and say that now anything is possible. Cognitive constraints of the user must be taken into account, as a we as humans are limited in our cognitive load (Hertwig and Todd, 2005). This means that new instruments developed to give players many control possibilities might exceed the cognitive capabilities of the player (Jordà, 2008). Secondly, a major challenge has been to achieve a musical 'feel' of such an instrument, as a huge part of the experience when playing an instrument lies in the embodied enactive perception of the causal relationship between the actions of the player and how those relate to the resulting sound (Essl and O'modhrain, 2006; Wessel, 2006).

In order to study these new instruments more systematically a typical approach has been to study either the sound synthesis part, the controller part or the mapping between the two (Levitin et al., 2002; Marshall et al., 2009; Arfib et al., 2002; Hunt and Kirk, 2000; Overholt, 2009). The advantages of this approach is that one achieves a generalizability, as the control structures, mapping strategies, or approaches to synthesis may be used in a wide range of different instruments—what is learnt is not strictly bound to a specific instrument. However, the experience of playing an instrument is most often an integrated experience meaning that controller, sound synthesis model and the mapping between them will often come together in unpredictable ways to form overall experience. Studying the separate parts and their influence on experience is challenging.

The goal of this thesis has been to understand the controller and sound synthesizer as integrated into one instrument—although in reality they are not. In fact, prototypes are developed where controllers only send control data to a computer, that then renders the sound. The goal, however, is to give the users the impression that the systems are

[3]Cook (2004) makes it apparent that this phenomenon appeared long before computers and digital sound synthesis, and gives the example of organ consoles that were separated by the pipes. Of course they are still part of the same mechanical system, but the player doesn't experience the direct physical interaction with the sound generator—the pipes).

integrated. For instance, PAPER III presents a study that tries to investigate the influence of different components of an instrument, but the aim is to do it in a setting where the instrument is perceived as integrated.

Traditionally a musical instrument is regarded as a single performance tool, that is played (rehearsed, explored, used to express, etc.) on its own. It is of course played within different contexts (in a band, orchestra, at a concert, in a studio, etc.) but the instrument in an overall sense is regarded as its own. In this thesis the instrument is regarded as a part of a larger collection of instruments or tools that are used in a mix of functions, depending on the musical approach of the user at a given moment. This is not meant in the sense that the instrument has to be played in conjunction with other instruments or tools. It is just acknowledged that in an electronic music compositional setting the instrument seldom functions alone. While still being able to play the instrument in the traditional sense, the main purpose of the instrument is thus to assist in the compositional process. In all stages of design, development and evaluation throughout this thesis the instrument is regarded more as a compositional music tool than an expressive live solo instrument.

How we define these new instruments differs based on what role they play in the overall musical context. Different terms have been used in the different papers presented in the thesis, as focus has shifted depending on the context of the specific research. The term *electronic instrument* is used as an overall term to describe the instruments that *electronic musicians* use to produce sounds. In other words, the electronic musician that uses the instrument to create electronic music is the main influence on how the instrument is articulated. This term is used in two of the papers (PAPER III and PAPER V) and emphasizes the context of not only the electronic musician but also electronic music as an overall musical genre.

One might argue that because the focus of the thesis is on the *control* of physical modeling that the term controller or interface is more representable. However, the focus has been on integrated instruments that are based on physical modeling or where physical modeling synthesis techniques form the majority of the sound production part of the instruments. In that sense it has not been enough to study only the controller. It has been important to understand the relationship between the specific physical modeling techniques and the integration of those into overall musical instruments or systems.

The digital musical instrument (DMI) is perhaps a more precise term as the synthesis algorithms that form the basis of the sound production are digital. The term is also widely used within the research community (NIME, ICMC, Organised Sound, Computer Music Journal, etc.). Thus, the term *digital musical instrument* has also been used in PAPER II and PAPER VI. This is regarded as a subcategory *electronic music instruments* emphasizing that the instrument is computer based and not comprised of analogue electronic sound producers.

The term *interface* is used in PAPER I as the focus at that stage was on the interaction between human and system. Finally, the term *musical tools* used mainly in PAPER IV is meant to encompass every piece of hardware or software that is used in the process of composing a piece of electronic music in a studio setting. Here the instrument is regarded more as a tool for developing and implementing musical ideas.

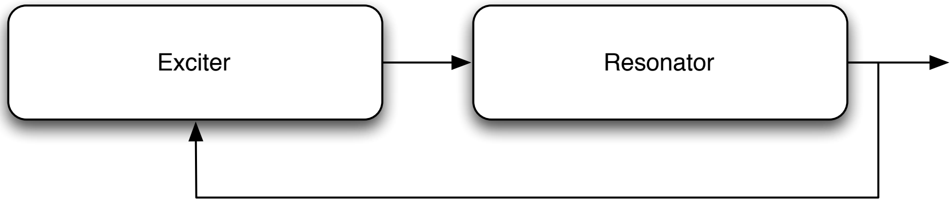

Figure 1.1: Most physical models used today consist of an exciter component and a resonator component (adapted from (Borin et al., 1992)).

1.2 Physical Modeling

As mentioned above, this thesis focusses on the exploratory control of physical modeling sound synthesis. This section presents an overview of physical modeling, including various synthesis techniques, forms of implementation and some initial thoughts on its creative potential.

Physical modeling sound synthesis is a synthesis technique that approaches digital sound simulation from the perspective of sound production. In other words physical modeling emulates physical mechanisms that take place when sound is acoustically produced in the real world. The models take properties found in real world sound producing objects, implementing algorithms that calculate how those objects sound based on the energy exerted into them (forces, velocities, etc..) and their physical properties (length, mass, stiffness, etc..). These techniques differ fundamentally from other synthesis techniques such as AM/FM, granular, additive and subtractive synthesis, which are based on psycho acoustic properties. In other words physical models are, contrary to most other synthesis techniques, modeled based on how sound is produced, not on how we as humans perceive sound.

Since its birth in the start of the 1960s at the Bell Telephone Laboratories (Kelly and Lockbaum, 1962), physical modeling has grown and generated a collection of various techniques which in different ways simulate a wide range of physical and acoustical phenomena. Most of the models can be divided into two components illustrated in Figure 1.1; (1) an exciter component representing how the energy enters and interacts with the model, and (2) a resonator component representing how the the energy resonates through the model (Borin et al., 1992). The exciter component represents the attack part or the transients in the sound being modeled and is often a non-linear component. The resonator component represents the resonating part of the sound, which is most often a linear system simulating linear resonating properties (McIntyre et al., 1983).

Throughout the thesis, four different physical models have been used—all based on the exciter-resonator principle. They have been chosen in order to explore differences in regards to technique, complexity and interaction possibilities. They rely on two overall approaches to physical modeling—digital waveguide synthesis and modal synthesis—both originally developed to produce computationally efficient simulations while still maintaining a high sonic and acoustic quality.

Digital Waveguides

The problem with numerical simulation of acoustic phenomena is, that it is computationally expensive to simulate complex timbres. In 1983, Alex Strong and Kevin Karplus found that injecting white noise into a delay line, which was fed back through a low pass filter would produce timbres that resembled those of a plucked string. This is widely known as the

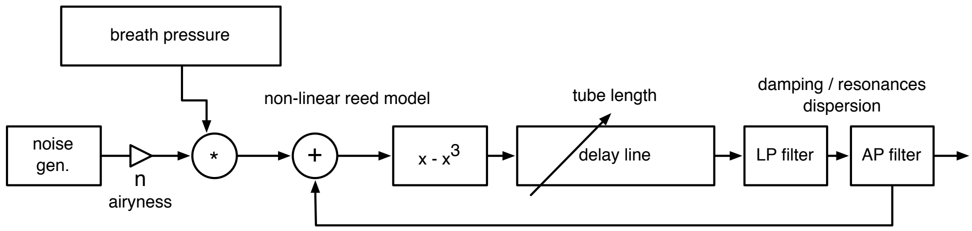

Figure 1.2: Block diagram of the tube model used throughout the thesis (adapted from Cook (1992)).

Karplus-Strong algorithm. The approach was extended by Jaffe and Smith (1983) turning into what is known today as digital waveguide synthesis (Smith, 2008). The general idea is to simulate a vibrating body such as a string or a tube by simulating a wave traveling back and forth in one dimension. This is done by feeding an enveloped noise signal into two directional delay lines. Losses and dispersion are simulated by introducing a series of filters lumped at discreet points (depending on the complexity of the waveguide) keeping the delay lines intact and drastically decreasing computation. The digital waveguide acts as a resonator, which can interact with various exciters to model a variety of structures. The exciter-part of the model determines how energy enters the model and how it interacts with existing waves traveling through the delay lines. For instance the waveguide used to simulate a clarinet and a flute might be fundamentally identical. It is then the difference in excitation mechanism that creates the difference in timbre between the two models[4].

Three of the physical models used throughout this thesis implement resonators that are based on digital waveguides. The last model is based on modal synthesis, which is a pseudo-physical model. The following contains a short description of each of the four physical models. These are; (1) a tube model, (2) a friction model, (3) drum model, and (4) a particle model.

Tube Model

The tube model implements a one-dimensional waveguide for the resonator part for the simulation of waves propagating back and forth through the tube. A simple exciter by Cook (1992) originally used to simulate the nonlinearities of the jet reed of a flute is used for the excitation part of the model. The exciter $(x - x^3)$ expresses the interaction between the energy of the propagating wave from the tube and the incoming energy (breath pressure) through the reed:

$$y = (x_{tube} - x_{reed}) - (x_{tube} - x_{reed})^3 \tag{1.1}$$

where x_{tube} is the wave velocity in the tube, x_{reed} is the incoming pressure from the players mouth and y is the outgoing wave velocity,

The incoming breath pressure is mixed with a variable amount of random noise simulating the airyness of the tube. The energy then propagates back and forth through a delay line (the resonator) with a two zero lowpass filter simulating propagation losses and a one pole one zero all pass filter used to simulate wave dispersion. A block diagram of the model can be seen in Figure 1.2

[4]accurate models will of course also implement differences in the resonator component such as propagation losses, simulate tone holes, etc.

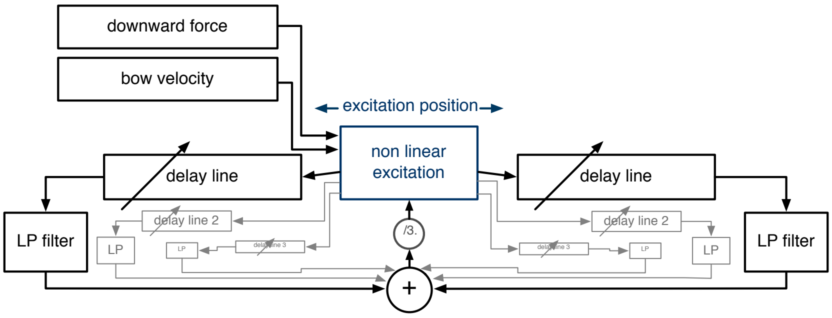

Figure 1.3: Block diagram of the friction model used throughout the thesis (adapted from Avanzini et al. (2002)).

Friction Model

The friction model is based on the Elastoplastic model originally developed by Avanzini et al. (2002) for modeling friction between two dry surfaces and extended to simulate a bowed string (the latter approach is used here). The model uses the exciter resonator principle implementing a digital waveguide as the resonator and a non-linear bow-string interaction model as the exciter. Figure 1.3 shows a block diagram of the model, which implements two delay lines for simulating waves that propagate in both directions back and forth from the excitation point. The delay lines vary in length based on the overall length of the string and the excitation position. Lowpass filters are lumped at both ends of the resonating string (nut and bridge) simulating the frequency dependent damping throughout the string.

The exciter models interaction between the incoming wave from the resonator and the stick/slip friction mechanism between the bow and the string. As the string is bowed the bow sticks to the string and pulls it until a certain point, where the force exceeds a certain threshold causing the string to slip back until it again sticks to the bow. This produces an oscillating wave that propagates throughout the string. The breakaway threshold is dependent on the downward force applied by the bow onto the string and the relative velocity between the bow and the string. It also depends on the temperature dependent friction coefficient, which models the plastic deformations of the rosin on the bow (Smith and Woodhouse, 2000) (this has an influence on how well the bow sticks to the string). In order to model the stick/slip behavior between the two surfaces the notion of bristles attached to one of the surfaces is introduced—see Figure 1.4. Each bristle acts as a spring accounting for a fraction of the overall friction load. Strain on each bristle is proportional to the friction load. As the strain exceeds a certain level the bristles start to slip according to the elasto-plastic model (Avanzini et al., 2002). The elasto-plastic model extends the LuCre model (Canudas de Wit et al., 1995) by introducing a breakaway displacement to avoid drift at small forces. The exciter model thus computes the new outgoing wave determined by the sum of incoming waves, the downward force of the bow, the transversal velocity of the bow and the friction coefficient. Finally, in order to simulate more diverse friction sounds the model is enhanced by implementing a total of three resonators, which all interact at the excitation point.

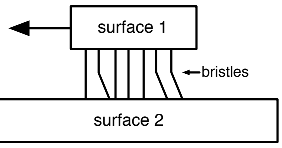

Figure 1.4: The friction mechanism between two surfaces is modeled as bristles attached to surface 1, which stick and slip to surface 2 producing an oscillation (adapted from Avanzini et al. (2002)).

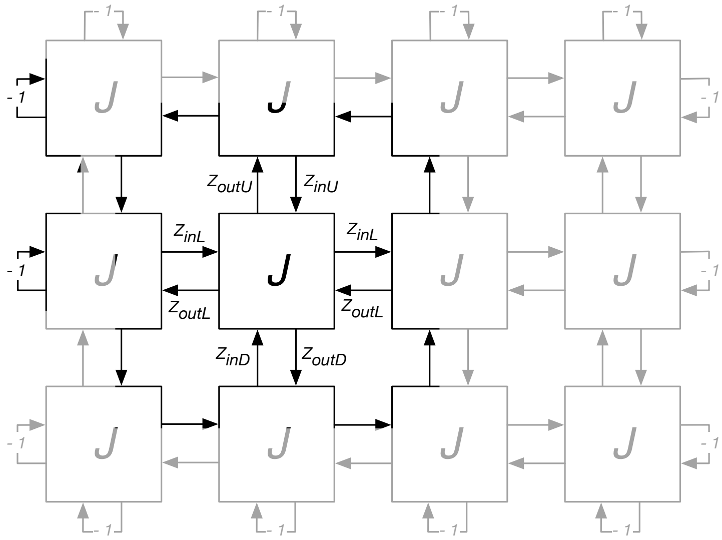

Figure 1.5: The two dimensional waveguide mesh is constructed as a grid of scattering junctions. Each scattering junction is used to calculate incoming and outgoing displacements in all four directions (Up, Down, Left and Right—these are highlighted for only one of the junctions). Arrows between the junctions represent unit delays, and at the boundaries the outgoing displacements are inverted to give the input displacements. The diagram is adapted from Cook (2002).

Drum Model

The last model, that is based on digital waveguides is the drum model. It implements a two dimensional wave guide mesh based on the technique introduced by Duyne and Smith (1993) to simulate an oscillating membrane. The resonator is constructed using a series of scattering junctions organized in a grid—see Figure 1.5. Between each of the scattering junctions are simple one-unit delay lines. As waves propagate in all directions from each scattering junction each of them need eight delay lines (four incoming and four outgoing). Each scattering junction can thus be regarded as having one overall displacement, taking four input displacements and outputting four output displacements. The output displacements are all dependent on overall displacement and the four input displacements (coming from the four neighboring junctions). The first step to computing the overall displacement at a given junction is calculating the average of the total incoming horizontal displacement (right/left) and the total incoming vertical displacement (up/down):

$$Z_j = 0.5(Z_{inU} + Z_{inD} + Z_{inL} + Z_{inR}) \tag{1.2}$$

However, the overall displacement at time n is also dependent on the overall displacement at time *(n - 1)*, at time *(n - 2)*, and the admittance (result of the tension of the membrane). Thus Zj at time n is given by:

$$Z_j(n) = 2*((Z_{inU}(n)+Z_{inD}(n)+Z_{inL}(n)+Z_{inR}(n)+(Z_j(n-1)-Z_j(n-2)))*Y_c/Y_j) \tag{1.3}$$

where Y_j is the admittance and Y_c is given by

$$Y_c = Y_j - 4 \tag{1.4}$$

The outgoing displacements in each direction are then calculated as the difference between the overall displacement at the junction and the incoming opposite displacement. For instance the calculation of the outgoing displacement upwards is:

$$Z_{outU} = Z_j - Z_{inD} \tag{1.5}$$

At the boundary junctions the outgoing displacements are simply inverted to give the incoming displacement.

The excitation part of the drum model simulates a simple drum stroke by filling the array with displacements that are calculated from the incoming excitation force and the admittance. For each junction five buffers are filled with displacement values that differ according to their position in the grid. This is done to simulate an initial distribution of force onto the membrane.

Particle Model

The last model used throughout the thesis implements a physical modeling approach that is known as modal synthesis. The technique models vibrating structures based on their modes (harmonics). The modes are dependent on the energy exerted into the model described by the excitation and the geometry, material, etc. of the vibrating structure. A typical method involves using bursts of white noise to model the excitation, passing the signal through several parallel bandpass filters—each corresponding to a mode. The center frequency and bandwidth of the bandpass filters will then determine the timbre of the vibrating structure. For instance a series of filters placed at inharmonic intervals with narrow bandwidths will simulate a metallic bell-like structure. Modal synthesis has mostly been used to simulate impact-like sounds or sounds with non-harmonic spectra. While modal synthesis can also be used to simulate harmonic sounds, digital waveguides are far more efficient as modal synthesis would typically demand a large amount of harmonics (Van Den Doel and Pai, 2003).

The modal synthesis model used here is an implementation of the Physically Informed Sonic Modeling (PhISM) technique described by Cook (1997). More specifically it implements excitation mechanisms of Physically Informed Stochastic Modeling (PhISEM). PhISEM implements an excitation mechanism that models random collisions between elements in percussion instruments such as shakers, but can also be used for particle sounds such as the sound of rain or the sound of someone walking in gravel. Rapidly decaying noise bursts that overlap each other are triggered using a stochastic mechanism that models collision probabilities based on the amount of colliding elements and the force applied to the system. If for instance the amount of beans in a maracas is high they will hit each other and the insides of the maracas more often and more softly than if the amount of beans is low. The noise is filtered using modal synthesis explained above producing the different resonance modes. By controlling the amount of beans, the energy injected into the system, and the center frequencies and bandwidth of a series of resonance modes, a flexible particle model has been implemented.

Accuracy versus Explorability

Common for most physical modeling techniques is that they were originally conceived in order to simulate real world instruments (Smith, 1992; Välimäki et al., 1996). It seems that the first priority has always been to recreate sounds found in the real world. Although this might seem uninteresting to some (the argument that we do not need to synthesize a flute when we have a perfectly working real one) it has been crucial for the understanding of not only the acoustics of the instruments but also the understanding of digital sound synthesis. In other words, without the inspiration from real world instruments and other sound generators, scientists and engineers would have never known where to begin.

Throughout this thesis I have been interested in pursuing more creative use of the technique in a compositional setting, by examining how more creative exploration of the sound models can be facilitated. This has meant that the creative use of the physical models have been tightly bound to the composers and how they work creatively with tools at hand.

Schaeffer argued that there are two approaches for a composer to take in order to create a piece of music. In one approach the composer starts out with a clear goal or idea of how the end result will be. The composer might create a plan of how to get there detailing *concrete* methods for realizing the idea. In the other approach the composer is inspired in an exploratory sense by a selection of sound material or available technologies and from there experiment to finally form a resulting piece (Manning, 2004). Wishart (1994) has pointed out how musicians and composers may not know exactly what their goals are when creating a piece of music. They set out to create music not always knowing what they are doing. In other words they engage in a process where they explore different tools, methods and approaches. This is what is meant, when throughout the thesis I refer to an exploration of the sound synthesis model. In most cases electronic musicians will not be interested in accurate simulations of "real" instruments. They are more concerned with "finding their own sound" - a saying that can be heard within all musical genres to a great extent.

Open program environments like Max/MSP[5], PD[6], Csound[7], SuperCollider[8], etc. provide environments where this exploratory principle is taken to what one may call the extreme. Here users are free to explore any part of the creation of digital sound they wish. However, as Thor Magnusson argues, they might be too free (Magnusson, 2006, 2007) and that total freedom lacks affordance. Users need to be presented with affordance in order to be guided or captivated (Gibson, 1986). They need boundaries or constraints in order to guide their exploration. Though these open environments are good for many tasks, the users must, to some extent, have a concrete idea of what they want from the start - a fact that doesn't seem to afford exploration.

[5]http://cycling74.com/products/max5
[6]http://puredata.info/
[7]http://www.csounds.com/
[8]http://www.audiosynth.com/

The technique and creative potential

Variations or sub-techniques of physical modeling have surfaced which try to explore the creative, exploratory, almost expressionistic qualities of physical modeling, while still retaining the natural-ness of the interaction. The techniques move away from the quest for accurate simulations of existing instruments by using physical modeling techniques to create non-realistic simulations. This is for instance achieved by combining elements from different physical models in non-natural ways (*hybrid physical models* (Van Stiefel and Cook, 2004)), or extending the parameters of the accurate models to break the boundaries of the real world (*replica extended models* (Böttcher et al., 2005)). Techniques also approach physical modeling from other mathematical perspectives, which are on the borderline to what one may define as physical modeling (*pseudo physical models* (Cook, 1996)). These extended techniques incorporate elements from the physical modeling principle, which lets them be controlled in a similar manner to physical models - with the same accuracy or natural-ness. Finally, physical modeling is also being used to enhance the natural-ness of interaction when controlling other synthesis techniques by for instance establishing connections between parameter nodes using rules from physics to control their interaction (Momeni and Henry, 2006; Muth and Burton, 2003; Johnston et al., 2008).

There are a number of different artists who have used physical models creatively in their pieces. Most are found having a connection to the academic world. A brief review of the various ways in which they implement physical modeling has served as basis for inspiration for the work performed throughout the thesis.

The SqueezeVox is a good example of a physical model used creatively (Cook, 2001). It implements an accordion interface used to control a physical model of the human voice. It exemplifies how the control of a physical model can extend the natural creative potential of the model.

An example of an alternative excitation method is presented by Janer (2005) who uses the human voice to control a physical model of a plucked bass guitar implemented using the Karplus-Strong algorithm (Karplus and Strong, 1983). In David Jaffe's piece *Silicon Valley Breakdown*, a physical model of a plucked string also implemented using Karplus-Strong is extended to reach unreal dimensions, such as the length of the Golden Gate Bridge.

In (Chafe, 2004) Chris Chafe presents a collection of different compositions which incorporate the use physical modeling. The article gives a very nice overview of how artists working with physical models try to stretch, distort and break the constraints of the physical domain that the models arise from. A couple of examples hereof are Paul Lansky, who uses Perry Cook's model of a flute (Cook and Scavone, 1999), extending it to 20 feet and Gary Scavone, who subtlety overblows physical models of saxophones in *Pipe Dream*. Another example is *S-Trance-S* by Matthew Burtner (Burtner, 2003), who uses a saxophone as a controller for a physical model of a string. Juraj Kojs (Kojs and Serafin, 2003; Kojs, 2007; Gluck et al., 2007) works with the interplay between traditional physical instruments and their extended physical modeling virtual counterparts.

Throughout many of the reviewed pieces the actual physical models are developed specifically for each piece. This seems to have become the norm for artists using physical modeling.

Commercially, Yamaha were the first to introduce a physical modeling based synthesizer in 1996 - the VL1. While the VL1 showed great potential, it had limited success. Other software and hardware synthesizers based on physical modeling have arisen since then but only within the last couple of years has physical modeling found it's breakthrough in commercial systems.

Applied Acoustics Systems (AAS) has developed a series of physical modeling based software synthesizers such as Ultra Analogue VA-1, which is a virtual analogue synthesizer that uses physical modeling to emulate electrical circuits, filters, tube amps, etc. found in traditional modular synthesizers. Modelonia by Nusofting is a more hybrid physical modeling software synthesizer letting users combine different physical models encouraging new sounds to be explored.

Most DAWs incorporate some sort of physical modeling synthesizer. For instance Ableton together with AAS has introduced Collision and Tension that like Logic Pro's Sculpture incorporates a flexible interface letting users experiment with various exciters and resonators creating hybrid sounds based on physical modeling. Cubase includes Mystic, which is a combination of physical modeling and comb filtering and Monologue, which is a virtual analogue synthesizer.

In recent years physical modeling has also been commercially implemented for detailed and flexible emulation of dedicated acoustic instruments. Pianotech by MODARTT emulates the grand piano letting users fine-tune hammers, soundboard, mechanical noises, various resonances, etc.. Lounge Lizard EP-3 by AAS incorporates a physical model of an electric piano emulating fork, pickups, mallets, etc. Brass by Arturia emulates brass instruments, and Spicy Guitar by Keolab and Strum Acoustic GS-1 Session by AAS emulate guitars. Nusofting offers a series of dedicated physical modeling software instruments emulating for instance harp, marimba, and saxophone. Finally, THROAT Evo by Antares models the human vocal tract.

All of the above implementations of physical modeling run as software synthesizers or plugins, that rely either on programming MIDI sequences or using general MIDI controllers for control. Physical modeling based hardware synthesizers, like the VL-1, are sparse and do not seem to take full advantage of the natural, expressive and exploratory potential that alternative control of physical modeling has to offer. Physical modeling used in hardware synthesizers are mostly confined to using physical modeling to emulate analogue synthesizers.

Physical Modeling and Natural Mapping

An important property of physical modeling is the natural relationship between input parameters and output sound. Because of the nature of physical models, the control of them can be achieved naturally. All the parameters used to control the algorithms are directly related to the parameters one would find in the real world, making the control situation more natural compared to other techniques such as spectral modeling (Roads, 1996). On a conceptual level, one could argue that there is a one-to-one mapping (Hunt et al., 2000) between physical control input and the parameters used to control the models. E.g., if a drum is hit with a higher velocity, the pitch, amplitude, duration etc. changes. But all this is taking care of by just altering one parameter of the physical model (*hit velocity*).

Hunt et al. (2002) argues that the focus when designing "new" electronic instruments should be on the parameter mapping and that parameter mapping alone can determine *"the very essence of an instrument."* They argue that one-to-one mapping is not desirable for expressive "instrument-like" instruments, and that complex mappings are not only more interesting and expressive, but can actually help users to perform certain musical tasks. Because of the nature of physical modeling, one-to-one mapping (mapping an input gesture directly to a model parameter) may be more interesting because a single model parameter normally affects multiple sonic properties.

In Smith (2004) Julius Smith argues that virtual instruments (physical models simulating real world instruments) *"contrast with "abstract" and "recording-based" synthesis algorithms that are capable of high quality sound synthesis, but which lack the intuitive and expressive control-response of model-based synthesis."* One way of understanding this is that when sound synthesis is used in an abstract way you might get a more interesting sonic result but the intuitiveness of the control is compromised (because of the abstract-ness). However physical models, which uphold an intuitive control because of the natural mapping situation, may be used in a more abstract manner. Hence a more abstract synthesis might be achieved while still sustaining intuitive and expressive qualities.

The following section will go more into detail with the interaction involved in playing or using a new digital musical instrument, including the *mapping* from input gesture to output sound.

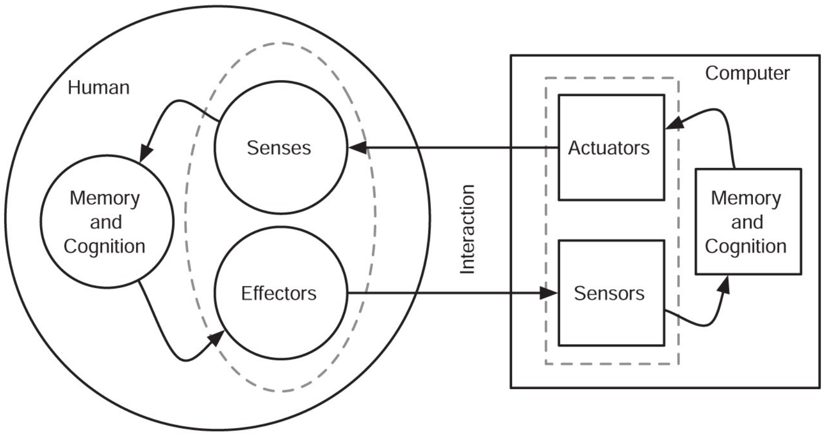

Figure 1.6: The interactive loop between human (solo performer) and computer by Drummond (2009) adopted from Bongers (2000).

1.3 Interaction Design for New Digital Musical Instruments

When designing and developing new digital musical instruments a primary goal is to understand the interaction that takes place when the musician plays an instrument. It is widely acknowledged that the interaction is highly complex integrating many elements that are all interrelated. However, it is beneficial to divide interaction into different layers or stages. These stages can then be examined in order to better understand how to design for desired forms of interaction.

Interaction Models

The interaction that takes place as a musician plays an instrument is typically described as a traditional HCI communication loop, where the user acts upon the system, the system senses what the user is doing and produces feedback, which is perceived by the user, who then acts accordingly (Moggridge, 2007). The overall model can be extended to include additional elements (for instance Paine (2009) introduces an interaction model that also includes the interaction with the audience), and each element can be described in greater detail in order to understand lower order causal relationships. Drummond (2009) presents a detailed discussion of interactive music systems (including music installations, systems that act on musical input, etc..). From Winklers five stage system model (Winkler, 1998) he describes an interactive model adopted from Bongers (2000) that illustrates the musical communication loop between human and computer—see Figure 1.6. The computer uses *sensors* to sense the gestures of the human, this is then processed in order to present feedback to the user via *actuators* (auditory/visual/tactile feedback). The human uses *senses* to sense the feedback from the instrument (audio, visuals, haptics), processes the stimuli using memory and cognition and then uses *effectors* to act upon the instrument (muscle action, breath, speech, bio-electricity). The separation of the controller and the sound production mechanism is apparent and here as it is the *Memory and Cognition* of the *Computer* that determines the relationship between the two.

Kvifte and Jensenius (2006) present an excellent overview of various interaction models, where the interaction involved in playing a musical instrument is described from three

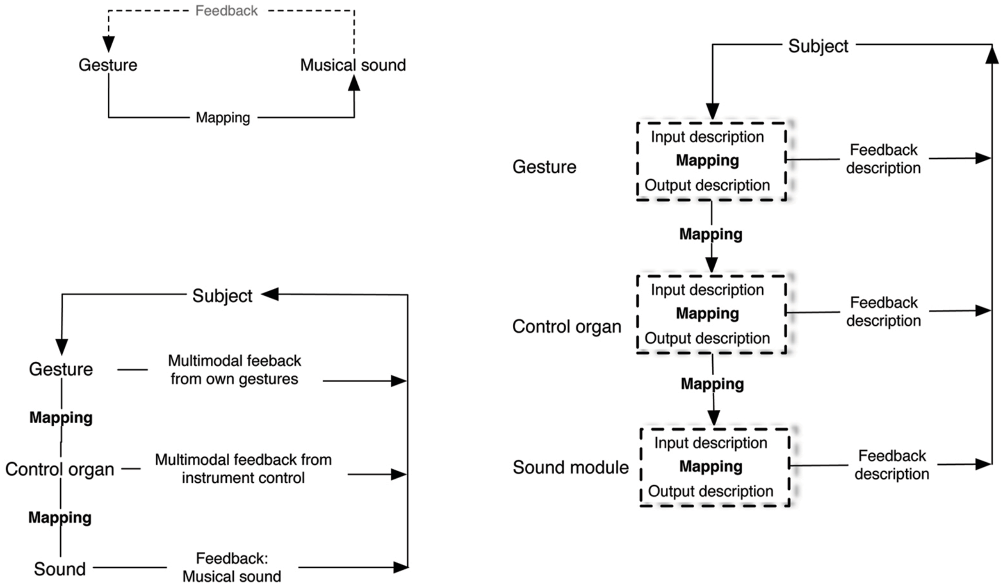

Figure 1.7: Three interaction models from the perspective of the listener (upper left), the performer (lower left), and the constructor (right) by Kvifte and Jensenius (2006).

different perspectives; the audience, the performer and the constructor, each requiring a different level of resolution—see Figure 1.7 They especially express the importance of feedback within the different layers.

The feedback loop is also emphasized by Chadabe (2004), who regards the interactive relationship between the performer and an interactive instrument as *conversational*, in the way that the instrument seems to exhibit a life of its own, by responding to the user in a way that changes or influences the user's actions upon of the system. Likewise Johnston et al. (2008) observed three different interaction modes (*instrumental, ornamental, and conversational*) while conducting an evaluation of a set of virtual instruments. Musicians were asked to explore a musical system (an instrument), which worked by augmenting the sound produced by the musicians playing their favorite instrument. The system worked by analyzing the sound of the incoming sound in order to detect pitch and onset of single notes. By playing different notes the user was able to exert forces onto masses connected in a mass-spring system (each mass corresponded to a specific note). Movement of each mass would cause the note of that mass to play. Observation revealed that three interaction modes (not mutually exclusive) were: (1) *Instrumental*, corresponding to how one would interact with a traditional acoustical instrument emphasizing control, consistency, trust and proficiency; (2) *Ornamental*, where the augmentation was seen as a kind of sonic background that would accompany the sound user; and (3) *Conversational*, where the user's musical decisions while playing the instrument were highly influenced by the feedback from the system. They suggest that the conversational mode is desired as it creates a balance between accurate control and surprise, a balance that leads to new ideas and divergent thinking, which can facilitate the creative process.

Bown et al. (2009) argue that the traditional understanding of the instrument, composer, performer relationship is inadequate when one wants to describe the interaction in

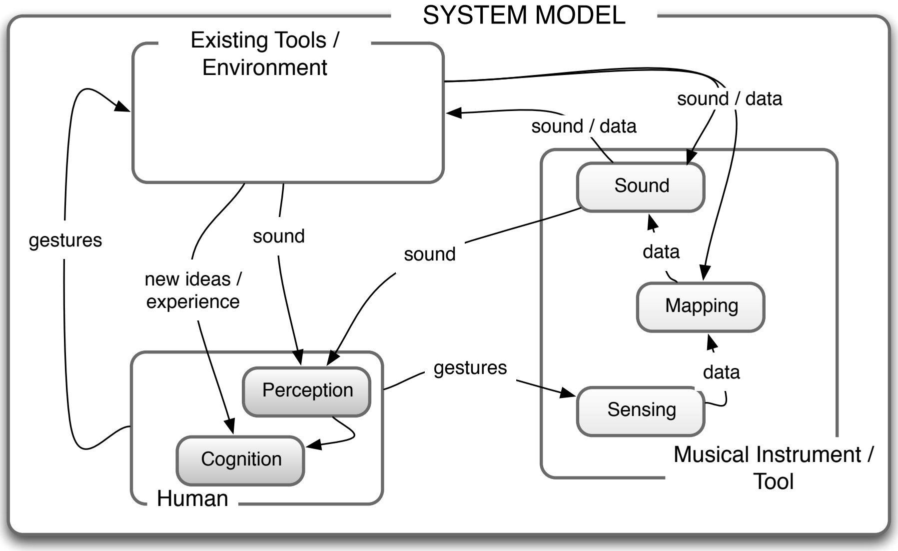

Figure 1.8: Interaction model that illustrates the interaction between the human, the instrument and the environment or context in which they interact.

contemporary digital music culture (specifically players' relationships to software instruments). Instead they propose understanding the interaction as a result of interactions between so-called *behavioral objects*. Behavioral objects are pieces of software, that can be shared, exchanged and altered on many different levels by individuals as if they were tangible objects—examples could include Max/MSP patches, VST-plugins or Ableton Live presets. They can be *passive* or *active* in regards to how they drive the overall interaction process, even interacting with other behavioral objects in generative ways. The views are similar to those described earlier by Bertelsen et al. (2009), who argue that musical software can be seen as chains of complex mediators. However, they seem to only consider software instruments as part of this overall social interaction, but it seems that many hardware based *objects* share the same properties (Arduino, Monomo, DIY controllers, etc.). The idea that an instrument does not behave like a traditional instrument within the practice of contemporary electronic/digital music is shared by the author. An interaction model that regards the instrument as a behavioral object that is closely related to the environment in which it is used (or with which it interacts) could be beneficial. The interaction model presented in Figure 1.8 has been used throughout this thesis and illustrates the contemporary musician interacting with the instrument in a strongly influencing environment.

Holistic Approaches

Describing design frameworks has been a way of putting forward ones view on what should be achieved for successful instruments to be developed. Many have proposed such frameworks with focus on various issues mostly concerning the relationship between human action and perception, and technology (sensors, synthesis models, programming techniques, etc.). The following will present examples of such frameworks, in order to illustrate how emphasis shifts between different issues depending on the approach.

The Music Technology Interface Design Space (MITDS) proposed by Overholt (2009) is a theoretical framework for developing expressive musical instruments. The framework takes a holistic approach in the sense that it tries to outline the many elements or issues, which interdependently influence the success of an expressive musical instrument painting an almost philosophical picture of how instruments should support the human urge to move and be moved by music. Overholt argues that a performer must be able to build a close relationship to the instrument in order to communicate expressively trough it. Seven MITDS principles are proposed that describe issues dealing with perception and intuitiveness of gestures from both the point of view of the player and a potential audience, with the controller and synthesis model, the mapping methodologies and the overall range of expression. Equal emphasis is put on technical and human issues and how they meet to form the overall goal achieving the same expressive qualities inherent in traditional instruments, the end goal being to exceed them—a goal that seems to drive much research in the field today.

Perry Cook (2001, 2009) has described a set of principles for designing computer music controllers. They are not a set of generic guidelines as such, but more a set of experiences gained from developing various controllers, experiences that might help others in the development of new musical interfaces. They deal with human/artistic issues to do with usability and system intuitiveness, practical issues, technical issues, and what one might call general tips and tricks (for instance *"Everyday objects suggest amusing controllers"*). The principles are very practical and accompanied by examples of how they can be applied. In (Cook, 2004) he suggests that much can be gained by designing synthesis algorithms and controllers in parallel as part of the same process. Problems with the controller/sound generator paradigm include the *lack of feedback* (haptic), *the lack of fidelity* (in the sense of latency or distortion between input gestures and output sound/feel), and *the lack of sense that the instrument actually makes the sound* (important for the overall feel of the instrument). Designing complete integrated systems where a close, high fidelity relationship between controller and synthesis model exists potentially leads to higher expressivity and intimacy for the player. Instruments that take this approach include "the Nukulele" by Cook (2004), Calichord by Schlessinger and Smith (2009), and the multi-touch force sensitive surface by Jones et al. (2009).

Magnusson (2009) argues that the typical approach to NIMEs deals with the *embodied experiences* of playing musical instruments and that we are missing the *epistemological* dimension. He suggests an approach to understanding new digital musical instruments as extensions of the human mind rather than the human body. There exists an inherent knowledge in the instrument that is symbolic and hermeneutic, and he argues that the cognitive connection with the instrument is at least as theoretical as it is physical. He further suggests an *Epistemic Dimension Space* for analyzing musical systems in regards to their epistemological qualities (Magnusson, 2010b). He deliberately contrasts the work to the dimension space proposed by Birnbaum et al. (2005), which takes a more traditional phenomenological approach. As can be seen in Figure 1.9, Magnusson focusses much more on the potential cognitive experiences facilitated by the instrument. Lastly he acknowledges the need for both approaches as instruments should both be a physical extension of our body *and* a cognitive extension (or scaffolding) of our mind.

Gestures

Dealing with the controller part of the musical instrument involves understanding the physical gestures that are performed when playing a musical instrument. Here gestures are defined by movements that somehow communicate pieces of information, striking a drum, blowing into a flute, constantly feeling the edges of piano keys, or tilting the upper-body to emphasize a musical event. The controller-part of the instrument is capable of sensing

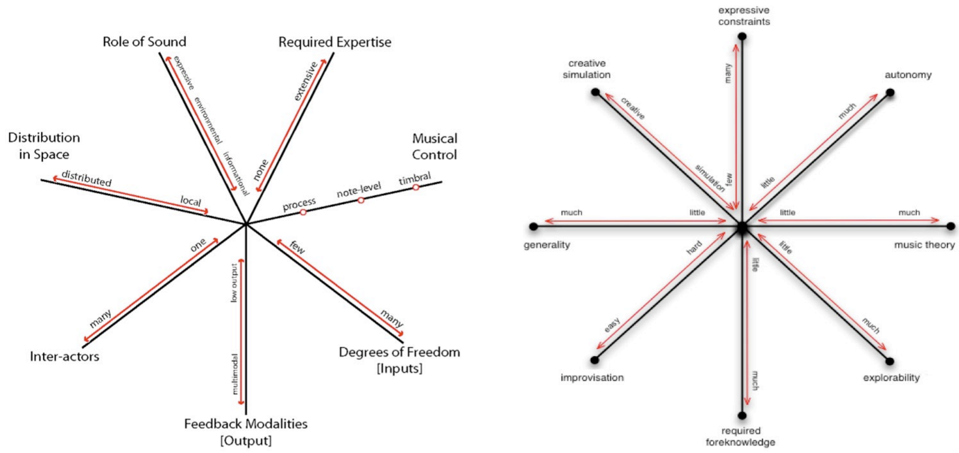

Figure 1.9: The two dimension spaces for musical devices. On the left is the original dimension space emphasizing phenomenological issues by Birnbaum et al. (2005). On the right is the epistemic dimension space proposed by Magnusson (2010b).

these gestures, after which they are digitizes and sent as variables to the synthesis model (in most cases through a specified mapping layer).

Ramstein (1991) proposed three overall levels for studying gestures: (1) the phenomenological level (descriptive / what goes on?); (2) the functional level (what is the function of the gesture?); and (3) the intrinsic level (from the point of view of the performer / what can my different body parts do?). Similarly, Cadoz (1994) considers instrumental gestures to have three overall functions, which are not mutually exclusive:

Semiotic gestures are used to communicate information that can be interpreted to have a specific meaning such as a 'wave hello', or 'thumbs up'. They can also be used to convey expression during a performance—consider the head movements of an expressive piano player during a dramatic passage.

Ergotic gestures are gestures used to manipulate physical objects. These are the gestures that are directly associated with the sound being produced.

Epistemic gestures are gestures that have to do with the perception of the environment. This refers to how knowledge is acquired by the muscular and tactile activities involved when performing a musical gesture.

The ergotic gestures involved in manipulating an instrument can further be divided into *excitation, modification* and *selection* gestures—each of which have their own subcategories. (1) excitation gestures used to exert energy into the musical instrument making it sound (for instance plucking a string) (2) modification gestures used to modify various parameters/properties of the instrument (for instance controlling the vibrato of a violin) and (3) selection gestures, which are gestures associated with making discrete choices between different elements (fingering of a flute).

Nort (2009) suggests approaching gestures from two perspectives in order to design meaningful and nuanced digital instruments. On one hand one can consider the control gestures that the player performs while interacting with the instrument. On the other hand one can consider perceived *sonic gestures* as the perceived human intentionality inherent

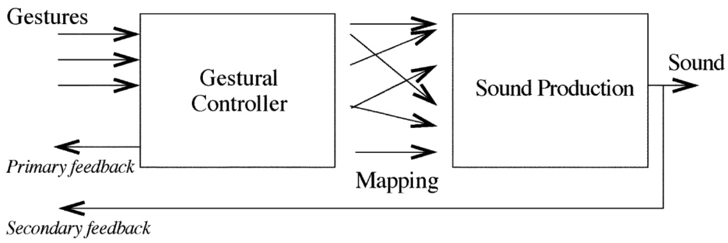

Figure 1.10: The system model by Wanderley and Depalle (2004) illustrates the separation of controller and sound production with an intermediate mapping layer.

within the sounds being played. He argues that any sound will encompass a perceived gestural intentionality, that a way of listening and perceiving sound is by evaluating the human physicality that lies behind it. He suggests that instrument design should be approached from the point of view of sonic gesture instead of physical gesture.

Musical gestures can be studied in order to analyze playing styles or techniques associated with traditional instruments (Rasamimanana et al., 2009), in order to understand how they contribute to perceived expressivity (Dahl and Friberg, 2007) or to understand which gestures are most efficient for performing specific musical tasks (Marshall et al., 2009). Throughout this thesis I have been interested in gestures in order to investigate how differences in the gesture space influence the explorability of the synthesis models. The potential of exploring the sounds of a synthesis model greatly depends on what gesture is used both to excite the model and to manipulate or modify its internal parameters. Not only are phenomenological aspects such as feel of the instrument influenced by the gestures used to control it, also the epistemic aspects of cognitively interpreting the model changes with different types of gesture.

Mapping

Understanding the gesture space (the space for physical movement) of an instrument helps make informed choices of how to physically control sound synthesis models. The relationship between the physical gestures and the synthesis model—*the mapping*—is a central part of what defines the instrument (Hunt et al., 2002).

Wanderley and Depalle (2004) make use of a system model for describing the role of mapping between controller and synthesis engine. The model depicted in Figure 1.10 shows how the gestural controller senses various gestures performed by the user and relates this data to the synthesis engine using a dedicated mapping strategy. The user receives *primary feedback* from the controller itself (for instance auditory feedback from mechanical sounds or tactile-kinestetic feedback from physically manipulating the controller) and *secondary feedback* produced by the synthesis engine (sound, haptic feedback).

As already mentioned, when dealing with digital musical instruments these two layers are separated (as apposed to traditional acoustic instruments, where the output sound is physically dependent on the input gestures). Different approaches exist for mapping between the musical gestures of the user and parameters of the sound synthesis model. Emphasis is put on understanding the blurry level that lies between the sensed gesture of the user and the manipulation of parameters of the synthesis model. Different strategies can be implemented including: *one-to-one, one-to-many, many-to-one*, and *many-to-many*

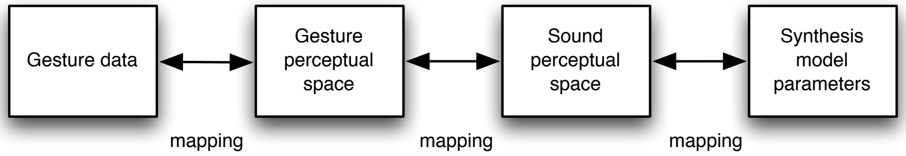

Figure 1.11: Mapping from gesture space to sound space using three intermediate layers by Arfib et al. (2002): gesture perception space, sound perception space, and mapping space between those two.

(Hunt et al., 2000). The mapping must provide the user with a meaningful conceptual understanding of the system which is to be controlled while maximizing the range for musical expression and exploration. According to Drummond (2009) the goal is to create *"mapping metaphors, balancing responsiveness, control and repeatability with variability, complexity and the serendipitous."*

Systematic approaches to understanding possible relationships between gesture and sound include the work by Levitin et al. (2002). They describe a structured approach of understanding musical events (for instance as monophonic tones) in terms of what the possibilities are of controlling their properties. The musical event is divided into three stages (Beginning, Middle and End). Each stage is examined on a continuum from gesture to sound, identifying which aspects within each stage can be manipulated and with which gesture types.

Another approach is to establish a meaningful mapping *metaphor*, which can assist in achieving a natural transparent mapping between the two levels (Fels et al., 2002). A meaningful metaphor enhances the cognitive integration of the physically separated layers - gesture input and sonic output. The mapping metaphors must align with the prior knowledge of the user for the interaction to be intuitive. Or as Norman (2002) puts it, the mental model of the user must align with the conceptual model of the system. As presented in Castagne and Cadoz (2003) *"A good mental model should let the user anticipate the results of his action and facilitate explorations"*—note that if the interaction is too predictable it might fail at facilitating exploration.

Arfib et al. (2002) suggests a three layered approach to mapping. Instead of mapping directly from gesture data to sound parameters using one mapping layer, one uses three mapping layers—these mapping layers are referred to as *perceptual spaces.* (1) First the gesture data is mapped to *"gesture perceptual space"*, defined by how that gesture is perceived. (2) Likewise the synthesis model parameters layer is mapped to the *"sound perceptual space"*, defined by how the sound (or change in sound) is perceived. (3) Finally there is the mapping between the two perceptual spaces. This approach resembles that of Nort (2009) described earlier, where the perception of changes in sound can be perceived as sonic gestures (perceiving the physical gestural intention that lies behind the sound). They argue that physical models provide a direct relationship between the sound perceptual layer and the synthesis model parameter layer because of the inherent nature of the technique. Changes in synthesis model parameters, such as short to long string or small to high velocity of a hit, correlate to perceptual changes in sound because we have extensive experience with these causal relationships by perceiving sound in our everyday lives.

Fiebrink et al. (2010) explores a many-to-many mapping space based on machine learning. Its implications bear resemblance to the perceptual spaces, in the sense that the user of the system is concerned with training the computer to map between perceived changes in gesture and perceived changes in sound. The idea is that the user need not deal with intricate parameters of the synthesis model or what specific data is derived from the sensing of gestures. They simply train the system by performing a desired gesture and link that to a perceived change in sound. The approach gives the user the freedom to define mappings between existing controllers and synthesis models to produce "composed instruments". The approach of giving the users the possibility of composing their own instruments is also used by Coughlan and Johnson (2008), where instruments are composed as a process of constraint development. Users can construct instruments by building interfaces on a graphical tablet using graphical widgets or *interaction shapes*. The user then determines how to interact with those shapes and how each interaction should be mapped to the properties of the sound model. As will be explained in the following section, creative activity involves freedom to explore, but also constraints to guide creativity. Coughlan et al. argue that the balance between freedom and constraints necessary for supporting creativity can be achieved by giving the user the freedom to define the constraints themselves, a balance, which aligns well with the creative exploratory approach pursued throughout this thesis (see Section 1.4 for more).

Magnusson (2010a) presents an excellent discussion of different types of constraints—for general HCI interfaces (Norman, 1999) and compositional constraints (Pearce and Wiggins, 2002), defining three types of constraints (*subjective*, *objective* and *cultural*), which take into account the philosophical-technological relation between the user and the musical tool as well as their social context. He even goes on to argue, that it can be beneficial to design new digital musical instruments, not by establishing their affordances (what possibilities they provide) but by establishing their constraints (the limits to those possibilities).

With the exploratory approach taken throughout this thesis the goal is to experiment within the mapping layers discussed above. The aim is still to establish a transparent mapping while maximizing the possibilities of experimentation. As described earlier, freedom for creating abstract connections between gesture and sound seems to be larger for physical modeling because of the inherent perceptually causal relationship between gestures, model parameters and output sound. However, this freedom must be carefully balanced with clear system constraints in order to support the creative process of the user. The following section will go more in depth with understanding this process. Understanding of the creative process has helped guide the design and evaluation of DMIs developed throughout the thesis.

1.4 Understanding Creativity

The daunting task of trying to understand creativity is approached from many different perspectives and as a result the definitions of what creativity is, are very diverse. Traditionally creativity was regarded as a skill that only very few people in the world possessed, and that truly creative people like Mozart, Einstein, or Picasso only came along and changed the world around them once every century. Recently research suggests that creativity lies in us all and that with the right support everyone has the possibility of enhancing their creative skills. But before exploring how creative activity can be facilitated one must first understand the fundamentals of human creativity. The following shortly presents different perspectives from which the study of creativity has been approached. The approaches or frameworks have different points of departure depending on what the methodological goals are for the specific research. Only the most fundamental research on creativity is reviewed here, as much of the work within creativity proceeds to touch upon specific fields such as education, psychology, music, artificial intelligence research, innovation science, etc.

The most widely used model of creativity is probably the four stage model by Wallas (1926), which divides the creative activity into four overall stages: *preparation, incubation, illumination* and *verification*. In the *preparation* stage one might identify problems, gain knowledge and/or explore possibilities. The *incubation* stage involves the unconscious processing of ideas, as one engages in unrelated activities. The *illumination* refers to the moment where the solution or idea presents itself, and finally *validation* describes the stage when the idea or solution is tested, put into context, shared with others, etc.[9].

Rhodes (1961) proposed the 4 P's of creativity. They describe different perspectives from which creativity can be studied:

1. *person*, one might study the person, who engages in the creative activity.
2. *process*, one might study the actual creative activity (exploring, learning, thinking, communicating). Rhodes refers to the Wallas' four stage model as part of this process.
3. *press*, one might focus on the environment or context in which the creative activity occurs.
4. *products*, finally, one may approach the study of creativity by studying the embodiment of the creative idea—this could be a product, or in this case a composition.

Guilford (1967) identified two cognitive processes involved with problem solving, divergent and convergent thinking. Divergent thinking involves thinking in new ways, putting elements into other contexts or approaching problems from different perspectives in order explore possibilities. Convergent thinking involves the deductive process of finding a single optimal solution to a problem. Later, the importance of being able to combine or switch between these two processes has been associated with creativity. For an idea to be creative, novel ideas are not enough. Sternberg (1998) defined the creative idea as the novelty of the idea combined with its appropriateness (usefulness or value). The appropriateness might emerge from the convergent process of turning the novel idea into a useful form that is acceptable within a sociocultural context.

Boden (2004) argues that the element of surprise is closely related to creativity and that creativity can take three overall forms: *combinational* (where familiar ideas, concepts or techniques are combined to form new ones), *exploratory* (defining a conceptual space in

[9] Originally the model had a fifth stage *intimation*, which lay between *incubation* and *illumination*. It described how one would have a feeling that the creative solution was just about to present itself.

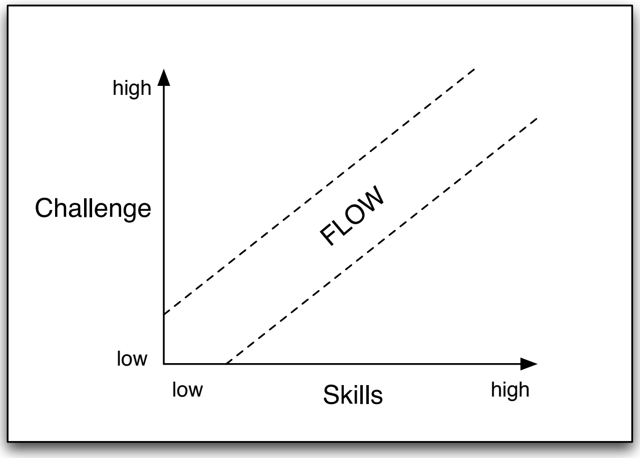

Figure 1.12: According to Csikszentmihalyi (1996), flow can be achieved if there is a balance between the challenge associated with a certain activity and the skills of the person performing that activity.

which one can explore possibilities), and *transformational* (where the conceptual spaces are transformed in order to facilitate ideas that were impossible before)..

Shneiderman (2007) proposes that research directions within creativity studies may be divided into three intersecting schools: *Structuralists, Inspirationalists* and *Situationalists*. Structuralists focus on creativity as something that may follow a systematic series of activities in order to be obtained. The aforementioned four stage model by Wallas (1926) is a good examples of this approach. Inspirationalists seek inspiration in order for the Aha moment of creativity to occur by engaging in methods diverging from familiar structures, promoting playful exploration, sketching, dreaming, meditating, etc.. Situationalists focus on the context, including social, environmental and cultural forces influencing the creative activity.

Csikszentmihalyi (1996) explains the challenge of getting into a state of *flow* in order for creative activity to thrive. The flow state is highly dependent on the balance between once skills and the challenges associated with the activity one engages in—see Figure 1.12. The feeling of flow is described as being completely involved in what you are doing, a sense of ecstasy, clarity, knowing that the task is doable, no worries, loosing the perception of time, motivational in itself. According to Csikszentmihalyi (1996) flow is achieved when there exists a fruitful relationship between the difficulty of the task at hand (the challenge) and the level of skill of the person performing that task. In close connection to the notion of flow, Overholt (2009) describes how the design of musical interfaces is analogous to the design of computer games in the sense that one must achieve a balance between challenge and skill. A game that is too easy will become boring after a short while. On the other hand, a game that is too difficult will potentially course the player to give up. It is essentially the balance of challenge and skill, that leads to flow, that determines the success of a game or a musical interface. The major difference though is, that unlike most computer games, playing a musical instrument should is not something that terminates when the player wins. In a way, the instrument should be designed so the player will never exhaustively master it.

There seem to be many overlaps between various proposed models/frameworks, and it seems that each one can be beneficial in a specific context. However, Eales (2005) criticizes the abundance of generic models for being too fixated on creativity as a sequential activity. He points out a simpler model described by Edmonds and Candy (2002), which describe the creative process as including activities of exploration, generation and evaluation. The model is similar to the Geneplore model by Finke et al. (1996)—a more heuristic model that describes the cognitive process of creative thought as a duality between *generation* and *exploration* of ideas. The Geneplore model has been used to underpin the importance of explorability of the digital musical instruments developed throughout this thesis.

Achieving the balance between challenge and skill, facilitating convergent and divergent thinking, or designing for a process of idea generation and exploration can be closely associated with the goal of designing for a balance between freedom and constraints—Magnusson (2010a) proposes to focus on the design of constraints in developing new digital musical instruments, Coughlan and Johnson (2006) uses scaffolding in order to let the player alter the constraints of a musical interface. Likewise, Fiebrink et al. (2010) lets the players compose their own instruments again achieving the balance between constraints and freedom.

Creativity Support Tools

An interesting field within HCI deals with Creativity Support Tools. This is a multidisciplinary field that was initially defined in 2005 at the workshop for Creativity Support Tools (Shneiderman et al., 2006). The goal of the workshop was to discuss design principles, research and evaluation methods related to HCI and creativity. Apart from outlining challenges of understanding how to design for such phenomena as creativity, innovation and novel discovery, the major outcome of the workshop was the description of 12 overall design principles for designing creativity support tools. Some resemble design principles found in other areas of HCI, but they are developed to specifically focus on creativity support. The design principles were:

1. Support exploration.
2. Low threshold, high ceiling, and wide walls.
3. Support many paths and many styles.
4. Support collaboration.
5. Support open interchange.
6. Make it as simple as possible—and maybe even simpler.
7. Choose black boxes carefully.
8. Invent things that you would want to use yourself.
9. Balance user suggestions with observation and participatory processes.
10. Iterate, iterate—then iterate again.
11. Design for designers.
12. Evaluate your tools.

The proposed guidelines have served as inspiration throughout the thesis. They are highly applicable for the design of new musical instruments that support creative exploration, especially those that have compositional focus. The focus here has especially been on principles 1, 2, 3, 5, 6, 7, 8, 9 and 12, the exploratory qualities of an instrument and on the search for effective evaluation methods, which can take into account the affective and situational or context dependent dimensions of being creative with a musical instrument.

1.5 Evaluation of Musical Instruments

A central part of the research and development of new musical musical instruments is being able to evaluate the effectiveness of ones design. While there is a widespread acknowledgement that more formal evaluations are needed within the DMI research field, the majority of research within the field lacks this important element (Stowell et al., 2009). The development of formal evaluation schemes can not only assist in comparing different musical devices, they also lead to designs that are based not *ad hoc* or *gut feeling* decisions, but instead are informed by more systematic approaches. The field of new DMIs has been looking towards research within HCI for inspiration (Wanderley and Orio, 2002). HCI has a strong tradition dealing with formal evaluation of various forms of interaction. The following will review various approaches found both in the field of new digital musical instruments and parts of HCI. It will start by describing existing traditional approaches leading to a discussion of how new approaches are needed in order to deal with the complex, subjective and context dependent interactions that are emerging within new digital musical instruments.

Evaluation Methodologies

Wanderley and Orio (2002) suggests a collection of evaluation methods for evaluating usability of input devices for musical expression. The activity involved with playing a musical instruments is quite complex. Wanderley and Orio introduce the musical task as way of reducing the complexity of the interaction involved in playing an expressive instrument in order to conduct more systematic and generalizable evaluations. The musical task used in the evaluation must be as simple as possible while still retaining elements that are musically relevant. A musical task could be to replicate certain musical gestures controlling for instance pitch, modulation, timed triggering of musical events and so on. A traditional approach in HCI is to measure various input devices based on how well they perform a given task—or how well a user performs a given task using them. A good example is the Fitt's Law acquisition task used for instance by de Götzen (2007), that evaluates the time it takes to move to a given object based on the size of the object and the distance from it. By applying this in a musical context using musical tasks it would be possible to compare the *usability* of input devices based on objective performance measures. For instance, Marshall et al. (2009) compared the appropriateness of several gestures for pitch modulation comparing performances of expert musicians performing simple musical tasks. Poepel (2005) evaluated the expressivity of different musical interfaces based on five cue-groups (timing accuracy, pitch accuracy, dynamics accuracy, articulation accuracy and timbre accuracy). Mäki-Patola (2005) compared different interfaces for controlling a virtual drum based on the measurement of temporal accuracy. Collicutt et al. (2009) used motion capture techniques to evaluate and compare four percussive input devices focussing on the differences in actions performed on devices ranging from acoustic instruments to gestural controllers.

In recent years a need has arisen within the field of HCI for extending evaluation methodologies to focus not only on *usability* (as seen in the examples above), but also on *experience* (Poppe et al., 2007). There seems to be a shift in focus that has to do with the emergence of new more complex forms of HCI—the field of ubiquitous computing is a good example. With the advent of the so-called third wave or third paradigm of HCI (Bødker, 2006; Harrison et al., 2007) a system or interface can no longer be assessed by deconstructing its use into specific tasks that it is intended to complete. Emphasis is shifting from usability to emotion and engagement, from tasks to activities, from user centered to use centered. Interaction design concerned with more affective aspects such as experience or emotion are more and more associated to the success of HCI systems, which makes it necessary to explore alternative evaluation methods.

Testing for pure usability factors can likewise be limiting when it comes to evaluating musical devices or musical instruments. Kiefer et al. (2008) discuss the methodologies proposed by Wanderley and Orio (2002) extending them to evaluate qualities related more to *experience* than *usability*. They pursue a more holistic approach using both quantitative questionnaires and formally conducted qualitative interviews. As an example, PAPER III of this thesis is an attempt to approach the evaluation of lower level elements of digital musical instruments where the focus is not entirely on usability, but also creative exploration, generation of musical ideas, and the likes.

A Methodological Shift

Stowell et al. (2009) present a nice review of various evaluation schemes for digital music instruments. They argue that traditional HCI methods (such as task-based evaluation schemes) are often inappropriate when evaluating the more creative and affective aspects of music making. Generally, there seems to be a tendency to move from the task based evaluation methods into more explore and report-like sessions where participants are asked to explore the instrument in a more free manner (Stowell et al., 2009; Johnston et al., 2008; Kiefer, 2010). While some important *tasks* can be identified for a musical instrument to be able to perform well, it is difficult to state tasks that have to do with experiencing an instrument—especially if it is to reflect how potential users experience such an instrument in real life. These kinds of experiences have to do with the way in which the instruments are integrated into the existing environments in which we make music—whether it is together with others, in large studios in connection with large musical setups, or in the dark night in the lonely attic where there are no other distractions. In other words the *context* of actual usage becomes more and more important for extracting an accurate assessment of the kind of experiences associated with using a musical instrument or tool.

As focus shifts from task based evaluation schemes towards more experience related methods, there is also a shift away from the quantitative statistical data collection towards a more holistic approach of gathering rich qualitative data that has a semi structured nature. Here emphasis is put on letting the participants perform naturally with the instrument in order to understand the underlying structures of interaction. This involves using a bottom up approach based on grounded theory (Corbin and Strauss, 2008)—an approach that has been broadly used within social sciences (and now also within HCI), where theory emerges from rich descriptive data. The qualitative approach acknowledges that objectivity is not possible, as it is very much based on subjective measures. This is very much incorporated into the gathering and analysis of the data and in how data is interpreted and communicated. This data can be gathered in many ways (case studies, observations, interviews, focus group sessions, etc.)—the challenge is to use rigorous methods both in the gathering of data and the analysis thereof. Formalization of various elements within of the qualitative research methodology means paying close attention to: choice of participants (novice/expert, academic/commercial, musical approach, genre, etc.), choice of context, choice of activity (forced/free, active/passive), choice of data collection (interview, 'think aloud', observation, artifact monitoring) and choice of analysis framework (grounded theory, activity theory, discourse analysis). Understanding and acknowledging what consequences these kinds of choices have for the generalizability of the outcome is crucial.

Stowell et al. (2009) employe techniques from discourse analysis to formally analyze interviews carried out in connection with an evaluation of a human beat boxing system. The technique approaches the transcribed data in a structured way by decomposing the text and formally reorganizing it revealing underlying patterns. The structured method helps minimize subjective interpretation of the data.

Duignan (2008) conducted a series of case studies in order to understand how the work of professional musicians was affected by the particular abstraction mechanisms in the user-interfaces of music production software. The participants were studied within well-known surroundings using interviews and observations (where participants were asked to illustrate issues arising from interviews in the studio). Manuals, observation notes, and photographs of setups and tool customizations were also used for more in depth analysis. Duignan used a similar technique to that used by Stowell et al. (from activity theory) to analyze the data using data coding. Here each item or passage was assigned codes, which were both predetermined (from the literature) but also emerged from the working with the data. The data was then reorganized by grouping or *categorizing* items based on their coding, revealing patterns that could then lead to new codification, which could then further be interpreted. This analytical process of finding structure in a normally large unstructured data set is highly iterative as codification and categorization leads to new insights, which demand new codings or re-codification of the material (Kvale and Brinkmann, 2009). The process ends once the material has reached a state of "saturation" where re-codification does not lead to any new insights.

Longitudinal Approaches

While the use of experience based evaluations of digital musical instruments seem to be increasing, they mostly employ exploratory sessions where participants are exposed to the instruments for a relatively short amount of time. *Longitudinal* approaches involve evaluation over longer periods of time (days, weeks, months or even years). Very few longitudinal approaches have been taken in the evaluation of new digital music instruments—but they have been used in HCI for two main reasons; the experience of using a digital musical instrument will no doubt change over time and employing a longitudinal approach makes it possible to evaluating more than just the first time experience. This is the main reason for taken a longitudinal approach (Jain et al., 2010). A second reason is to be able to carry out evaluations in real world environments, where test participants explore new products at their own time in accustomed surroundings. Collins (2005) underlines the importance of conducting research in real world environments—especially when studying subjective aspects of interaction such as creativity. He followed a composer for three years in order to understand cognitive processes involved in compositional activity. He argues that studying such aspects should be done in "real world" settings where the participants are allowed to act within well known, familiar and personal contexts. Creative activity will be distorted by constrained time periods, constrained tasks, simplified setups or the mere presence of the researcher. Understanding how especially professional users interact with musical devices involves understanding how they are integrated in existing work processes. As described earlier, when musical devices are used in practice, they are seldom used completely on their own. They are integrated with existing tools in various ways, which to a large degree determines the musical identity of the device. Understanding these integral interactions seems to become more and more important as musical instruments shift from musical artifacts to behavioral objects (Bown et al., 2009). Longitudinal evaluations are especially effective at naturally taking this real world context into account.

Longitudinal studies may be carried out over several weeks, months or even years. As constant observation over such long periods is challenging to say the least, other methods of data collection must be employed. Most existing techniques involving user feedback are retrospective to various degrees—scheduled interviews can be conducted asking participants to reflect on what they have been doing within a given time period or participants can be asked to write diaries of their activities. Karapanos et al. (2010) present various techniques that may help participants retrospectively recall relevant activities. The major concern with retrospective reporting is that what participants answer when they are asked to describe what they have experienced retrospectively will undoubtably differ from what they actually experienced (Ericsson and Simon, 1993). Participants will typically forget what actually occurred, reporting events that happened in the wrong order, more structured than in reality or more coherently than they occurred. While this is a highly important element to consider when analyzing such data, Norman (2009) raises the question of the importance of the actual experience. What is most important for your experience of an event—the actual experience or the recollected memory of an experience? Karapanos et al. (2010) argue that although retrospective descriptions of experiences are not accurate in regards to what actually happened, the reliability of the descriptions may be, if the participants' answers are consistent over multiple recollections. Furthermore they argue that these recollections are important, as they influence the attitude towards future products and are communicated to others.

Work towards formal methodologies when dealing with these blurry and subjective experiences is challenging. Springett (2009) presents an overview of the challenges that arise when evaluating affective and emotional aspects of interaction including how experiences are bound to instrumental goals and human values. Springett points out that a major challenge has to do with extracting subjective information from participants that to various extends is tacit (in the sense that a person knows and experiences more than he or she can articulate). Sometimes the participant is not even aware of what is being experienced (Moffat and Kiegler, 2006). AMUZE is an example of a tool used to objectively measure changes in one's physiological state when interacting with an embodied conversational agent (ECA) in a theatre play game, revealing tacit changes in emotional states (Chateau and Mersiol, 2005). The repertory grid technique, card sorting and laddering are also examples of methods that aim to extract semi-tacit knowledge from users. The aim is, in a structured way, to guide the user in expressing what he or she is experiencing. These techniques can be used either as retrospective assessments of encounters with products (Desmet et al., 2001) or to extract user attitudes towards various phenomena (Fallman and Waterworth, 2005; Carroll et al., 2009). Another questionnaire based approach—AttrakDiff by (Wechsung and Naumann, 2008)—lets users rate their experiences using bi-polar scales related to general experience criteria. This questionnaire has been explored in PAPER III and V.

In PAPERs V and VI of this thesis a technique is suggested that incorporates retrospective reports of what participants have experienced. This is done by carrying out the interview in the participant's own studio as in (Bertelsen et al., 2009). The interviews were conducted as 'show and tell' sessions, where test persons were encourage to show examples of what they were reporting. This is somewhat similar to the 'think aloud' protocol used in calibrated form by Stowell et al. (2009) and Johnston et al. (2008). There is reason to believe that having the participants give examples of their approaches, being able to open up files, play passages, or show how tools are used in practice can not only give the interviews more detail, but can also help the participants better and more reliably remember more specific details regarding the discussed issues.

1.6 Objectives of the thesis

The objectives of this thesis has been to work towards a conceptual framework that takes a user/use centered approach to the design and evaluation of physical modeling based instruments—understanding especially the complexity of what occurs when users adopt instruments or tools working them into their existing musical practices. Much of the research reviewed so far has served as background for developing this framework bringing together knowledge from different research areas in order to understand how to take advantage of the potential of physical modeling, but also how this understanding can be applied in the design and evaluation of concrete musical instruments. The practical approach taken throughout the thesis involves building prototypes, understanding the users (electronic musicians), forming a conceptual framework (including design directives), and exploring evaluation methods on different levels within the framework. Common for all the presented work is the concern with the facilitation of creativity. The general goals for this thesis have been the following:

1. To practically explore creative uses of physical modeling sound synthesis in order to describe an overall framework for creative exploration of physical modeling. The goal with the framework has been to situate the research within a creative context and to understand what was the role of creativity in regards to the specific synthesis methods—i.e. is it something that is inherent in the technique and/or can it be encouraged in the way the development is approached?

2. To explore how creativity is embodied at different levels of interaction (from the lower level of the physical gestures used to control the instrument to a higher conceptual level where the instrument is regarded as a whole.)

3. To understanding the importance of real world use in regards to design and evaluation of these forms of instruments. Specifically, the aim has been to understand how contemporary electronic musicians work creatively within a compositional setting and how that understanding can help inform the aforementioned framework.

4. To understand how to evaluate digital musical instrument with special focus on creative musical activity. What methodological issues might arise when dealing especially with the context in which the creative activity unfolds?

Chapter 2

Contributions of the present work

This thesis includes papers that take the same overall approach to the development and evaluation of new digital musical instruments based on physical modeling. While they all deal with an instruments ability to be explored in order to facilitate creativity, each of them does so from slightly different perspectives. Early in the thesis it became evident that considerations had to be made with emphasis on the context in which the instruments were to be played. Especially within the compositional setting that has been the basis of all the research carried out here, it has been important to work closely together with commercial electronic musicians, understanding their work practices, goals, and needs.

Issues regarding musical interaction and creativity presented in the introduction has helped underpin the overall framework used in the various approaches presented here. Additionally, understanding the new digital musical instrument not as a tool for effectively carrying out musical tasks, but as a creatively inspiring instrument has been crucial in the forming of the thesis. This is also why new forms of evaluation have been explored that take a more qualitative approach dealing more with the experience of using an instrument.

The research started out by exploring creative use of physical modeling leading to an overall framework for creative exploration. Specifically, a modular approach has been taken in order to create a musical instrument that resembles approaches found in old modular synthesizers in order to present physical modeling in a form that is first of all familiar to commercial electronic musicians, but also which strikes a balance between the constraints of each modular element and the freedom of the instrument as a whole[1]. Additionally, by providing the possibility of performing different physical gestures for controling the instrument, the exploratory properties of the instrument are enhanced. From there the development and evaluation of physical modeling instruments has been approached from both a micro-level of interaction with focus on specific musical gestures and sounds, as well as a macro-level regarding the musical instruments as a whole situated in a real world context.

The contributions of each of the papers presented in this thesis are:

Paper I describes the early work of developing a prototype (the PHYSMISM) to explore the implications of approaching physical modeling from a user centered creative perspective.

Paper II presents the exploratory framework for Physical Modeling. Thoughts on how to approach the development of physical models and physical modeling-based musi-

[1]the approach is similar to that of the Reactable (Jordà et al., 2007), which also makes use of the modular synthesis metaphor, striking a balance between constraints and creative freedom.

cal systems are summarized into seven design directives. They all are based on the overall aim that a musical tool should be exploratory in order to support the creative work processes of todays electronic musician. A more in-depth description of the development and evaluation of the PHYSMISM is presented in order to concretize the thoughts that underlie the framework.

Paper III examines physical interface evaluation with a quantitative focus. The aim was to explore a low level evaluation evaluation method situated within the overall exploratory framework. A set of modules (the SPLORER system) were developed to be able to randomize different control structures in order to examine the influence of (1) simple input devices, (2) more expressive input devices, and (3) the synthesis model, on the creative and exploratory qualities of an physical modeling instrument.

Paper IV presents a qualitative investigation into the existing work processes of today's electronic musician. A series of interviews were conducted with contemporary electronic musicians in order to understand how they approach composition of electronic music, with an underlying focus on creativity.

Paper V describes the development of a set of modular electronic instruments based on physical modeling sound synthesis (the PHOXES). They extend on the PHYSMISM and SPLORER systems to implement a truly modular system that lets user (contemporary electronic musicians) explore various physical models. A pretest was conducted in order to explore an in-depth qualitative evaluation methodology, which was later used in PAPER VI.

Paper VI deals with the evaluation of the PHOXES. A formal qualitative method is proposed that also contributes to the recent directions that look towards movements within HCI for understanding how digital musical instrumets can be evaluated within a complex context of music composition. Specifically a longitudinal approach is implemented, that emphasizes the context of use.

PAPER I and PAPER II are tightly bound, as they present the development of the PHYSMISM leading to the conceptual framework for physical modeling, which focusses on augmenting the exploratory qualities of the technique.

PAPER V and PAPER VI are also related. The former describes the initial development and pre-test of a prototype (PHOXES) and the latter presents the resulting improvements to the system together with a formalized qualitative evaluation.

Figure 2.1: The PHYSMISM is a digital instrument for creative exploration of physical models.

2.1 PAPER I: PHYSMISM: Re-introducing physical modelling for electronic musical exploration

The motivation for this study was to give real world users the possibility of exploring creative aspects of physical modeling. A physical interface for exploring physical models (the PHYSMISM) was developed and tested, with the aim of approaching physical modeling from a user centered perspective—users being commercial electronic musicians. While many interesting physical modeling techniques exist, few succeeded in being implemented in the commercial world of electronic music. Much research within physical modeling focusses on developing models that can simulate real instruments as accurately as possible. The goal was to shift the focus away from accuracy and focus on the use of existing models in a more creative and exploratory setting.

Inspired largely by analogue modular synthesizers from the 1960's, an interface was developed with the following criteria in mind; implement a variety of different models, balance simplicity of controls with endless possibilities, simulate real instruments with possibilities of extending them beyond physical limitations, combine models in an intuitive way, and investigate implications of using different physical control gestures. The criteria guided the process of developing a testable prototype. This process assisted in developing a more formalized conceptual framework including a set of design directives presented more in depth in *PAPER II*.

The PHYSMISM implemented four different physical models (flute, stochastic, friction, and impact), which could be excited by manipulating four dedicated excitation controllers (flute, crank, 2D-slider, and drum pads). Additionally four model parameters could be adjusted for each model using four knobs. Following the inspiration from modular synthesizers, the user was able to patch two models together by directing sound output from one model to the input of another using a patching system. See Figure 2.1.

Test and Reflections

In order to test the PHYSMISM, 11 test subjects were asked to first explore different aspects of the PHYSMISM (models, controllers, patching system) for 30 minutes. Comments were noted down and data revealing how input devices had been used was logged. Finally the subjects were asked to fill in a questionnaire regarding the different models, controllers, and overall system. The paper only describes parts of the evaluation. For the full evaluation, see *PAPER II*.

Results revealed that models were preferred based on their sonic diversity and unpredictable qualities. Models that received low ratings became interesting when combined with other models. Finally the physicality of the interaction was emphasized as having a positive effect on the exploration of the models.

The potential of physical modeling to be used in a more experimental environment (as within electronic music) is definitely there. It is shown that approaching the control if physical modeling from an exploratory perspective opens up the potential of the models. Musicians used here showed an increase in positive attitude towards the technique.

Finally it should be remarked that the quantitative parts of methodology employed in the evaluation were of little use (for instance measurements of controller use). Because of the exploratory nature of the evaluation sessions, the way in which each test participant worked with the PHYSMISM differed a great deal, making it difficult to carry out any meaningful comparisons of the quantitative data.

2.2 PAPER II: A Practical Approach towards an Exploratory Framework for Physical Modeling.

The motivation for the paper was to collect the ideas and experiences that arose from especially the first half of the PhD, where focus has been on trying to understand how physical modeling can be approached from a more use-centered perspective. Special focus is put on creative exploration of novel musical instruments. By encouraging specific forms of interaction it is possible to achieve a greater creative potential of the physical modeling technique.

A conceptual framework is proposed based on these overall thoughts. The framework draws upon recent work in various fields within NIME[2] (for example importance of musical gestures, mapping strategies, and musical interaction design paradigms) as well as research from cognitive studies (creativity, embodiment) and HCI. The framework puts emphasis on exploratory features of physical model, such as sonic diversity/plausability, physicality, gestural control, inherent perception of causality, and the balance between constraints and freedom that a modular approach can entail. The framework includes a set of 7 design directives, which articulate the exploratory potential of physical modeling. The design directives are:

1. Balance Sonic Diversity and Plausibility of the Model
2. Experiment with the Energy that Drives the Model
3. Control Physical Models with Physical Gestures
4. Make the User Work
5. Encourage Exploration of Sound Parameters and Exploration of Gestures
6. Experiment with the Interplay between Instantaneous and Continuous Instrumental Gestures
7. Make the System Modular

[2] New Interfaces for Musical Expression

The second half of the paper presents a more detailed description of the development of the PHYSMISM as an example of how to apply the framework. The description accounts for choices made regarding system design, interaction, models, and sensors used. Finally the evaluation of the PHYSMISM is re-visited analyzing the data with respect to the issues presented in the framework with emphasis on the design directives.

Reflections

Controlling the physical models with directly related physical gestures seems to extend the embodied cognitive perception of the models themselves. Exploring alternative physical gestures furthermore makes it possible to form and alter the very essence of an instrument extending the exploratory potential of its underlying model.

The modular approach of the PHYSMISM shows an effective way of achieving the balance between constraints and freedom and between intuitiveness and creative exploratory potential (which demands some degree of mystery, richness and complexity). The idea is to design each element of the modular system to be relatively constrained and intuitive. It is then up to the user to combine the elements in an exploratory fashion achieving more complex interaction.

2.3 PAPER III: A Quantitative Evaluation of the Differences between Knobs and Sliders

Two of the simplest continuous input devices used in electronic music interfaces today were evaluated—namely knobs and sliders. The aim was to examine whether one input device was generally preferred over the other, and if so, what the importance of that preference was. In order to weight such an importance, two secondary objectives of the study were formulated: One was to asses the importance of more expressive input devices (*touch pad, 2D slider* and *crank*). The other was to asses the importance of the synthesis engine (physical models of *flute* and *friction*).

The approach was to present test subjects with instruments that implemented different combinations of *simple input devices*, more *expressive input devices* and *synthesis model*. This gave the possibilities of 1) evaluating the differences between knobs and sliders in a variety of different contexts, thereby generating more generic results, and 2) evaluating which of the three influences have the biggest impact on the overall impression and performance of the instruments. For this purpose the SPLORER system was developed. The system was comprised of two resonator control modules (knob and sliders) and three excitation control modules (touch surface, 2D slider and crank)—see Figure 2.2. A resonator module and an excitation module must be combined to constitute an overall control interface. The modules provided the capability of combining our way to 6 different overall interfaces, and these interfaces were able to control either of two synthesis models, which gave 12 unique instruments to test on.

Test Method

Instead of conducting a pure interface usability test (like for instance a Fitt's law task based test, described in section 1.5) the majority of the evaluation focussed on the rating of perceived qualities of the overall instruments. 20 test subjects were carefully selected to participate in the study by consulting two experts within contemporary electronic music. Each test took place in the test subjects' own studio in order to copy a real world scenario as closely as possible. The actual test was comprised of three parts:

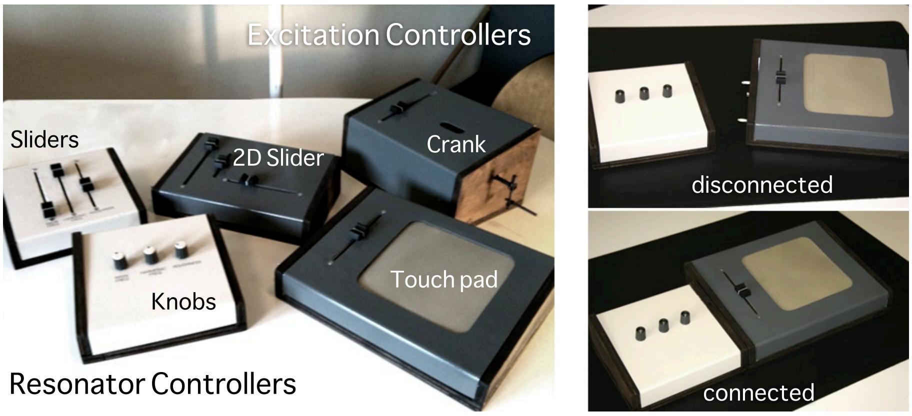

Figure 2.2: The SPLORER system was comprised of two resonator modules (white) and three excitation modules (grey). From the left they were sliders, knobs, 2D slider, touch pad and crank. The pictures to the right show how the two modular parts can be connected to form one overall instrument.

1. a 7 minute exploratory session, where subjects could explore the instrument as he or she wished.
2. a musical task, where the test subjects were asked to listen to and imitate 5 reference sounds that were prepared using the synthesis model of the instrument in question. How well the subjects were able to complete the musical task was assessed by rating how closely the audio recordings of the subjects' imitated sound resembled the reference sound it was attempting to imitate. This produced an average score for each unique instrument.
3. a Likert-style quantitative questionnaire, that was to be filled out regarding the overall impression of the instrument—they were asked to rate the instrument in regards to *accurate control, intuitive control, inspiring, frustrating, nice feel, predictable, whether it gave them musical ideas, felt like an acoustic instrument, used for composition, used for live performance, time to master* and *overall likeability.*

(The test subjects were observed during the exploration session and when performing the musical tasks). Each participant carried out the test three times, each time with a different combination of *resonator controller / excitation controller / synthesis model.*

Results

Surprisingly only slight differences were found between knobs or slider—see Figure 2.3. Unfortunately the measured differences were not statistically significant. Results from the musical task suggest that the instruments that implemented sliders provided slightly better control, but here also the results were statistically insignificant.

Larger differences were found between the different excitation controllers. The crank stood out by receiving the most positive ratings of the three. Not only did sound ratings indicate that the crank provided the best control, the crank was also rated higher than 2D slider and surface in *intuitive control, inspiring, feel, musical ideas*, and *likeability.* It was also rated least *frustrating.* 2D slider and surface received surprisingly equal ratings with the exception of *accurate control*, where 2D slider scored the highest.

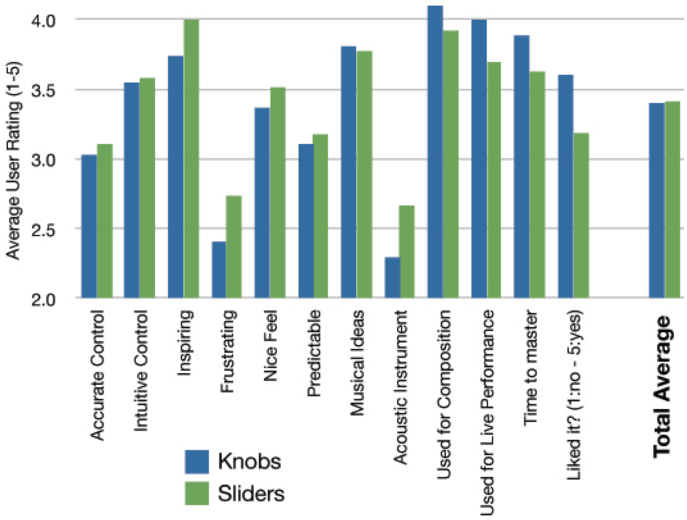

Figure 2.3: Average perceived quality ratings for instruments comprised of knobs and sliders respectively. Only slight differences were measured between knobs and sliders—but the differences were not statistically significant.

Ratings of the two synthesis models revealed considerable differences when it came to *inspiring, feel, musical ideas, used for composition*, and *likeability*, where the friction model was rated highest. Interestingly it was rated lowest in *intuitive, predictable* and *accuracy*. This could indicate some sort of tradeoff between perceived creative features and features to do with predictability and accuracy.

Discussion

Although the presented results were not statistically significant interesting aspects arose. Differences in preference between knobs and sliders definitely did exist, but it was not possible to measure whether one was generally preferred over the other. Subjective differences (based mostly on comments from test subjects) were mostly due to habits, tradition and routines.

Finally the evaluation method applied in this study is a contribution to the recent movement within the NIME research fields, where the need for more formalized testing is being articulated. This study particularly focusses on the need to use established contemporary musicians, and to perform the actual testing under circumstances that are as close to a real world scenario as possible. Comments did suggest that the task was quite boring compared to the actual instruments. It seems crucial to have users perform evaluation tasks in a context that is actually relatable to how they work in the real world. Finally, it seems that performing traditional HCI usability testing alone is not enough to understand interfaces within this highly complex world of electronic music. Results show that accuracy, predictability and intuitiveness are not unequivocally properties to strive for when developing creatively inspiring musical instruments.

2.4 PAPER IV: From Idea to Realization - Understanding the Compositional Processes of Electronic Musicians

In order to understand the compositional processes of the contemporary electronic musician, 18 Danish musicians were interviewed. Special focus was put on the approach to music making, the creative idea, and the use of musical tools. The aim was to investigate the context in which the exploratory framework presented in *PAPER II* is meant to be situated. As the framework focusses largely on exploration in the compositional process, we were interested in how exploratory processes were used, in which situations, and with what kind of tools.

Method

The interview series was conducted with the same musicians as participated in the evaluation presented in *PAPER III*. The participants were first asked to fill in a questionnaire where they were asked about their musical background, their musical approach and their use of musical tools/instruments—also asking them to give critique on their musical tools. Then a semi-structured interview was carried out after which a series of musical tasks were performed (the latter has not been presented here). Each interview lasted approximately 15 minutes and was guided by three overall questions:

1. *"What is the most typical work process for you when composing a piece of music?"*
2. *"In which situations do you find yourself most creative when creating music?"*
3. *"In which situations do you find yourself exploring when creating music?"*

Transcriptions of the interviews underwent a filtering process where the most interesting statements, viewpoints, or quotes regarding each of the above questions were extracted. For each interview, the nine most central issues (three for each question) were kept. In few cases it was decided to keep one or two additional issues. The points that remained after this filtering process were compared and contrasted using a bottom up approach. The aim was to find correlations or commonalities that could indicate general tendencies.

Results

Results from the questionnaire showed that the majority (17 out of 18) used either Logic or Cubase a their main Digital Audio Workstation (DAW). Critique given of software and hardware in the questionnaire was relatively sparse. Commonalities included: too little physical interaction (software), too linear (software)—meaning that the software would imply a piece of music to be produced linearly over time—, too many options (mostly software), hassle setting up (hardware). 15 out of 18 classified themselves as having a very experimental compositional approach. Commonalities extracted from the interviews can be grouped into 3 overall categories; (1) The overall process, (2) The creative idea, (3) The use of musical tools.

The overall approach. The overall approach seems to change throughout the compositional process. Three overall modes are proposed for describing the change of approach; the *exploratory mode, editing mode* and *pragmatic mode*—see Figure 2.4. In the exploratory mode, the composition can start with an idea but most of the time the process will start with an exploration of a musical tool, a technical phenomenon,

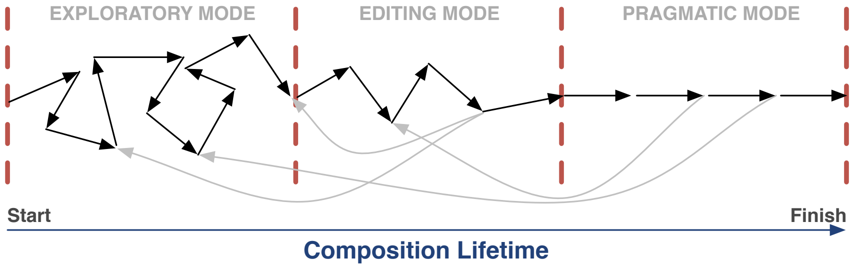

Figure 2.4: The compositional mode can be divided into three overall stages or modes. An *exploratory mode, an editing mode* a *pragmatic mode.*

a sonic space, etc.. Ideas may arise, but in most cases these will lead to new explorations. This corresponds well to the Geneplore model—see section 1.4. The exploratory mode will continue until an overall idea or concept emerges or simply if enough sonic material is gathered. The editing mode is a sort of semi-experimental mode where the end goal is in sight, but the approach is still somewhat experimental. Finally, the pragmatic mode is the very linear. In this mode the composer will have the full overview of the composition and the end goal. He or she will use well known tools at hand in finalizing the composition.

The creative idea. When asked in which situations the participants feel most creative most describe factors that are not directly connected to a compositional approach or musical tool—certain times of day, in certain locations, alone or with others, when listening to music. A creative idea that sparks a musical piece is mostly of a technical nature, a mood, an overall theme or a philosophical approach.

The use of musical tools. Especially in the *exploratory mode* participants highlight that the musical tool should somehow have "a life of its own". They use the tool in ways that were not intended, and they feed upon the unpredictable or surprising element of not being able to fully control the tool. Freedom is desired in an overall sense, but most express the need for constraints in order to be able to guide their exploration. Figure 2.5 depicts the difference between having total freedom and having overall freedom within certain constraints. The transition from exploratory mode into editing and pragmatic modes requires more precise control and predictability from the musical tools at hand.

Discussion

Results of the study illustrate some challenges involved in designing novel musical tools targeted at electronic musicians. First of all it seems crucial to determine in which part of the compositional process the tool is intended. This can help determine whether to focus on exploratory qualities or more pragmatic features, where control and predictability are desired. Presenting the user with fixed constraints can help guide the creative process, but there is also a demand for freedom in regards to ways in which the tool can be used. The tool should suggest certain types of interaction, helping the user make choices, but also letting them break free of predefined schemes. Probably due to the experimental nature of electronic music, tools are often used in unintended ways.

A modular design approach seems to balance many of the contradictory desires found throughout the compositional process. Finding the level of modularity (how simple or

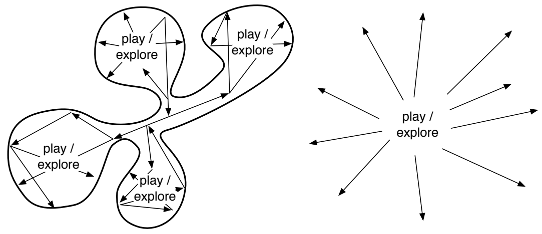

Figure 2.5: Illustrates two ways of working with musical tools. Left: Overall freedom, but within certain constraints. Right: Total freedom at all times.

complex should each element present itself?) is then the question. Designing for connectivity seems essential, as most tools that at a first glance work as isolated instruments that are used in a restricted sense, will actually be incorporated in the whole studio setup of the electronic musician.

Finally it is important that the findings are based on interviews with a carefully selected group of musicians. They represent the experimental part of electronic music in Denmark. Larger studies must be conducted in order to make more generalized deductions. Furthermore there were also considerable deviations from the major findings within the interview sample (mostly regarding musicians with a programmer approach). For future studies it might be interesting to divide the sample into nationality, hardware/software preferences, and even age (it seems that especially the younger generations differ in the way they approach experimental electronic music).

2.5 PAPER V: PHOXES - Modular Electronic Music Instruments based on Physical Modeling Sound Synthesis

The paper describes the development and pre-testing of a system of physical modeling based electronic instruments—namely the PHOXES. The system is modular, meaning that each individual elements can be combined to form larger systems, that can be physically and sonically explored. Both the design directives presented in the exploratory framework described in *PAPER II*, and inspiration from the HCI field of creativity support tools have served as inspiration for the development of the PHOXES. Additionally the focus has been on controlling physical models in a way that can facilitate the creative work processes of the electronic musician.

Each individual module consist of the same elements. They each implement a physical model (*tube, particle, friction*, and *drum* respectively), four knobs for adjusting model parameters, an excitation device (*flute, crank, slide surface*, and *drum pads* respectively), and a menu system for controlling mapping settings.

The user performs a gesture using the excitation device to inject energy into the model. He or she can then adjust different model parameters (such as length of tube, size of drum, roughness of friction) by manipulating the four knobs. The PHOXES can be played as individual instruments with clear constraints in a relatively straightforward interaction. Here it is possible to explore the sonic diversity of each model obtained by adjusting different settings of the model parameters, by exploring different physical gestures associated with the excitation controller, and exploring the interplay between the two.

The PHOXES can also be combined in various ways in order to extend the creative capabilities of the models. This is done by controlling what injects energy into a PHOX.

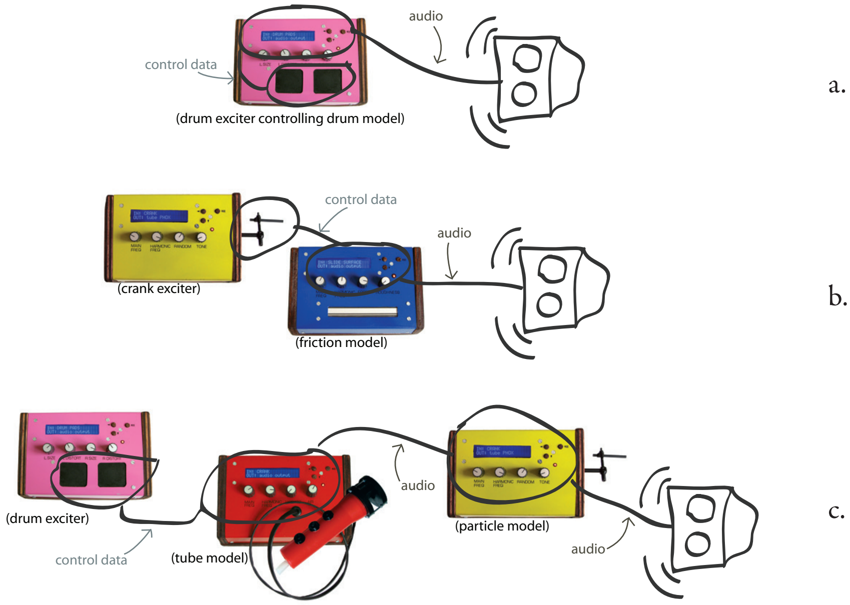

Figure 2.6: The modularity of the PHOXES. (a) PHOXES can be played individually, (b) It is possible to use any excitation device for injecting energy into a PHOX, (c) PHOXES can also be combined by letting the sound output from one PHOX serve as energy for exciting a different PHOX.

By default a PHOX gets its energy from the default excitation controller associated to that PHOX (for example the flute is associated to the tubePHOX). But the user is also able to use any of the other excitation device associated to the other PHOXES (for example using the flute to drive the frictionPHOX). On top of that it is also possible to use sound output from one PHOX to drive another, transforming the physical model of that other PHOX into a kind of audio effect. The idea is to extent the exploratory capabilities of the models, by making it possible to interact with them in many different ways. At the same time the modular approach balances the need for low thresholds, high ceilings and wide walls, while also balancing the need for freedom within certain constraints. See Figure 2.6 for an overview of the modular approach.

Pre-test

A pretest was conducted in order to evaluate the exploratory qualities of the PHOXES and how those were integrated in the work processes of contemporary electronic musicians. The main goal of the pre-test was to identify methodological and technical issues that might arise from this sort of approach. The method explored a longitudinal approach where an established electronic musician borrowed the PHOXES for 10 days. The test was totally free. There were no tasks to be carried out and the test subject was asked to treat the instruments as any other instruments that he had borrowed or bought. It was important not to give any suggestions as to how the instruments could be integrated in the existing work practices of the musician in order to see how the freedom would influence the evaluation process.

After having been introduced to the PHOXES, the user was asked to fill in a questionnaire. We used the AttrakDiff evaluation form (Hassenzahl et al., 2003) that let the user rate the instruments using Likert-style bipolar word-pairs associated to both hedonic and pragmatic issues (for instance *impractical-practical, cumbersome-straightforward, dull-captivating, discouraging-motivating*). After the 10 days test period the user was asked to fill in the evaluation form again, and a semi-structured interview was conducted with the focus on how the subject had worked with the PHOXES, how they were integrated into existing processes, how working with the PHOXES changed over the test period, and which kind of technical issues might have arisen (including suggestions for improvements).

Results and Discussion

Data from the questionnaire and the interview indicated that the PHOXES succeeded in being motivational and stimulating to work with. It was pointed out how easy they were to initially approach and that they felt like playing an acoustical instrument. They were easy to set up, they felt durable, the physicality of the interaction with the models was very inspiring and finally, they sounded amazing. Two major issues were discovered, which were crucial for the methodological approach. The first had to do with the fact that the subject did not get to fully explore the modularity of the system. Either the modularity was not presented in an intuitive enough manner—demanding too much effort from the subject—or the subject simply did not have enough time, meaning that the evaluation method needed to be altered to accommodate this issue. A compositional task could be introduced or the evaluation period could be extended (both measures ended up being used). The second issue had to do with computation of the models. The models were run on the test subject's own computer, which would demand so much DSP CPU load making it almost impossible to use the computer for other musical activities. This was a crucial point as the intention with the evaluation was to asses how the PHOXES were incorporated into existing compositional work processes.

2.6 PAPER VI: Longitudinal Evaluation of the Integration of Digital Musical Instruments into Existing Compositional Work Processes

In this paper, a longitudinal approach to evaluation of new digital musical instruments is proposed and used to formally evaluate the PHOXES described earlier in *PAPER V*. The paper discusses how to evaluate user experiences involved in learning and adopting a new digital musical instrument by looking towards recent movements within HCI, where more and more focus is put on longitudinal experience evaluation. This is used to propose a an evaluation framework that emphasizes the importance of addressing real world issues arising as users integrate new musical tools into their existing work processes. The PHOXES are evaluated in a compositional setting (as apposed to a live performance setting) using an in-depth holistic approach.

Evaluation

The paper describes how the pretest described in *PAPER V* was extended leading to a qualitative longitudinal evaluation design developed for evaluating the experience of integrating the PHOXES into existing work process of commercial electronic musicians. The evaluation involved lending the instruments to three selected commercial electronic musicians for a duration of four weeks. The electronic musicians where chosen based on a set of criteria insuring that they all had a somewhat experimental approach to music making while still differing from from each other. Two individual show and tell sessions were used to gather information from the participants about their use of the PHOXES throughout the evaluation phase, one after two weeks and one after four weeks. The sessions, which were set in the test person's normal work environment, involved individual semi structured interviews where the test persons were encouraged to illustrate various issues that were verbally reported by physically showing how they occurred using the PHOXES or other tools at hand. Everything was video taped and transcribed for further qualitative analysis—see Appendix A for the interview guide.

The test period was divided into three phases. During the first two weeks the test persons where totally free to explore the PHOXES in any way they liked. The third week involved a compositional task, which was meant to force them to explore parts of the system that they had not already worked with. During the last week the test persons where again free to use the system as they saw fit. Three sets of the PHOXES were produced and the tests were carried out over two months.

The analysis of the show and tell interviews was carried out employing a bottom up approach inspired by grounded theory (Corbin and Strauss, 2008), where the transcriptions underwent a filtering process used to reveal patterns that would point to key issues having to do with the experience of using the PHOXES in this context. Statements and actions were first coded and then recoded. Code words such as *sound, learning, exploring, other tools, etc.* were partly derived from preconceptions of what issues where most important and partly emerging from working with the data. By employing an iterative process in the codification process, one is open towards surprising and unexpected issues arising from the data—see Appendix B for an overview of code words and for excerpts of the final codification.

Results and Discussion

Results point towards 9 main issues that arose from the data emphasizing the importance of context and pointing to central issues such as playability, explorability and connectivity. Some of the issues had to do with the methodological approach including the impact of technical difficulties and compositional task, while others point to the influence of context on the experience with working with the PHOXES including connectivity and integration with other tools. Finally, results revealed important issues related to exploration and playability of the PHOXES and with digital musical instruments in general.

There was a large difference in how much and how well the PHOXES were integrated into the work processes of the three test persons. While one test person succeeded in embracing the PHOXES using them in his own work, the other two only explored the PHOXES to a minimum extent. While some reasons have to do with external issues (sickness, snow, Christmas), many had to do with the context in which the PHOXES were explored and the differences in musical approach between the three test persons.

The importance of context became apparent throughout the show and tell sessions as everything that was reported about the PHOXES was said in relation to the context. Very seldom did the test persons show or play passages that were made purely using the PHOXES—everything was somehow processed, cut up, or in other ways manipulated using other musical tools. Additionally, the test subjects all mentioned the lack of MIDI support as an important issue in how they ended up using the PHOXES. This emphasizes the importance of thinking about existing tools and processes when anticipating how these new tools are used in such compositional settings.

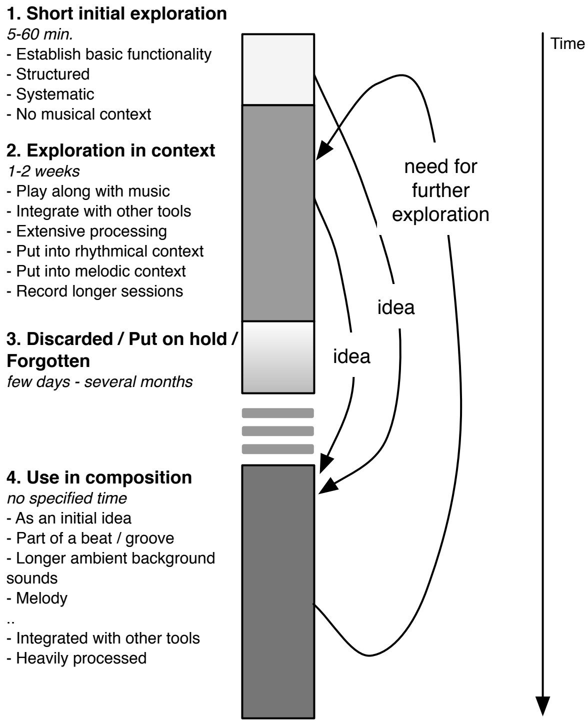

Figure 2.7: The learning process involved in adopting and integrating the PHOXES into composition would go through several stages of exploration. Time periods for each stage are suggested to illustrate their temporal relation.

Playability, which the test persons defined as the immediate and refined musical control of the instrument (playing the instrument as one would an acoustic instrument, as opposed to in a compositional/editing mode), was a large concern. The PHOXES were reported to focus too much on exploration of timbre alone, and not enough on playability issues such as note control, melody, harmony and rhythmical structure.

The learning or adoption process was interestingly very similar for the three test persons and was reported to be typical of how they normally would adopt a new musical tool. Figure 2.7 illustrates how there would be a short systematic exploration of the different features of the system after which they would be integrated into a musical form. This important integration would help the test persons understand the system's capabilities in a musical context. There would then be a phase where they would somehow put the instrument or tool on hold until a possibility arose where it would make sense to use it. As can be seen from Figure 2.7, the last three stages do not follow a strict sequential form.

The modularity of the PHOXES that was developed in order to accommodate the need for a balance between constraints and freedom needed for exploration was not used to its full potential. Only one of the test persons found reoccurring use of a combination of PHOXES. Otherwise the PHOXES were mostly used on their own. This seems partly to do with the lack of intuitiveness of the combination feature either because of difficulties with using the menu system or an unclear cognitive understanding of the PHOXES as a system. It seems that the focus on making music here and now demands for an extremely straightforward interface, and that the exploration needs to be easier to access immediately (e.g. the patching system implemented by using physical chords used in the PHYSMISM seemed more effective than pressing buttons to toggle through menus).

From a methodological point of view several important issues were found throughout the evaluation. The test subjects emphasized the naturalness in how the test was carried out. They all emphasized the importance of the free exploratory phase for getting to know the instrument, but also the familiarity of having a deadline throughout the compositional task. The goal of creating a natural non-intrusive test design was definitely achieved with the overall structure. On the other hand technical mishaps with the PHOXES had too much influence on how they had been used throughout the test phase. When carrying out longitudinal evaluations where one has limited control over the test environments, it is crucial that the prototypes that are tested work under extreme circumstances. Finally, the show and tell sessions worked well as they would force the test persons to reflect more carefully about their experiences. There were several instances were test persons would show something differently, recall issues they had forgot about or change their mind because they had to physically show what they meant, both regarding interaction with the PHOXES and with their other tools. Subjects would exhibit positive experiences with parts of the instrument that they had discarded or been critical towards while showing which parts did not work, or they did not like.

For future evaluations it would be interesting to explore more multidimensional methodologies, combining qualitative and quantitative methods, while also exploring ways of dealing with the problems associated with retrospective assessment.

Chapter 3

Conclusion

Throughout this thesis the overall motivation has been to examine how new digital musical instruments based on physical modeling can be developed so they facilitate exploration and creativity. In particular, I have been interested in developing instruments that integrate naturally into the working process of the commercial electronic musician in a compositional setting, while at the same time exposing the musicians to the exploratory potential offered by a flexible physical control scheme, a scheme that fits well with the nature of physical modeling sound synthesis. Finally, the thesis has investigated new evaluation methods inspired by recent movements within HCI that emphasize the importance of real world context. In this chapter I will first conclude on my findings, after which I will summarize the major contributions of the thesis. Finally, I have included propositions for future work within the topics addressed throughout this thesis.

3.1 Conclusions

In PAPER I and PAPER II a new interface for the exploration of physical models was developed, where the development itself was rather exploratory. The motivation was to take the strengths of physical modeling and adapt them to a hardware synthesizer metaphor that was well-known to electronic musicians, but while doing so, opening up for more gestural exploration (meaning also that they were forced away from the traditional MIDI keyboard interaction metaphor). This work helped formulate a set of design directives for exploratory control of physical modeling, which focuses on the synthesis model, the physical control of the model, and the modularity of the system as a whole. At the same time it helped defined the framework that was used throughout the rest of the thesis. It became clear that exploration could be encouraged not only on a sonic level, but also by providing exploratory possibilities on a gestural level. Furthermore, the modular approach taken here has been continued on throughout the thesis, as it became clear that the ability to combine the physical models enhanced the exploratory capabilities of each model. Finally, the evaluation carried out in this study gave indications of the importance of context, when evaluating new digital instruments. This became a focus point throughout the thesis.

PAPER IV took many of the ideas that arose while working with the development of the framework and used them for carrying out a series of semi-structured interviews with 18 contemporary electronic musicians. The goal was to understand more about the compositional context, the importance of which has been emphasized throughout this thesis. Special focus was on how the subjects conceived musical ideas, engaged in creative activities, explored musical tools, and on how these issues would change throughout the overall process. The most significant findings emphasize how the need for exploration changes throughout the process of composing a piece, and how creative exploration is facilitated best by balancing freedom and constraints, and intuitiveness and unpredictability.

In PAPER III presents an attempt to carry out a low level evaluation of simple input devices within the framework described above. From a methodological perspective the idea was to explore how lower level task-based evaluations could be conducted while still taking the exploratory creative context into consideration. The major challenge one faces is that carrying out these quantitative evaluations might demand setups and musical tasks that become musically unnatural for the test participants. This has the danger of leading to results that are inaccurate or weighted wrongly because they represent something that takes place in an unnatural context. Several methodological handles were implemented in order to avoid this. They included a more careful selection of test subjects than normally used in these kinds of evaluations, carrying out evaluations in natural or familiar environments and a mix of free exploration and constrained musical tasks. The goal with the study was to asses the importance of different influences of the overall perception and performance of the instrument. Although results were statistically insignificant they suggested that differences between simple input devices (knobs and sliders) had little or no influence. It seemed that differences between more expressive input devices and differences between sound synthesis models had an increased influence. While contributing to the field of task based evaluation of musical instruments, the research also pointed towards some of the difficulties with these highly constrained evaluations. This later lead to the more qualitative and subjective evaluation methodology where fewer musicians were exposed to the instruments for longer periods of time—a so-called longitudinal approach.

The goal pursued in PAPER V and VI was thus to evaluate a set of modular physical modeling based instruments in regards to how they were integrated into the natural work processes of a representative selection of electronic musicians. Focus was put on understanding the context in which they were integrated and on discovering which design elements had an influence on how creatively the instruments were used. In short, results suggest that there is a general learning/adoption process that goes through defined stages. They also suggest that the instruments were too focussed on creative exploration of the sound models in regards to timbre and gesture, and that intimacy, immediate playability and accurate control was more important to creativity and to the exploratory compositional process than first presumed. Finally, connectivity proved to be a huge issue for creative exploration, which also emphasizes the importance of context in these kinds of evaluations.

The methodology that was used seemed to be successful in regards to establishing a natural test-environment, which subjects reported as being very close to how they would normally adopt a new musical device. However, the study also showed how vulnerable the method was to technical mishaps, personal factors regarding the test participants, and finally that the freedom given to the participants meant that parts of the instruments were not explored.

3.2 Contributions

Besides the development of the actual digital musical instruments, the thesis presents two overall contributions to the field of new digital musical instruments:

1. Contributions to the understanding of how to develop musical interaction for encouraging exploration and creative use.

2. Contributions to the the field of evaluation methodologies for new digital musical instruments, emphasizing the need for more qualitative in-depth context dependent evaluation methods.

Although the control of *physical modeling* has been the focal point throughout the thesis I believe that the majority of the findings regarding exploration and creativity and regarding evaluation methodology can be applied to the development and evaluation of digital musical instruments in general. Creativity is at the very core of musical expression and being able to develop for it and evaluate its effects is important if we wish to grow and evolve musically with help from technology.

3.3 Future Directions

The following will summaries on how the presented research has sparked ideas for future work within the field. Four overall areas within creativity and exploration of musical instruments are presented here, that leave room for interesting further work; gestural exploration, unpredictability, modularity and connectivity and finally, overall methodology.

Gestural exploration

An important part of the framework presented throughout the thesis has dealt with the notion that with physical modeling one can achieve a more natural and intuitive connection between gesture and sound, because physical modeling naturally possesses a perceived causality that can be difficult to achieve using other synthesis methods. It would be interesting to explore the causality principle further both in regards to how important it is for intuitive control, but also in regards to differences between physical modeling and other synthesis techniques. For instance one could compare various gestures and mapping metaphors for controlling different models focussing on when the perceived causal relationship is diminished. Another interesting study would be to investigate possible differences in perceived energetic relationship between gesture and sound, and what this does to the intuitiveness of the mapping.

The crank in conjunction with the particle model has been especially interesting for musicians throughout this study. Besides the actual sound of the particle model, there seems to be two reasons for this. The first is the truly continuous gesture used for manipulating the crank. The other has to do with the stochastic element of the particle model. It would be interesting to explore various forms of continuous gestures in conjunction with stochastic variation for controlling audio in general (for stochastic triggering of events, for semi-random manipulation of audio effects, etc.)

When using the crank to control the particle model many have noticed that there is almost a sensation of tactile feedback in the crank. It could be interesting to explore what the addition of e.g. vibrotactile feedback has on the exploratory qualities of an instrument where the feedback is used as an additional communication channel (direct sound, for communicating timbral qualities of the sound, etc.).

Unpredictability and unintended use

An issue that has surfaced many times throughout this thesis is that many electronic musicians feel most creative when using a tool in unintended ways. This is nothing new. One does not have to look far to find musical tools that have had a great impact because they were used in unintended ways (turntables, distortion guitar, etc.) It would be interesting (but also challenging) to further investigate the idea of designing for unintended use. What is unintended use? What is intended use, and how constrained should the intensions be to make it interesting to break them?

Another closely related issue that arose throughout the thesis regards unpredictability and how unpredictability can spark creativity and exploration. It would be interesting to develop and evaluate interfaces that where designed solely for being unpredictable. For instance an instrument could implement 8 knobs that would automatically be mapped differently to the synthesis model each time you used it. It would also be interesting to carry out a line of experiments where parameter control was distorted at different levels, in order to explore the relationship between accuracy and unpredictability. How random can for instance the sonic variations be while still supporting playability? Is there a certain threshold for when unpredictability compromises accurate control? And what happens when users have control over the unpredictability (the notion of an unpredictability knob)?

Exploring modularity and connectivity

Although the modularity of the instruments developed throughout this thesis has shown to enhance the creative potential of the implemented models, there were unsolved issues regarding how to control the modularity. I would like to explore possibilities of controlling modularity, especially on the PHOXES (see PAPER VI). One way would be to return to physically connecting devices (using for instance patch coords). This seemed to be very intuitive and immediate for the musicians (although musicians did complain that wires are an inconvenience when working with hardware). Another approach could be to use a form of auto-connect for connecting the different PHOXES (as seen with great success in for instance the Reactable by Jordà et al. (2007)). This could be done by exploring a proximity sensing system implemented using RFID tags and readers. Finally, it could be interesting to explore completely different domains for implementing the modular metaphor (Reactable, music blocks, etc..), while still providing exploratory physical gestural capabilities.

While connectivity has been emphasized throughout the thesis as being crucial for facilitating exploration, one needs to realize the creative strengths of tools that do very few restricted things and which also have a low degree of connectivity. The idea of the modular approach is that you can work with something in a constrained manner while still being able to export it, use it to control something else, or use it to somehow interact with other elements, leading to an overall exploratory freedom. The strengths of learning smaller constrained elements before connecting them to explore more complex structures not only presents a natural learning curve, it also balances the creative guidance of the user. However, there is reason to believe that especially very experimental artists see the benefits of using elements that are not naturally connectable. Sonic, control-related, or idea-related artifacts can emerge as a result of transferring work between two domains that are not easily connected. Besides the mere challenge of connecting the elements, these artifacts help spark the creative exploration of new ideas.

Evaluation Methodology

I am interested in further exploring evaluation methodologies implemented throughout this thesis. It would be interesting to conduct a more practical (show and tell) set of interviews with musicians to further understand the creative compositional process. There should be more focus on establishing well-defined categorizations of the musicians based on their compositional musical approach and the way they use tools in their work. While quantitative investigations of this sort have been carried out by for instance Magnusson (2007) it would be interesting to keep within the more qualitative approach pursued throughout this thesis. Extending the retrospective show and tell method, implemented in PAPER VI, to work in more open interviews would be interesting.

In relation to this, it would be interesting to explore differences between the think aloud method by Ericsson and Simon (1993), the retrospective show and tell method presented here, and other reflective methods proposed by for instance Karapanos et al. (2010).

Inspired by the evaluation of simple input devices in PAPER III, it would be interesting to explore and compare musical evaluation tasks in regards to musical naturalness. A balance needs to be found between the simplicity of the task, which is important for being able to compare results and the interestingness crucial for establishing the appropriate musical context. Another interesting direction could be to implement musical evaluation tasks that involve the environment of the test participant (test participants could for instance be asked to perform a musical phrase using the instrument in conjunction with another device of their choice).

Finally, I would like to implement evaluation schemes that combine overly simplistic task based quantitative methods with in-depth context dependent qualitative methods. The mix of the two can be used not only for drawing inspiration from each other, but also for validation purposes (if something is true both in a highly controlled quantitative study and in an in-depth qualitative context dependent one, then there is a good chance it is in fact true).

3.4 Concluding Remarks

This thesis has hopefully contributed to understanding the complex ways in which creative ideas and activities develop when playing and composing with digital musical instruments. Furthermore it is my hope that the thesis can inspire more research to be carried out in this interesting field of musical creativity.

Thank you.

Chapter 4

Appendices

4.1 Appendix A - Interview guide for PHOXES evaluation (PAPER VI)

The following is a copy of the interview guide used for the show and tell sessions performed when evaluating of the PHOXES described in PAPER VI.

How would you characterize the sound?

- accurate simulations?
- sounded like real acoustic sounds? (plausability)
- sonic diversity?

How did the physicality of the interaction influence the way you used the PHOXES?

- Did using another gesture to control the same synthesis have an influence on the sound?
- Were there latency issues?
- user has to work... good/bad
- accurate control?
- exploration of gestures..? how much and in which way?
- Did you understand all control parameters?

Did you feel creatively inspired and why/why not?

- Motivated?
- Sparked new musical ideas?
- Integration with other software/hardware? (connectivity)

Overall issues

- Favorite instruments/combos?

- mostly synth or audio effect?
- - Aspects you didnÕt use so much?
- live vs. studio/composition?
- tonality vs. free mode?
- mobility? (the bag :-)
- how long would you keep playing the phoxes?
- (social aspects?)
- Improvements?

Visual

- How do they look?
- Do you think it influences what you think of them? how much? why?

Where there any technical issues?

- Did you use the manual at all?
- How easy were they to setup?
- How often did they not initialize properly?
- Did they crash a lot?

4.2 Appendix B - Interview codification data for PHOXES evaluation (PAPER VI)

The following is excerpt of the codification data used to analyze the show and tell sessions in PAPER VI. The interviews were first transcribed and coded (those data sets are too large to include here). The data presented here is a result of the re-codification of the transcribed and coded data. It has been used to inform the overall results presented in PAPER VI. Figure 4.1 is an overview of the code-words used for codification of the interview data. The following tables are excerpts of actual codification data and are divided into three columns: Summary of the observed, code-word, test subject, where to find the original transcription.

Technical			Test							
Problems			Composition task					Presets		
Limiter			Instruction					Limits		
			context							
					Live	Genre				
					Studio	Performance				
					collaborations					
pads										
drum										
tube										
particle										
friction							Tonality Control	Notes/Keys		Sound generation
							Melodies	Tones		Timbre
Combinations							MIDI	MIDI vs. samples		Music vs. sound
Parameters										sound
Exitation Devices										Sound vs. Instrument
External Sound										
					INTEGRATION	Portability				Playability
					Other Gear	"wrong sound"	External Sound		Playing Technique	
					Creativity	Potential			Interface	
					Constraints	Raw material		Gesture/Sound/ Feeling	organic feeling	Accuracy
				Engaged	Motivation				Physical Control	
					unpredictability	randomization			Physical interaction	Intuitive
					Exploration		Approach		Overview	
					Learning	Misunderstanding the instruments			Ease of play	

Figure 4.1: Overview of the different code-words used in the codification of data. They are grouped together in regards to relation.

Table 4.1: Technical Issues - 1 of 1

trouble with the drumPHOX being buggy	drum	Subject 2	Initial - 8
Difficult to start up.. 2-3 times... difficult to see what the process is and if you are doing it wrong	startup	Subject 3	Initial - 1
Drum pads had too much latency..	latency	Subject 3	Initial - 1
problems with tube... but didn't matter.. just tried again and it worked fine	tube	Subject 1	Initial - 1
Had to put on a limiter	limiter	Subject 1	Initial - 1
Squeeky crank	crank	Subject 1	Initial - 4
Had to disable drum	drum	Subject 2	Final - 1
PHOXES work smooth without drum	drum	Subject 2	Final - 6
The fact that it was so difficult to start up.. and sometimes buggy interfered with how the PHOXES were perceived	startup	Subject 3	Final - 1
Was not able to take it home... (too much of a hassle)	portability	Subject 3	Final - 1
Particle would have its own life... didn't course too much trouble but was again irritating	crank	Subject 3	Final - 3
No latency please.. both drums and friction.. gives more rhythmical possibilities	latency	Subject 3	Final - 7
No technical problems.. easy to just start.. had them setup so they were ready to go.. even took them to a friend without problems	no problems	Subject 1	Final - 13

Table 4.2: Specific Phoxes - 1 of 3

mostly had crank control other things	combi	Subject 3	Initial - 1
Difficult to explore combinations when there is no tonality	combi	Subject 3	Initial - 1
has tried the routing.. likes to modulate things.. is used to it from modular synths	combi	Subject 2	Initial - 3
Only tried to combine crank with others	combi	Subject 2	Initial - 7
Drum controlling friction - good for controlling a sort of opening/closing of the friction noise	combi	Subject 1	Initial - 2
Nice routing system .- that works	combi	Subject 1	Initial - 3
Didn't go for creating feedback loops as he had wanted	combi	Subject 3	Final - 5
Nearly only played them individually... carried on to making music/mixing/editing	combi	Subject 3	Final - 5
Only used PHOXES individually	combi	Subject 2	Final - 2
plays drum through friction - with hardly any effects - they sound good as they are.	combi	Subject 1	Final - 1
Has not gone into depth with combinations	combi	Subject 1	Final - 5
Expressive play on crank	crank	Subject 2	Initial - 5
Crank is more fun	crank	Subject 2	Initial - 5
Crank is better.. more alternative gestures.. makes you think	crank	Subject 2	Initial - 8
Crank is good.. but will maybe look weird on stage	crank	Subject 3	Final - 4
plays expressively on the crank..	crank	Subject 2	Final - 6
works on the "tone" of the particle	crank	Subject 2	Final - 6
Drum has too much latency	drum	Subject 3	Initial - 1
less latency or control it with MIDI	drum	Subject 3	Initial - 1
drums.. not so good friends	drum	Subject 2	Initial - 2
drum is boring.. few sounds... sounds don't "scratch" enough... you could use many other percussion sounds instead	drum	Subject 2	Initial - 8
pads are seen before	drum	Subject 2	Initial - 8
Pads are not good for fast accurate beats	drum	Subject 1	Initial - 2
drumPhox sound is very dominent.. difficult to mix/edit	drum	Subject 1	Initial - 4
Would be able to use long time on playin drum if the pads were good enough.	drum	Subject 3	Final - 2
Gets more interested in drums when he shows them	drum	Subject 3	Final - 2
Didn't use drum at all in final session	drum	Subject 2	Final - 1
Likes the digital edge of the drums.. compared to other acoustic drums (bongo)	drum	Subject 1	Final - 2
Wants more parameters, but then rationalizes himself to that he could have combined more to get more parameters - is not sure why he didn't do that.	drum/combi	Subject 3	Final - 4
drum also needs more parameters, more pads	drum / parameters	Subject 3	Final - 3
Has also tried to send sound to particles and drum	external sound	Subject 2	Initial - 7
Expressive play on flute	flute	Subject 2	Initial - 5
Flute is fun but seen before	flute	Subject 2	Initial - 5

Table 4.3: Exploration / Learning - 1 of 3

Interested in finding out how to take new gear places it was not intended	learning - exploration	Subject 2	Initial - 2
Seems like he systematically manipulates the parameters one at a time... [from observation]	learning / exploration	Subject 2	Initial - 6
Is new to MachineDrum AND PHOXES so they are explored together	learning / exploration	Subject 2	Initial - 7
Just turned all the knobs to see what happened	learning	Subject 3	Initial - 1
played around a bit	learning	Subject 3	Initial - 1
Has learned them pretty well... but not gotten to really use combination / tonality because he didn't get it or he didn't have anything to use it for	learning	Subject 3	Initial - 2
First systematic through every phox - then combined them... but didn't get to the interesting feedback/unintentional use	learning	Subject 3	Initial - 4
First explore the instrument alone... then hope it sparks idea.. integrate it... if it doesn't do something pretty fast it is left behind	learning	Subject 3	Initial - 4
Most important is how it works with the music	learning	Subject 3	Initial - 5
15 minutes to understand new gear... then it goes on the shelf until I get inspired to use it...	learning	Subject 3	Initial - 5
Normally plays a lot with gear.. makes "sketches"	learning	Subject 2	Initial - 1
Started with the phoxes alone... then brought them into the drumMachine	learning	Subject 2	Initial - 6
First systematic through every phox - but want to put them into context fast..	learning	Subject 1	Initial - 3
You understand them right away.. they are very hands on.. and the routing system just works	learning	Subject 1	Initial - 3
never learns synthesizers fully... is too focussed on the context / making music/pieces	learning	Subject 3	Final - 5
particles opened up fast... then friction and tube	learning	Subject 2	Final - 3
says that he feels he knows them well... [but there are still misunderstandings especially regarding combination]	learning	Subject 1	Final - 8
dosn't understand precicely how they work.. but there are only 4 parameters so they are still easy to learn	learning	Subject 1	Final - 9
have combined them but difficult to incorporate in his music because of it not being tonal enough	exploration	Subject 3	Initial - 1
One wants something to happen pretty fast when exploring... otherwise it is on to something else	exploration	Subject 3	Initial - 3
Crank makes something happen..	exploration	Subject 3	Initial - 3
Drum does not make something happen.. latency	exploration	Subject 3	Initial - 3
Has not explored the "audio In"	exploration	Subject 3	Initial - 4
Be lead by the parameters	exploration	Subject 2	Initial - 2

Table 4.4: MIDI - 1 of 2

MIDI input could help with latency of drums	MIDI	Subject 3	Initial - 1
MIDI would make it better for Live stuff	MIDI	Subject 3	Initial - 6
Crank with MIDI would really be interesting	MIDI	Subject 3	Initial - 6
MIDI signal from stochastic crank would be interesting with filters/modulations and such	MIDI	Subject 3	Initial - 7
Says right away that we would love to have MIDI in/out - for sequencing especially	MIDI	Subject 1	Initial - 1
Uses MIDI a lot.. makes demos...	MIDI	Subject 1	Initial - 1
MIDI would make it a cool live instrument - sequencer	MIDI	Subject 1	Initial - 2
A MIDI sequence would free a hand... I am very used to that	MIDI	Subject 1	Initial - 2
MIDI had made a really big difference.... both in/out	MIDI	Subject 3	FInal - 1
The drum with MIDI pads would be really interesting (he is a drummer) - would like a drum pad with dedicated controls for adjusting drum parameters	MIDI	Subject 3	FInal - 2
Crank with MIDI keyboard for controlling tones would work	MIDI	Subject 3	FInal - 3
PHOXES are not really well controlled... and there is no MIDI support... so they end up between two chairs... it′s about playability	MIDI	Subject 3	FInal - 4
Would keep the particlePHOX if it had MIDI in/out	MIDI	Subject 3	FInal - 5
Asks again for MIDI in...	MIDI	Subject 1	FInal - 5
Is in doubt whether he would prefer keys because the randomness makes you work differently... pushing you to new boundaries.. however, he would like MIDI	MIDI	Subject 1	FInal - 6
Tones / harmonies is important, and MIDI would make it easier	MIDI	Subject 1	FInal - 6
No MIDI on drums has made him create beats he would not have made with a sequencer	MIDI	Subject 1	FInal - 12
You might get inspired by the challenge of no MIDI... but then you need better tonal control... not enough to quantify the knob... too delicate	MIDI - constraints	Subject 3	FInal - 6
Tried the sampler approach with Machine-Drum but the PHOXES show more potential... they are more handplayed	MIDI - constraints	Subject 1	FInal - 3
It has been difficult to work with PHOXES because of no keys / MIDI, but then you achieve something else... when working with them in a sampler	MIDI - control	Subject 1	FInal - 2
It is okay with no MIDI if there is a playability (the crank has it)... but you can′t just isolate timbral exploration ... it needs to be used for music	MIDI - playability	Subject 3	FInal - 7

Table 4.5: Sound - 1 of 3

wrong sounds from friction are interesting	sound - wrong	Subject 2	Initial - 6
wrong sounds from friction foundation for composition	sound - wrong	Subject 2	Final - 1
dusty sound of tube	sound - tube	Subject 2	Initial - 2
tube sound as basis - floating melodic sounds	sound - tube	Subject 2	Final - 1
doesn′t like the airiness of the tube	sound - tube	Subject 2	Final - 5
tube sound can replace other synths... they sound more analogue	sound - tube	Subject 1	Final - 7
Ever phox is within same timbre spectrum... not so musical	sound - timbre	Subject 3	Initial - 4
abstract sounds	sound - timbre	Subject 3	Initial - 4
More free in their sound... demands more from the user	sound - timbre	Subject 1	Initial - 5
Will work more with the composition ... they make some really fun (nice) sounds.. especially particle bell sounds	sound - timbre	Subject 3	Final - 2
friction makes a nice little ekko there... looks for the little subtleties	sound - timbre	Subject 3	Final - 2
(during the show and tell).. he rediscovers many nice sounds in the long recording that he says.. oh, I also wanted to use that one	sound - timbre	Subject 3	Final - 6
You can′t isolate exploration of timbre.. there has to be a certain amount of playability/control... something that helps me make music faster	sound - timbre	Subject 3	Final - 7
more focus on timbre than on control... although he unconciously plays quite expressively to gain the timbres...	sound - timbre	Subject 2	Final - 3
Phoxes almost sound like hardware.. they are very bombastic.. he is puzzled about this	sound - timbre	Subject 1	Final - 4
When exploring timbre, he is very aware of the mix... low cut if it interferes with the bass track, etc...	sound - timbre	Subject 1	Final - 5
particle with low tone is common.. friction is difficult to find elsewhere	sound - timbre	Subject 1	Final - 6
Looks for something that harmonizes with the rest when exploring	sound - timbre	Subject 1	Final - 6
plays other of his own tracks to illustrate how phoxes could be used for the analogue edge	sound - timbre	Subject 1	Final - 7
they sound great.. (talking about a concrete track where is uses them)... they just take up so much space	sound - timbre	Subject 1	Final - 12
Good when synthesizers have a distinct sound	sound - timbre	Subject 1	Final - 12
because of their sound the ideas were rhythmical	sound - rhythm	Subject 1	Initial - 3
when using noise it has to be more rhythmical	sound - rhythm	Subject 3	Final - 5
white noise from phoxes is used rhythmically	sound - rhythm	Subject 1	Final - 2
uses phoxes sounds as raw material to work / edit /mix /cut	sound - raw material	Subject 3	Initial - 5

Table 4.6: Playability / Interface - 1 of 2

constraints can be good but only to a certain degree... I want to be helped as an electronic musician.	constraints	Subject 3	Final - 6
difficult to control them, when you don′t really know them too well	control	Subject 3	Final - 2
friction is impossible to control... so I have done a lot of editing afterwards... the others were easier (not so much clipping)	control	Subject 2	Final - 4
The difficult/challenging control brings something to the music...	control	Subject 1	Final - 11
something fun has to happen fast... or you are on to something else.. crank has it	crank	Subject 3	Initial - 3
likes the organic feel of the crank	crank	Subject 3	Initial - 6
expressive crank play	crank	Subject 2	Initial - 5
It just feels more like an instrument when everything is there right away.. better for creativity... no menu systems	creativity	Subject 3	Final - 5
latency on drums	drums	Subject 3	Initial - 1
crank is fun to play	ease of play	Subject 3	Final - 3
friction , particle and drum are easy to make good sounds with... tube is not my friend	ease of play	Subject 1	Final - 9
the need for continuous energy brings something to the sound	energy	Subject 1	Final - 3
works with the params of the drum / the friction slide surface in different ways	expressive	Subject 1	Initial - 2
A filter would be good for zooming in to learn the harmonics, etc..	filter	Subject 2	Initial - 10
didn′t care to blow the tube too much	flute	Subject 3	Initial - 3
Likes the flute.. an extra hand as you play	flute	Subject 2	Final - 5
flute frees up two hands	flute	Subject 1	Final - 10
frustration in the friction.. hard to control the sounds.. or to bring a certain sound forward [maybe like an acoustic instrument]... interesting to see if total control would help this..	friction - accuracy	Subject 2	Initial - 7
friction would loose something if it had keys	friction - accuracy	Subject 1	Initial - 4
seems motivated with the slideSurface and friction ... really tries out a lot gestures	gestures	Subject 3	Final - 3
observation shows that he really tries to work with the instruments	interaction	Subject 3	Final - 2
interface is bad for the combination... you want to make music here and now.. or you quickly move on to something else.. menu systems are in general a bad idea	interface	Subject 3	Initial - 3
Interface and setup is too difficult... which has a negative influence on the overall perception of the phoxes	interface	Subject 3	Final - 1
If it would have been just one thing with on/off, then I would have used it more.. also taken it home	interface	Subject 3	Final - 1
playability, tactile feel, here and now, no menu systems	Interface	Subject 3	Final - 4

Table 4.7: Studio vs. Live - 1 of 3

for live use it has to be more controllable, usually something more subtle.. something to do.. there should be no menues.. presets.. MIDI.. crank would be cool, but it looks stupid.. the slideSurface would work, but the friction is too uncontrollable.. more playable	live	Subject 3	Initial - 6
In the studio, I would have much more things to patch the phoxes up with... not just the machineDrum... they would be used very diferenty.. the machineDrum is in charge now of how they are used	studio	Subject 2	Initial - 6
If there was MIDI phoxes would be cool live	live	Subject 1	Initial - 2
Mostly for studio... you want accuracy in a live situation... but you don′t bring your most accurate tools with you in a studio... those are not the ones that open up and provides you with new sound material	studio vs live	Subject 2	Final - 4
would like to explore the combinations / output sound in more detail.. but then he should have been in his studio	studio vs explore period	Subject 2	Final - 7
Played the music at a night club... dj-ing	dj-ing	Subject 1	Final - 2
WOuld not use them live	live	Subject 1	Final - 12
Would not put them in a genre specific box... it depends on how you use them... maybe the more avantgarde ... but you really can use them how you want...especially if they had MIDI	genre	Subject 1	Final - 12

Table 4.8: Integration / Approach - 1 of 4

sampled, chopped up, made beats	Integration	Subject 3	Initial - 2
"wrong sound" of friction	wrong sound	Subject 2	Final - 1
Good with some unpredictability... gives something you wouldn't have thought of on your own	unpredict-ability	Subject 3	Final - 5
Likes the unpredictable stuff in the studio	unpredict-ability	Subject 2	Final - 4
particles are motivating	motivation	Subject 3	Final - 3
motivated by using the tube+flute.. long floating sounds.. good controller	motivation	Subject 2	Final - 3
also really works with finding the "wrong sound"	motivation	Subject 2	Final - 5
uses the sampler to get keys to explore them	integration / exploration	Subject 1	Final - 3
wants to have better tone-control... but also says that it would maybe take away some of the newness, that makes you do things differently... which produces new ideas	integration / exploration	Subject 1	Final - 6
Sampled the PHOXES and worked with a lot of effects - as he always does - delay, compress, EQ, reverb, distortion, random triggering, etc..	integration	Subject 3	Initial - 2
makes a little groove that will become something later, that can then turn into something different.. etc... so would probably use these phoxes sounds later	integration	Subject 3	Initial - 5
again shows how much time is used in the mixing/cutting etc..	integration	Subject 3	Initial - 5
Usually has something playing in the background when exploring	integration	Subject 3	Initial - 6
usually wants elements to modulate organically... strength w. phoxes	integration	Subject 3	Initial - 6
would like to integrate the control in the crank (including stochastic triggering) to modulate or for applying other effects..	integration	Subject 3	Initial - 7
PHOXES are used as raw sound generation... that can then be used for something else (modulated, cut up, applied with effects, etc..)	integration	Subject 2	Initial - 2
Uses the particles with the drumMachine.. sends beats from drumMachine to particles, gets sound back into drumMachine, where they are modified	Integration	Subject 2	Initial - 3
works well with particles + drumMachine... interesting things happen fast	integration	Subject 2	Initial - 4
Most time on modifying the sounds afterwards... very small samples of particles/flute	integration	Subject 2	Initial - 4
PHOXES are structured by what it integrates with... here the machineDrum puts them into its world	integration	Subject 2	Initial - 6
Uses phoxes with a sampler	integration	Subject 1	Initial - 2

Table 4.9: Methodology - 1 of 1

found that the sound was a bit thin (coming from a minijack on the mac mini		Subject 3	
finds out that you can make a feedback loop	misunder-standing	Subject 3	Initial - 2
Didn't find out about "audio in"	misunder-standing	Subject 3	Initial - 4
Uses a lot of time on exploring the drum Machine at the time of the test... not in the studio	context	Subject 2	Initial - 1
Thought that energy only had to do with amplitude	misunderstanding	Subject 2	Initial - 9
When using one PHOX to control another he didn't distinguish between the control output and the sound output... maybe just lucky that he "found" the drumAudioOut to Friction	misunderstanding	Subject 1	Initial - 6
Only played with them 2-3 times.	test	Subject 3	Final - 1
Not good for the overall impression that they are so difficult to get to work... also, you are not very eager to start them up and start playing them	test	Subject 3	Final - 1
Had many other things to do, snow, other band, christmas, not well incorporated into normal workflow...	test	Subject 3	Final - 1
Forgot sound input and feedback loop... didn't combine them either	test	Subject 3	Final - 5
Test procedure was good... but they were too much of a hassle to work with	test	Subject 3	Final - 7

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Part II

Included papers

Paper I

PHYSMISM: RE-INTRODUCING PHYSICAL MODELLING FOR ELECTRONIC MUSICAL EXPLORATION

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ABSTRACT

In this paper we describe the design and implementation of the PHYSMISM: an interface for exploring the possibilities for improving the creative use of physical modelling sound synthesis.

Four different physical modelling techniques are implemented, to explore the implications of using and combining different techniques.

In order to evaluate the creative use of physical models, a test was performed using 11 experienced musicians as test subjects. Results show that the capability of combining the physical models and the use of a physical interface engaged the musicians in creative exploration of physical models.

Figure 1. The final look and feel of the PHYSMISM was among other things inspired by old analogue synthesizers.

1. INTRODUCTION

To synthesize sounds using physical models means to understand the physics of sound production mechanisms and simulate these using numerical algorithms. Physical modeling techniques provide the possibility to add new perspectives to the constant search for novel interesting sounds present in the world of electronic music.

Different physical modeling techniques have been researched for decades [5, 8, 2], but they have not been completely accepted in the performance and production of electronic music compared to many other synthesis techniques.

Only a few and not completely successful attempts have been implemented in commercial synthesizers. It appears that physical modeling techniques have been mostly used in the academic milieu.

In this paper, we are interested in investigating the reasons for the lack of use of physical models in electronic music production and performance. It seems necessary to re-introduce physical models by rethinking their role in the electronic music scene and the ways in which they can fill it.

After talking to different musician experts in electronic music, we realized that physical models have not been utilized to their full potential. This might be due to the lack of musically interesting implementations of the technique.

Most of the physical models we have encountered focus mainly on the interactive aspects of physical modelling or the ability to simulate an existing acoustic instrument as accurately as possible. If one were to only focus on the sonic qualities of a sound itself without being concerned with accurate simulation of physical mechanisms, would it be possible to further explore the musical potentials of physical models?

Many physical models have been created, emulating acoustic instruments and physical phenomena found in nature. A lot of characteristics of the natural instruments have now been captured and a diversity of physical models has been developed. Most of the physical models produce sound like an original acoustic instrument with the possibility to change the physical parameters and characteristics of the instruments. Would using these models to keep the characteristics of the existing instruments, but then merging them with something completely different, help to enhance the creative exploration of physical modelling?

In the early 60s the so-called modular synthesizers were introduced. [1] These synthesizers gave the users the possibility to have full control of the sounds they produced and to combine the different parts of the synthesis techniques themselves instead of simply using a preset from the factory. Together with the synthesizers followed a variety of manuals concerning how to combine different oscillators, envelopes, filters and so forth, to reproduce existing sonorities such as bells or bird sounds. Several musicians used such synthesizers to simply reproduce sounds existing in nature, while others tried to create their own experimental sonorities. Some users followed the manuals, while others tried to experiment with the modules as part of a creative process. The output produced consisted of artificial electronic sounds far from the every day sounds or existing instruments.

The initial idea behind this research is that the same creative process could be achieved when exploring physical modelling sound synthesis.

In order to achieve this goal, the possibilities as well as the benefits and drawbacks of physical modelling synthesis have been explored and analyzed.

Parts of the work review in the analysis is presented in the following section.

1.1. Creative use of physical modelling

Most commonly used in compositions is the use of physical models to extend possibilities offered by traditional instruments. One of the pioneers of the use of physical models in compositions is David Jaffe. In his piece *Silicon Valley Breakdown*, premiered in Venice during the International Computer Music Conference 1982, a physical model of a plucked string implemented using the Karplus-Strong algorithm [6] is extended to reach unreal dimensions, such as the length of the Golden Gate bridge. Another pioneer in the use of physical models in creative applications is Chris Chafe. In [3], he reviewed the work of himself and other composers regarding this topic.

Paul Lansky also used physical models in his creations. In [3] it is described how he has enjoyed using the physical model of a flute by Perry Cook, using a 20 feet long tube with a diameter of 3 feet as the resonator in some of his pieces.

Other composers are using replica extended models to achieve abnormal excitation. An example is the piece *Pipe Dream* by Gary Scavone, written in 2003. In this piece, Scavone uses a physical model of a saxophone, over-blowing the excitation.

Other examples of creative and alternative use of physical models in compositions include hybrids of physical models, where composers combine different resonators or excitations. As an example, *S-Trance-S* by Matthew Burtner is a piece where a saxophone acts as a controller for a physical model of a string [1].

As another example, *Voice of the Dragon* by Juraj Kojs is a composition where physical singing tubes interact with virtual ones, simulated using physical models [7].

[1] http://moogmusic.com/history.php

2. PHYSMISM

The PHYSMISM, shown in Figure 1, is an interface designed to investigate how physical models can be controlled and used creatively. Based on the review presented in the previous section, a set of goals for what the sound synthesizer should be able to implement, was proposed.

It can be difficult to present an electronic musician with everything physical modelling has to offer because of the complexity of the technique. A balance between simplifying the control of the models while still leaving room for creative exploration must be achieved. We are interested in making the controls simple enough to comprehend while still giving the user the feeling of endless possibilities. Furthermore we want to explore the implications of interacting physically with the models.

The goal of the sound synthesis engine is to implement many different physical models. They must be able to simulate real instruments, with the possibility to vary their parameters in order to make them extend limitations of the real world. Furthermore, we want to allow the possibility to use the same excitation device to control different models.

Finally, we are interested in combining different physical models in an intuitive way.

2.1. Implementation of physical models

In the PHYSMISM, each model chosen represents a difference in sound, technique, complexity, resonator, and exciter. This is mainly in order to show the diversity of physical models. For the current prototype the following physical models were chosen:

- A **turbulence model**, which implements a one dimensional waveguide [8] with a non-linear excitation [8].
- A **stochastic model**, which implements the PhISM model [4] having a randomized stochastic excitation.
- A **friction model**, based on one dimensional waveguides with a complex non-linear excitation, described in [7].
- An **impact model**, based on two dimensional waveguides [9] with a simple nonlinear excitation.

The models were written in C and compiled as Max/MSP [2] externals in order to control and combine them inside the Max/MSP environment.

2.2. Mapping strategies

The users had the possibility to control four parameters related to the resonator. By limiting each model to having only four parameter controls the user is provided with a fast overview of each model thereby achieving control.

[2] www.cycling74.com

Model	Excitation	Excitation device
Turbulence	Blowing	Flute
Stochastic	Grinding	Crank
Friction	Rubbing	2D-slider
Impact	Hitting	Drum pads

Table 1. A physical excitation device is created to suit the excitation of each of the physical models.

The user was then able to combine each model with each other. This was done by taking the output sound from one model and using it as an input for another model, thereby creating the possibility of obtaining different hybrid models. In this way the second model is not excited by the energy from the user, but by the sound from the first model. This feature demanded some extra work concerning the implementation of the actual models. All the models needed a sound input. This sound input needed to have a significant impact on the sound produced, in order to avoid the effect of just adding the two models together.

3. HARDWARE INTERFACE

The PHYSMISM was implemented as a novel hardware synthesizer where the goal was to take advantage of what the physical models had to offer. This was achieved by creating a physical excitation device for each of the four physical models (See Table 1 and Figures 1 and 2).

Furthermore the PHYSMISM was equipped with two parameter control stations. The user was then able to assign whichever model he wanted to a control station and control the parameters of that model using the four dials (See Figure 2).

Finally, in order to let the user combine the models a patching system very similar to the old analogue modular synthesizers was implemented. The user was capable of patching two models together, one being the output, and one being the input model, using a patching cord to connect the models (See Figure 2).

4. THE PHYSMISM IN ACTION

A test of the PHYSMISM was conducted using 11 professional musicians. The test was conducted as a session where the subjects were free to explore the sonic capabilities of the PHYSMISM for approximately 30 minutes. After this the subjects were asked to fill in a questionnaire. During the whole test period, observations and additional comments from the test persons were annotated.

In general the subjects had very low expectations to the capabilities of physical modelling and were therefore quite impressed with the PHYSMISM. We noticed that subjects got easily adjusted to the physical interface, and appreciated especially the natural interactions it provided.

A problem observed with the turbulence and impact model was the high predictability of the sound produced, which contributed to make it uninteresting after a very short amount of time. On the other hand, models which created rather rich, unpredictable and complex sonorities like the friction model were appreciated by most of the test subjects.

Figure 2. Top left: Flute, top right: Crank, middle left: 2-D pressure sensitive slider, middle right: Drum pads, bottom left: Control station, bottom right: Patching chord system.

Concerning the combination of the physical models, it was interesting to notice that many subjects expressed the fact that the predictable models became much more interesting when combined with other models. As an example, using the rich sonorities of the friction model as input device for the drum resonator, opened up several interesting novel sonic possibilities. Even the impact model and turbulence model, which were the two lowest rated models, became interesting when combined.

Based on the reviews made by the test subjects there is no doubt that where the PHYSMISM succeeds, is in it's physicality and capability to combine the models. One could perhaps argue that combining the models simply produces more complex models. This is somewhat true. However, by presenting the users with the models separately and letting them do the combining/exploring gives them a better idea of what each parameter does while also giving them the creative freedom required.

Although some of the observations made by the test subjects were rather expected, it is noneless interesting for us to observe that they are shared by several musicians, regardless of their level of expertise with sound synthesis and physical models.

Table 2 provides an overview of the positive and negative elements of the PHYSMISM gathered from the test.

The PHYSMISM was presented at the Sonic Arts Research Centre (SARC), Queen's University of Belfast as part of the meeting "Physical Models in Action", December 2006. The application and interface were presented as part of a demo and poster session and later used to give a small concert at the Sonic lab. The feedback from the demo session was very positive. Especially it was noted that the PHYSMISM presented a fine combination of high accessibility of the physical models while still presenting creative explorative potential.

Positive	Negative	Application
Many parameters		Friction
	Few parameters	Drum
	Predictability	Drum
Unpredictability		Friction
Sonic Range		Friction
	Sonic Range	Drum
	Sonic Range	Flute
Low frequencies		Drum
Combined models		All models
Bi-manual control		Physical interface
Natural interaction		Physical interface
Clear interaction		Crank

Table 2. Summary of the positive and negative features of the different physical models as expressed by the test subjects.

5. CONCLUSION

The starting point of our research was the exploration of the possibilities for improving the creative use of physical modelling sound synthesis.

Based on a review of physical modelling a set of possible factors for improving the creative use of physical modelling was proposed and an application and interface, the PHYSMISM, was designed and implemented.

The PHYSMISM was created using four different physical models each implemented with its own excitation device. The models were each controlled using four parameter controls. Finally, in order to combine the models a patching system was implemented.

A test was performed with 11 different musicians, in order to evaluate the creative use of physical modelling. The test showed that especially the models with significant possibilities of variation of sonorities were desirable. Some of the models had an element of unpredictability and this seemed to enhance the creative use of the models and the application.

The effect of combining the physical models was also evaluated and it showed that some of the more simple and unpopular models, became much more interesting for the users when they were combined with other models.

It seems possible to use physical modelling much more in modern music production if the creative exploration of the models is enhanced. This sound synthesis technique has a lot of potential for creative use, and the musicians seemed much more positive towards the technique after having tried the PHYSMISM.

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Paper II

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A Practical Approach towards an Exploratory Framework for Physical Modeling

Much of the research on physical modeling deals with developing accurate simulations of different physical mechanisms (Keefe 1992; Bensa et al. 2002; Välimäki et al. 2006; Bilbao 2009). The research presented in this article focuses instead on the control of these simulations. Our work involved developing a framework for controlling physical models that focuses on creativity and exploration. Understanding the qualities of physical models, not only in regard to algorithmic and sonic properties but also in regard to intuitiveness, naturalness, interaction features, mapping possibilities, and potential gestural control can assist in the creative exploration of physical modeling.

When developing new musical interfaces, whether they are based on instrument-like, instrument-inspired, extended, or alternate controllers (to use the classification by Miranda and Wanderley 2006), a central goal seems to be to enhance the expressivity and intimacy of novel musical instruments (Poepel 2005; Dobrian and Koppelman 2006; Schlessinger and Smith 2009; Jones et al. 2009). Although we acknowledge that these are indeed important features, they are not the focus of this article. Rather, the article focuses on the ability of a novel instrument to be explored in order to produce interesting sonic output and to spark creative ideas in the mind of the user. In other words, we try to implement models based on existing techniques in ways that encourage the user to explore sonic properties in a creative manner.

The creative cognitive processes that occur when creative activities take place can be described by the Geneplore model (Finke, Ward, and Smith 1996)—a heuristic model that describes creative activities as a combination of generative and exploratory processes. There is a generation of ideas, which might not even be complete or accurate ideas but merely germs of an idea; they just bring with them signs of originality and appropriateness. These "preinventional" ideas are then explored, and the creative activity is thus the alternation back and forth between generation and exploration. Because the activity of generation and exploration is a continual, iterative process, it is not always known whether a particular process can be categorized as either one or the other. However, for creativity to occur (according to the Geneplore model), both generation and exploration must take place.

For our purposes, we must examine the exploratory qualities of the sound-synthesis model, the physicality of the interaction, and how the integration of the two can encourage exploration. Exploration has to do with the manner in which a user interacts with the instrument. The sound-synthesis model in itself will of course affect what sort of sounds one will produce using a given instrument, but so too will the perceived affordances and constraints of the overall instrument, which exist on all levels—from the complexity/accessibility of the sound synthesizer, to the mapping of sensor data to sound, to integration with other musical systems. These guide the user, proposing/recommending a certain use of the instrument. The user acquires knowledge about how the instrument works—knowledge that is inherent in the instrument (which is what Magnusson 2009 calls an *epistemic tool*). It is the interplay between this inherent knowledge and the user's knowledge that determines the interaction. By acknowledging that the different instruments can encourage different types of interaction, it is possible to design specifically for a certain type of interaction.

The rest of the article is composed of two parts. First is a discussion about control of and interaction with physical models leading to a set of design directives for exploratory control of physical models. The second part describes the implementation and

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evaluation of the PHYSMISM: a hardware interface we created to investigate these design directives.

Design Directives for Exploratory Control of Physical Models

To understand how an instrument can encourage exploration, we must examine the space in which the user navigates when using the instrument. Exploration is facilitated when the system responds to the user in an intuitive but not necessarily predictable manner. The response can be unpredictable as long as it brings with it clues to how one could reproduce such a response. The epistemic (knowledge-related), heuristic, and hermeneutic (interpretation-related) interaction, which one could argue normally takes place when learning a new instrument, is central to the exploratory features with which we are dealing. Systems that we do not fully understand (or that we are trying to understand) tend to encourage exploration; however, these kinds of systems are effective only if they uphold a certain amount of intuitiveness. An environment that encourages exploratory interaction must be rich, complex, and somewhat mysterious without compromising intuitiveness, or while still maintaining a low threshold—i.e., the ability of a system to give new users the confidence that they can succeed (Myers, Hudson, and Pausch 2000).

We propose that physical modeling is particularly amenable to being successfully implemented in such systems owing to the perceived causality inherent in physical models. Humans as young as six months old (Kruschke and Fragassi 1996) try to make sense of their environment based on causality: that one event occurs as a consequence of a previous event. Understanding the technique of physical modeling (conceptually) means understanding how physical properties and actions cause changes in sound—a skill we as humans have adopted through years of experience. Even mathematically complicated physical models will tend to be perceived as intuitive, because generally their causality is easily perceived. The inherent causality leaves room for experimenting with richer, more complex implementations that encourage exploration without compromising intuitiveness.

This section presents seven design directives for developing such systems for exploratory control of physical models. These design directives constitute a framework where creative encouragement and exploratory work processes are in focus. The directives are: (1) balance sonic diversity and plausibility of the model; (2) experiment with the energy that drives the model; (3) control physical models with physical gestures; (4) make the user work; (5) encourage exploration of sound parameters and exploration of gestures; (6) experiment with the interplay between instantaneous and continuous instrumental gestures; and (7) make the system modular.

Balance Sonic Diversity and Plausibility of the Model

The framework does not focus on accurate models for imitating existing acoustic instruments. Rather, it focuses on the exploration of sonic potential of existing physical models. For exploration to take place, the diversity of sounds a model can produce is more important than the physical accuracy. Castagne and Cadoz (2003) propose a set of ten criteria for evaluating physical modeling schemes for music creation. They point out how the effort toward diversity of the models can minimize how faithful the synthesized sounds are—i.e., how comparable they are to real instruments. They also suggest that systems based on exploratory, empirical, and intuitive uses must still produce plausible sounds—sounds that are perceived as having been produced in a physical manner. The latter consideration is an important balancing principle in our framework. Striving for diversity and "explorability" is of greater concern here than producing faithful sounds, but it must not compromise plausibility.

Experiment with the Energy that Drives the Model

A physical model will typically be driven by energy injected into a system—striking a drum, plucking a string, blowing a whistle. The anatomy of the system (excitation and resonator mechanisms) will distinguish how that energy is transformed into sound.

The energy can correspond in predictable ways to the sound produced, as for instance when the gesture of bowing produces the sound of a violin. But unpredictable relationships between the exerted energy and the resulting sound can also occur (see Monache et al. 2007 for an exploration of these relationships) when, for instance, bowing produces the sound of a flute. The gesture-to-sound mapping can seem unfamiliar but if the amount of energy exerted by the user relates in a meaningful way to the produced sound the unpredictable relationship will still be intuitive. When we as humans perceive the sound caused by the energy that we have exerted into a system, we immediately form a mental model of the anatomy of that system based on the perceived relationship between the input energy and the output sound.

We propose that as long as the system upholds an energy consistency, it is possible to experiment with letting physical actions control seemingly unrelated physical models without compromising the intuitiveness of the system. In other words, the energy produced by any gesture is able to drive any physical model as long as the energetic relationship between gesture and sound is intact. This is possible because of our innate perception of causality (Michotte 1963). Overholt (2009, p. 218) argues that "More imaginative techniques can be interesting, but an interface may become less optimal for performance if the causality relationship is broken." This is less likely to happen with physical models because causality is inherent in physical modeling owing to the nature of the technique.

Control Physical Models with Physical Gestures

Many exploratory qualities can be associated with graphical user interfaces (GUIs) owing to their dynamic capacity to withhold a multitude of layered information that can be explored in stages that are natural for the user. This would make it natural to suggest controlling physical models in the graphical domain for encouraged exploratory control. When explaining the benefits of digital instruments over acoustic instruments, musicians surveyed by Magnusson (2007) pointed out that "the computer was often seen as a symbolic system that can be configured differently according to situations, thus highly open, flexible and adaptable to infinite situations," and that "they found their time better spent working with digital technology, creating music or 'experimenting with sound'." Note that whether physical models are controlled using a physical interface or a GUI, the instrument will still constitute a digital instrument—not an acoustic one. The Cymatic (Howard and Rimell 2004) is a concrete example of how the power of GUIs can be exploited for exploratory interaction. (The system also presents the user with flexible, tactile-feedback gestural control using a force-feedback joystick or mouse.)

Controlling physical modeling by way of physical gestures, however, brings with it a natural relationship in which the physical gestures can be closely coupled to the sonic outcome. In other words, the physical characteristics of the technique are fully exploitable if there exists a coupling to the human body, including the physical gestures that control them.

Cognition is embodied, meaning that we process thought not only in our brains but through the whole nervous system, including through sensorimotor activities (Varela, Thompson, and Rosch 1993; Thompson and Varela 2001; Armstrong 2006). The embodiment, which is achieved through the physical interaction with the environment (in this case the physical instrument), leads to a perceptually extended understanding of the instrument, including a better understanding of affordances and constraints, potentially encouraging exploratory interaction. This question is, however, open for experimentation, as will be explored later.

Make the User Work

Hunt, Wanderley, and Paradis (2002) argue that the feeling of playing "an actual instrument" is enhanced if the user needs to keep moving to sustain the sound being produced. This is highly suited for the control of physical models. Exerting physical energy into the musical system to drive it maintains the natural mapping. The embodiment that entails a richer perception and control of the instrument is increased by constantly letting the user perceive small variations in the result that are caused by corresponding variations in gestural motions.

Encourage Exploration of Sound Parameters and Exploration of Gestures

When mapping gestural data to sound-synthesis parameters, the system typically performs some sort of processing of the data. The goal is to identify the variation range of the gestural data (typically given by what is physically and technically possible to achieve with the controller at hand) and then map this to the desired variation range of the sound-synthesis parameters (which is determined by the subjective judgement of the software instrument's developer). This variation range helps determine a large part of the sonic character of the instrument. But the way in which a user is able to navigate within this range is just as important: What are the possible gestures made available within this variation range? A linear slider potentiometer, for example, is continuously restrained, meaning it is not possible to jump from one value to another (distant) value without going through intervening values; a touch-sensitive slider would make this possible. Exploration of the sonic potential of physical models must be encouraged both in the defining of variation ranges but also by experimenting with the way in which possible gestures facilitate different movements (physical and sonic) within these ranges.

Experiment with the Interplay between Instantaneous and Continuous Instrumental Gestures

In Cadoz (1988), instrumental gestures are functionally classified as excitation gestures, modification gestures, or selection gestures. The focus of this article has been on the excitation gestures, which are gestures used to exert energy into the physical model. These kinds of gestures can again be divided into instantaneous gestures (e.g., hitting a drum) and continuous gestures (e.g., bowing a string). (A continuous gesture may also produce a series of instantaneous excitation events, as when scraping on a guiro.) Experimentation with both continuous and instantaneous excitation gestures may help to enhance the flexibility of physical models, thus making them more "explorable." Experimenting with the interplay between excitation, modification, and selection gestures and how their integrality or separability affect the exploration of physical models is also an interesting topic for investigation, but it is not the focus of this article.

Make the System Modular

Castagne and Cadoz (2003) propose that a modular approach to physical modeling can improve or transform the compositional potential of the technique. An example is their mass-spring modular system that lets the user construct unique complex physical structures using different modules. They make it possible not only to generate sounds but also to let systems interact with each other, thereby opening up more compositional possibilities. Mass-spring systems such as CORDIS-ANIMA (Cadoz, Luciani, and Florens 1993) and Cymatic (Howard and Rimell 2004) are based on this modular approach. The approach lets the user explore the creative potential of the physical models. Other systems, such as the Synthesis Toolkit (STK) (Cook and Scavone 1999) and PeRColate (Trueman and DuBois 2001), which is partially based on the STK, are also modular in the sense that they provide a collection of primitive elements in the form of programming functions for sound synthesis that can be compiled for easier development of musical software and potentially for exploring the power of creating unique physical models.

We propose that users do not need to be able to construct their own physical models as such but simply be able to connect existing models in meaningful ways. This way users can explore the boundaries of each fixed model while still having the possibility to obtain the uniqueness achieved through a modular approach.

The design directives described here have been used in the design of a musical instrument for exploration of physical models called the PHYSMISM. The concept, implementation, and evaluation of the PHYSMISM are described in the following sections.

The PHYSMISM

In the music-technology community, it is acknowledged that a tighter connection is needed between the technical development of physical models and an investigation into how physical models can be controlled and how they are perceived in that context (Widmer et al. 2007). The feedback loop of controlling changes in sound, listening to the changes, and processing them must be taken into account when developing new physical models.

The PHYSMISM is a physical-modeling digital instrument. We created it to study what happens when emphasis is taken from physical accuracy and moved to creativity, exploration, physicality, and control. How can creative exploration of existing physical modeling techniques be facilitated by focusing on a certain development framework? When researchers first developed physical models, the emphasis was for the most part on the programming of accurate models that simulate sounds from the real world. The framework examined here uses this as a point of departure and tries to shift the focus towards creativity, user, and use. In other words, well known physical-modeling techniques will be used to manipulate aspects of the model to suit control and creative exploration.

The goal here has been to create an instrument that acts as a sort of black box (Magnusson 2009) in which the user does not possess deep knowledge of the functionality of the underlying physical models. (Many artists using physical modeling in new instruments today are themselves designers of their instruments; this, however, is not the premise here.) However, the user must be able to understand enough to be able to explore the instruments in a meaningful way. The PHYSMISM is meant for electronic musicians who have considerable experience using commercial software and hardware for both composition and live performance but who have not experimented with novel experimental interfaces or physical models.

The design directives presented in the previous section entitled "Design Directives for Exploratory Control of Physical Models" can be viewed as postulates that we wish to examine during this development. The directives are incorporated into the PHYSMISM in various degrees in order to examine their importance. We are trying to learn if it may be possible to approach physical modeling sound synthesis from a user-centered explorative perspective—a perspective with inspirational boundaries (both physical and sonic) that lead to exploratory and creative work patterns.

Creating the PHYSMISM

This section explains the design and implementation of the PHYSMISM. Two versions of the PHYSMISM were created: a GUI and a physical interface. The focus here is on the physical interface, and then the GUI is briefly described.

Sound Synthesizer

The PHYSMISM implements four physical models that are based on well established techniques for simulating acoustic instruments. They vary in the physicality and interaction that they naturally facilitate, in sonic quality and in complexity. They also provide different forms of exciters and resonators, which helps us make distinctions when assessing their exploratory qualities. The hybrid or modular possibilities are also improved by incorporating a variety of exciters and resonators. Finally, they make it possible to experiment with instantaneous or continuous excitation gestures, as each model naturally proposes one or the other type of gesture, or a combination of the two.

The first physical model is a turbulence—or tube—model that implements a one-dimensional waveguide (Smith 2008) with a nonlinear excitation (Cook 1992). The second model is a stochastic—or particle—model, based on Physically Informed Sonic Modeling (PhISM) (Cook 1997) with a randomized stochastic excitation. The third model is a friction model, based on one-dimensional waveguides with a complex nonlinear excitation, described in Avanzini, Serafin, and Rocchesso (2002), and the fourth model includes two identical instances of an impact—or drum—model, based on two-dimensional waveguides (Duyne and Smith 1993) with a simple nonlinear excitation. The models

Figure 1. The PHYSMISM is a digital instrument for creative exploration of physical models.

were implemented as Max/MSP externals so that the development of the software functionality and interfacing with input devices could all be handled in the Max/MSP environment. (The models can be downloaded at media.aau.dk/~stg/physmism.)

Physical Interface

The PHYSMISM was created first and foremost as a physical device. The actual design of the PHYSMISM was inspired by old analog modular synthesizers. Apart from appreciating their physical aesthetics, inspiration has been drawn from the exploratory qualities and the modular approach of such instruments. Figure 1 shows the final look of the PHYSMISM. The layout of the physical interface is presented in Figure 2. Details regarding the sensors used to capture the control gestures of the user and the mappings of those gestures into sound parameters are described in the sections entitled "Excitation Control" and "Resonator Control."

All sensors were interfaced with Max/MSP using six rapid-prototyping input/output boards: Two Teleo Starter Kits, one Teleo Analog In Module (from makingthings.com), one Phidget Interface Kit 0/16/16, and two Phidget Text LCD Integrated 8/8/8 Interface Kits (from phidgets.com). Liquid crystal display (LCD) screens were used to present users with feedback on which parameter of which model was being manipulated at any given time. Pulse-width modulation (PWM) and digital outputs were used to provide feedback in the form of light-emitting diode (LED) level meters for fast monitoring of sound-parameter states. Specifications regarding the implemented sensors can be accessed at media.aau.dk/~stg/physmism.

Excitation Control

The PHYSMISM implements four different physical devices for controlling excitation—one for each model. They enable users to perform physical gestures that by default are closely related to the typical excitation of the particular model. Additionally, because the users were provided with the ability to combine models (as described later in the section entitled "Combining the Models"), a variety of different control possibilities regarding the same model were enabled.

As mentioned earlier, Hunt, Wanderley, and Paradis (2002) argue that the feel of a real instrument can be enhanced by letting the user work continuously to sustain sound. Therefore, none of the excitation devices produce sound without constant energy from the user.

The excitation device for controlling the tube model implements a flute-like controller (see Figure 3). The user blows into a small tube that leads to a fan attached to a small DC motor. The motor rotates and creates a measurable voltage. This is used

Figure 2. The layout of the physical interface of the PHYSMISM. The different elements are described in the section entitled "Physical Interface."

Figure 3. The flute-like controller is used to control the excitation of the turbulence model.

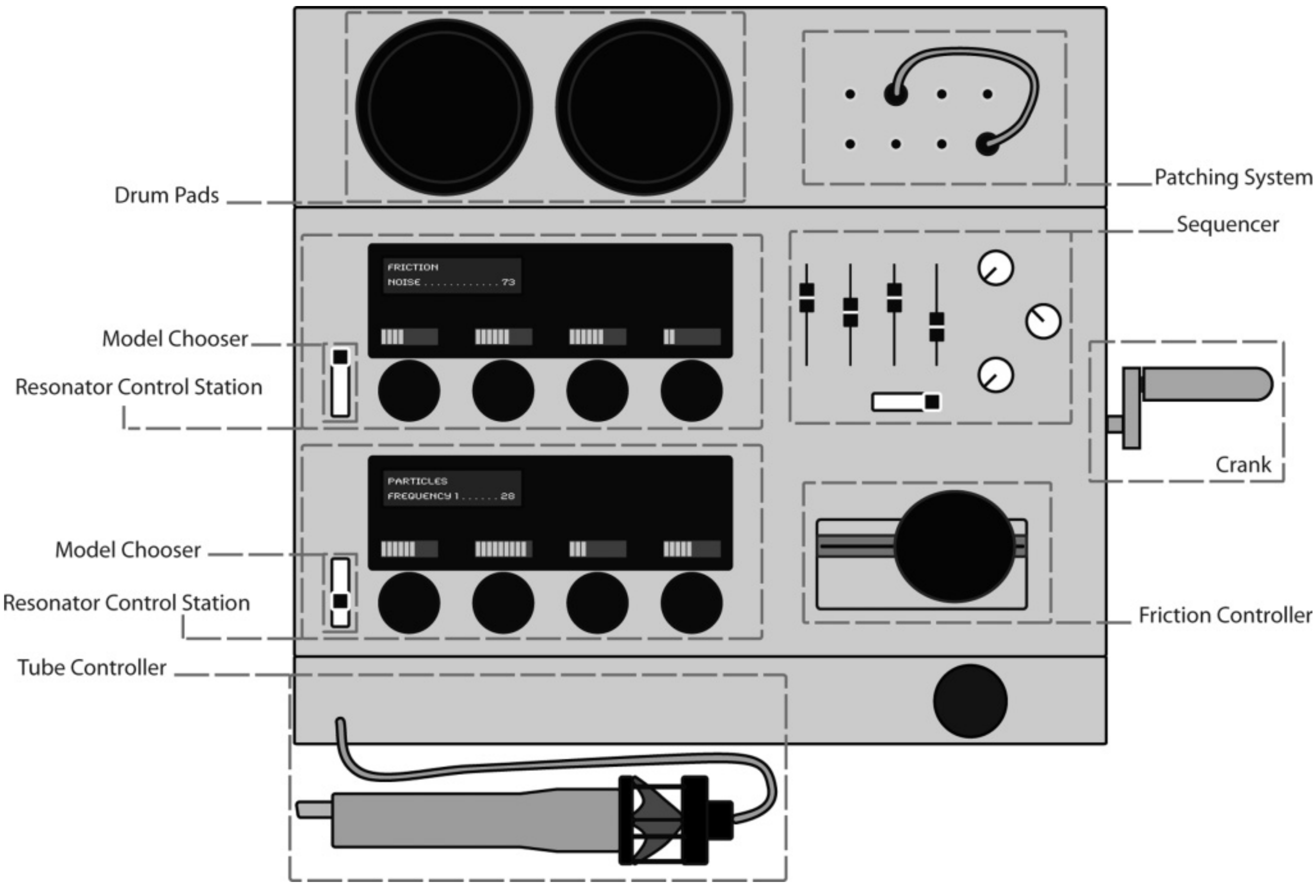

Figure 2.

Figure 3.

to excite the tube model by mapping the rotational velocity to the amount of energy put into the system (as white noise). The device is borrowed from an earlier project (Böttcher et al. 2005) and was implemented to resemble the controllers traditionally used with these kinds of tube models (Rideout 1994).

Figure 4. The friction excitation controller implements a 2-D slider and pressure sensor.

Figure 5. The crank controls the stochastic model.

For the friction model, we moved away from the specific instrumental domain of the violin by deciding not to excite the model with a violin-like controller, using for example the VBow (Nichols 2002) or the Hyperbow (Young 2002). Work towards more generalized friction controllers is presented in Serafin and Young (2004) and Essl and O'Modhrain (2005). For example, the Scrubber implements a sort of pressure-sensitive computer mouse-like interface that uses microphones to sense friction on a given surface. The friction controller of the PHYSMISM shown in Figure 4 (see also Figures 1 and 2) was designed to facilitate the general feeling of friction similar to the Scrubber's. It implements a two-dimensional slider with an incorporated force-sensitive resistor. The force-sensitive resistor is placed on top of a handle that is attached to the horizontal slider, which is then attached to a track that makes vertical positioning of the horizontal slider possible. The vertical slider is attached to this track, sensing the vertical position. The horizontal velocity is mapped to the model's velocity parameter. The vertical position (perpendicular to the horizontal axis, but along the surface of the instrument) is mapped to the model's excitation position, and the force measured is mapped to the model's excitation force parameter. Thus, to produce and sustain sound, the user must keep the slider in constant motion while finely adjusting the amount of force applied.

The excitation of the stochastic model was approached with a grinding gesture instead of the shaking gesture that the physical model used might suggest. The model is based on Cook (1997), which emulates the beans in a maraca to calculate the probability of a hit. The crank (see Figure 5) not only lets users apply continuous motion, but it also lets them experiment with physicality and the possible mapping metaphors. The crank's rotational velocity is measured using a small DC motor in a manner similar to the tube excitation controller. The velocity is mapped to the number of beans (i.e., the hit-probability) of the physical model. This means that slow movement of the crank produces a very sparse or diffuse particle-like soundscape, and fast movement produces a dense one.

The excitation device for exciting the impact model consists of two custom-made drum pads shown in Figure 6 (and Figures 1 and 2). Inside each pad, a force-sensing resistor measures the force applied to the pad by the user. (The intention is for the user to use fingers to hit the pads.) A threshold is applied to the signal, and the peak is detected to identify a hit (including the velocity of the hit). These velocities are mapped to the velocity of each of two impact models. The position of the hit is not detected: The model is always excited from the center of the drum (center of the 2D waveguide). However, owing to the poor quality of the force sensors, one must apply a somewhat continuous force to trigger a hit. This means that, metaphorically, one is pushing the drum more than hitting it, which lowers the percussive qualities of the drum in favor of a more timbral-exploratory quality.

Figure 6. Two drum pads were implemented in order to control the excitation of two impact models.

Resonator Control

The user must be able to interact with the resonator part of each physical model to shape the sound and explore sonic capabilities. Most existing systems use buttons and knobs, like the Yamaha VL1 or NUSofting Modelonia (Rideout 1994; NUSofting 2008), mapped directly to selected resonator parameters, but some give the user capabilities of freely controlling the resonators' sizes and shapes (Howard and Rimell 2004), and some are controlled by augmenting the excitation devices to also control parts of the resonators (Burtner 2003).

Whereas each of the four models we used provides a completely different interaction for the excitation part, we wanted the interaction with the resonator to be somewhat generic for all models. This was partly done to keep the complexity of the PHYSMISM as a whole low, but also to connect the models so that the PHYSMISM would feel like one instrument/device, and not just four different instruments that happened to be stuck together.

It was decided that each of the four resonators would have four control parameters. This number was determined to constitute an adequate compromise between simplicity and "explorability" of the models. Each of the four parameters would be controlled by a separate knob, implemented using a 10-kΩ linear rotational potentiometer. However, the knobs would be reused for the four different physical models. When combining two models (as described later in the section entitled "Combining the Models"), the user needs to be able to control two resonators at the same time; therefore, two control stations were implemented, each having four knobs (Figures 1 and 2). Users choose which resonator they want to control by assigning it to a control station.

Some of the resonators are simpler than others. This means that some by default have few parameters and others have many. The challenge was to find out which parameters were important to change for the user and if any parameters could be cross-mapped with others or left out. Table 1 shows the four controllable parameters of each resonator.

Combining the Models

The PHYSMISM implements a modular approach by letting the user combine the models with each other. This is achieved by using the output sound from one model as energy to drive the excitation of another model. In this way, the first model does not change internally; it functions exactly the same when not combined. The second model, however, now functions as a kind of audio effect, transforming the sound of the first model. Other systems such as Cymatic (Howard and Rimell 2004) and some implementations of scanned synthesis (Boulanger, Smaragdis, and ffitch 2000) also experiment with using audio to drive physical or physically inspired models.

This approach demanded that all models be equipped with an audio input that could drive the model in a meaningful way. This audio input needed to have a significant impact on the sound produced to avoid the effect of just adding the output sound of the two models, or losing the properties of the first model altogether. For our purposes, an effect is not considered interesting if after passing a sound through it, all one hears is the effect with no reminiscence of the starting sound (Wishart 1994). Table 2 provides an overview of how an audio input was implemented into each of the four models.

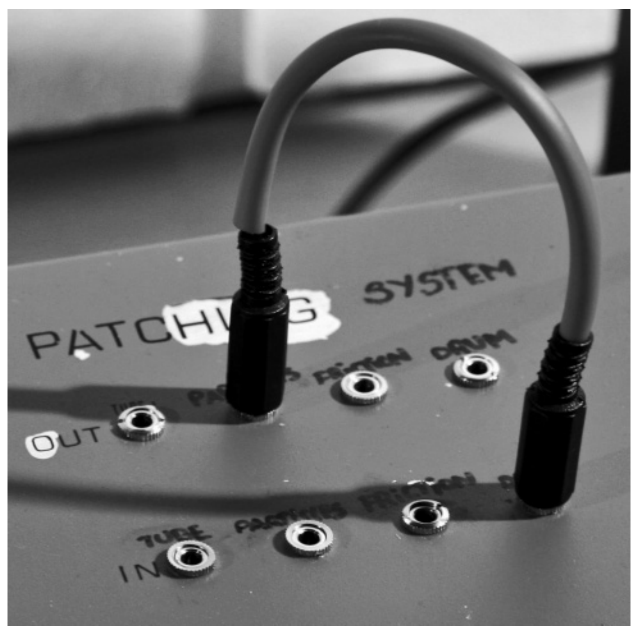

Figure 7. The models can be combined using a patching cord system. The output sound from one model is patched to a second model, driving the excitation of this second model.

Table 1. The Four Controllable Resonator Parameters for Each of the Four Physical Models

Model	*Parameter 1*	*Parameter 2*	*Parameter 3*	*Parameter 4*
Tube	**"Length 1"** / length 1	**"Length 2"** / length 2	**"Harmonicity"** / allpass filter coefficient	**"Air"** / amount and mix of pink noise into the system (emulating flute "airiness")
Particles	**"Frequency 1"** / fundamental frequency	**"Frequency 2"** / approximate frequency of four partials	**"Tone"** / bandwidth of the partials	**"Intensity"** / energy (amount of white noise into the system)
Friction	**"Frequency 1"** / frequency 1	**"Frequency 2"** / frequency 2	**"Frequency 3"** / frequency 3	**"Noise"** / roughness (randomness of force)
Drum	**"Left Size 1"** / left drum size 1	**"Left Size 2"** / left drum size 2	**"Right Size 1"** / right drum size 1	**"Right Size 2"** / right drum size 2

In quotation marks are the parameters as they are presented to the user.

Table 2. The Audio Input Implemented for Each Model, to Allow Connecting Two Models Together

Model	*Audio Input*
Tube	Audio input replaces the white noise that injects energy into the system.
Particles	Audio input replaces the white noise that is enveloped in the stochastic excitation.
Friction	Audio input is clipped (applied an amplitude threshold between 0 and 0.99) and replaces the horizontal velocity.
Drum	Audio input is added to one of the scattering junctions in the 2D mesh.

To implement the combination feature, we used a patching system very similar to that of an old analog modular synthesizer. The user is able to patch two models together using a patching cord as shown in Figure 7.

Another interesting modular approach would be to divide everything into exciters and resonators. We felt, however, that the average user would struggle with the whole concept of exciters and resonators, leading to an undesirable gap between the mental model (the way the user perceives the system) and the conceptual model (the way the designer has conceived it) (Norman 2002).

Sequencer

To make the PHYSMISM more interesting as a musical tool and better-equipped for live performance, a simple four-track sequencer was added to the device. The user is able to record the produced sounds on different tracks and play them back at different speeds (and for different durations) and mix between them. The sequencer was implemented to provide the eventual test subjects with a better idea of how the sounds created with the PHYSMISM could be used in a musical context.

Figure 8. A GUI version of the PHYSMISM was implemented in Max/MSP.

Software Interface

The PHYSMISM was also implemented as a GUI in order to investigate the differences/similarities in the explorative interactions between the two types of system. What were the implications of interacting physically with the physical models compared to the simple gestures of using mouse and keyboard?

The GUI version was implemented in Max/MSP (see Figure 8). The goal was to simulate the gestures that were performed in the hardware version of the PHYSMISM. For instance, the stochastic model is excited by performing a circular motion with the mouse (simulating a crank). The only functional difference between the GUI and the physical-interface version is that while the physical interface version implements two resonator control stations (requiring the user to first assign a model to a control station before being able to control it), the GUI version includes all resonator controls at all time.

Evaluation of the PHYSMISM

To evaluate the PHYSMISM, a test was conducted using eleven experienced musicians from different musical backgrounds. The test was performed as an exploratory session where the subjects had approximately 30 minutes to explore both the GUI version and physical-interface version of the PHYSMISM. They were then asked to improvise and perform a five-minute long musical piece using the sequencer. Subjects were allowed to comment during the session, and the comments along with interesting observations were noted by an observer. Additionally, actions performed on the PHYSMISM by the subjects were recorded by tracking changes in exciter and resonator values. After the session, the subjects were asked to complete a questionnaire that comprised qualitative explanatory questions and quantitative Likert-scale ratings. Questions were asked regarding the perceived qualities of individual models, of combinations of models, and of the PHYSMISM as an overall instrument—both in the GUI and physical interface domains.

To benchmark the PHYSMISM in regard to the design directives presented earlier in this article, the test data was analyzed with the main focus on exploration based on issues underlying the directives: faithfulness/plausibility of the models, physicality, gestural control, and the implications of modularity.

Results

Owing to the instrument's complexity and the generality of musical tasks assigned to the participants, results of the quantitative part of the evaluation turned out to be for the most part inadequate for any meaningful evaluation. The relatively low number of participants combined with a general "explore the instrument" task resulted in sparse data for some parts of the instrument. Many of the participants found themselves occupied in some areas of the instrument and not having enough time to explore the rest. In retrospect, we should have put more focus on qualitative aspects of the test, testing over longer periods of time and performing the evaluation using qualitative methods such as interviews individually or in focus groups. The results here are therefore mostly based on observations, comments, and qualitative parts of the questionnaire.

Regarding the individual models, observation showed that when initially encountering a model, users would typically start by producing emulative sounds, after which they quickly moved on to exploring sonic variety. Some found it difficult to produce any faithful sounds to start with in the case of some individual models, which seemed to entail a difficulty in initializing the exploration. A few participants expressed the need for presets, which in hindsight would provide the user with a starting point from which they could then explore.

Users remarked that the unpredictable or unexpected elements of the friction model gave them an urge to explore its capacities. The opposite was apparent for the tube and drum models, which were rated lowest owing to their predictable nature. The friction model was also emphasized for the "warmth" of the produced sound. It seemed to produce plausible sounds even in its most extreme settings, whereas (for instance) the tube model would produce plausible sounds only in its natural-parameter regions.

The crank and friction controllers were the only excitation devices that were gesturally explored. One could argue that because the tube controller and the drum pads are interfaces that are more tightly coupled with the physical models they are controlling, they are not as interesting as the crank and friction controller. Unfortunately, the quality of the tube controller and the drum pads was most likely too low for the users to perceive any nuanced gestural implications on the produced sound. This is probably what led to little exploration of the gestural interaction. Resonator parameters with greater impact on the produced sound were explored more than parameters with subtler impact.

Two of the subjects preferred the GUI version of the PHYSMISM over the physical interface version, because it gave them a better overview of the synthesizer. Eight of the subjects preferred the physical interface, owing to the naturalness of the physical gestures with respect to the excitation controls, and the fact that the user was able to control multiple parameters at the same time. The recorded data also showed that more parameters were changed when using the physical interface than when using the GUI.

When users investigated the combination of models, data showed that all models (except for instances where other models were directed through the particle model) were rated more interesting compared to when they were played in isolation. Sonic and gestural properties were taken from one model and transferred into a different model. Directing the tube model through the friction model would for instance give the tube more unpredictable sonic character. Even the turbulence and impact models, which were the lowest-rated models on their own, became interesting not only when combined with other models, but also when combined with each other. The particle model exhibited problems when passing other models through it, as almost all timbral properties of those models would be lost, (which was unfortunately in contravention to the important criterion stated earlier in the section entitled "Combining the Models").

Participants were asked which combinations of models they preferred/disliked and why. It turned out that no combinations were disliked. Answers were quite diverse as to which combinations were preferred; however, user responses revealed three commonalities: interesting sonic properties from one model were transferred to another; it was interesting to explore the implications of combining two timbrally different models; and models would alter characteristics as unconventional excitation gestures were used to control them. For example, one user reported, "It was an interesting experience to blow on a drum."

In December 2006, the PHYSMISM was presented at the "Physical Models in Action" workshop at the Sonic Arts Research Centre (SARC), Queen's University of Belfast. The presentation included a demonstration session and a subsequent performance, consisting of three short pieces that presented a semi-improvised exploration of physicality and sonority. Feedback from participants during the session was generally positive. It was noted that the PHYSMISM presented a fine balance between high accessibility of each model and creative potential of the overall instrument.

Discussion

Though this study itself is rather exploratory, it has raised new questions and potential hypotheses to be studied further. Two experiences arose during the project that point to future research questions. One is the notion that a physical model "works best" when it is controlled using an interface that affords physical actions. The other is that the capability of combining the models affords creative exploration.

Future research should deal with exploiting physical modeling techniques to develop creative, exploratory environments suited for creating complex hybrids of all sorts of simulated sonic phenomena. Not only does physical exploration provide users with an extended, embodied perception of the instrument, but also the physical control gestures can form and alter the essence of the instrument, and being able to explore diversities in this gestural domain adds a natural exploratory channel to the physical-modeling instrument.

The modular approach achieved when combining the physical models proposed here lets the user enter this environment by taking advantage of the naturally perceived causal properties of physical modeling. By presenting users with the models separately and letting the users themselves do the combining and exploring, we provide a better understanding of each physical model while also providing users with creative freedom for exploration.

This framework can help users better understand what they are dealing with, creating mental models which relate more closely to the developer's conceptual ones (Norman 2002). The modular approach can provide users with an extended individuality, unpredictability, and an exploratory freshness. We believe that the framework offers a balance, crucial for an exploratory process, by providing a complexity that gives users a sense of endless possibilities, while presenting fixed boundaries around this exploration.

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Paper III

A Quantitative Evaluation of the Differences between Knobs and Sliders

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Abstract

This paper presents a HCI inspired evaluation of simple physical interfaces used to control physical models. Specifically knobs and sliders are compared in a creative and exploratory framework, which simulates the natural environment in which an electronic musician would normally explore a new instrument. No significant difference was measured between using knobs and sliders for controlling parameters of a physical modeling electronic instrument. The reported difference between the tested instruments were mostly due to the sound synthesis models.

Keywords: Evaluation, Interfaces, Sliders, Knobs, Physical Modeling, Electronic Musicians, Exploration, Creativity, Affordances.

1. Introduction

The motivation for this research was to investigate physical interfaces for controlling physical models. The research is situated within a framework introduced in among others [2], which approaches physical modeling from a user centered creative exploratory perspective. The framework deals with interfaces which afford creative exploratory processes.

On one hand the framework attempts to analyze the work processes of potential end-users. On the other hand it evaluates interfaces, which facilitate the needs of these end-users.

In our case the end users are electronic musicians which compose music working in an exploratory fashion, feeding off the affordances and constraints of the tools at hand for creative inspiration. Our approach is somewhat similar to the ecological [6] approach of Thor Magnusson, used for GUIs in among others [12].

It was decided to work bottom up, starting with the evaluation of the simplest traditional (continuos) input devices found in musical interfaces - knobs and sliders. In order to give a valid assessment of the differences between the two it was found important to somehow weight the influence of any differences that might appear. This was done by evaluating other influences on the overall impression and performance of musical instruments. For this study they were limited to 1) the influence of more expressive input devices and 2) the influence of the sound synthesis model (in this case physical models described later).

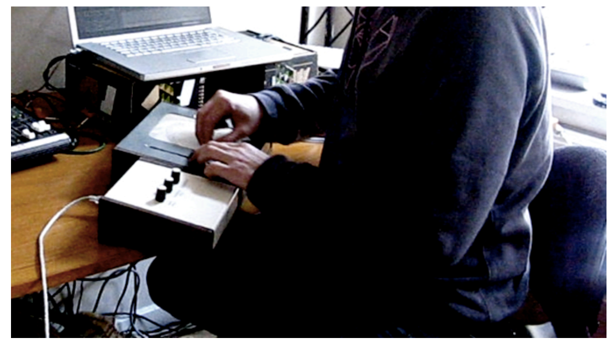

Figure 1. The interfaces were tested by experienced test subjects in their own studio in order to get as close to a real world scenario as possible

The main objective of this study was to investigate if there exist preferences when comparing simple physical interfaces such as knobs and sliders. Our null hypothesis was that knobs and sliders are equally preferred.

The study additionally had two secondary objectives: to investigate if there are physical interfaces, which afford creativity and exploration more than others, and what is the role of the sound synthesizer compared to the user interface.

2. Related Work

2.1. Interface Evaluation

The need for more effective evaluation methods has been addressed in recent years within the NIME community [3]. In [18] methods are proposed for evaluating musical interfaces, which are inspired by HCI research. Among other things the authors propose to use simple musical tasks to evaluate exploratory features.

A very nice overview of the recent literature has already been given in [11] which is a more detailed look at the methodological approach used in [10], where a Wiimote is evaluated as a musical controller. Their approach resembles to a large degree the methodology used here.

In [5] the authors distinguish between traditional usability evaluation (Fitts's Law [18] is a rigorous example) and a broader approach evaluating HQI (how "a user identifies with the product") and HQS (how the "product stimulates the user").

Quantitative and qualitative methods are applied in [15], which deals with evaluation of expressivity of string instrument based musical instruments from a performance point of view. A more qualitative method is proposed in [17] where discourse analysis is used to make qualitative methods more rigorous.

This paper will not deal with the expressivity as such, as it focuses on the compositional side of music making. The users are not merely musicians but also composers of electronic music - a trend that seems very common for electronic musicians. Inspiration has in general been found in the above approaches.

2.2. Interfaces for Controlling Physical Modeling

Physical modeling is a sound synthesis technique that is approached from a physical sound production perspective. Here the algorithms are designed to simulate the actual physical mechanisms, which produce sounds in the real world.

Interfaces for controlling physical models have naturally mostly revolved around input devices which were closely related to physical properties found in the model.

Almost all of these are interfaces designed for a specific project. However, a few attempts have been made towards general interfaces for physical models [4, 14] (each of them being general within subcategories of physical models, each representing different physical phenomena). Former research by the author et al. has examined the possibility of breaking free of these subcategories for a while in order to investigate interfaces, which may apply for physical modeling in general [2].

3. Knobs versus Sliders

Both sliders and knobs are used to control parameters of musical interfaces and they mostly have more or less the same output range. When designing novel musical interfaces one is often presented with the decision whether to implement either one or the other.

Knobs are often used when controlling parameters that have little relation to each other, whereas sliders are used for controlling parameters that are more comparable. Using only one hand, one is able to control multiple sliders at once - this is hard to do using knobs. Multiple aligned sliders can be easily monitored just by a glance, while one has to take a closer look at each knob one at a time in order to get an overview. Knobs on the other hand have the advantage of taking up less space. Using them with rotary encoders also provides the ability of very fine tuning.

These observations might seem trivial. However, the differences might matter a great deal when designing novel interfaces for musical purposes.

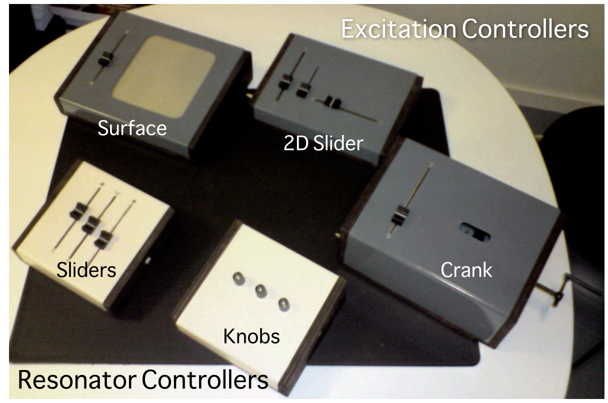

Figure 2. Two resonator controllers (white) implement three knobs and three sliders, respectively. Three excitation controllers (grey) implement a 2D touch pad, two sliders placed orthogonally and a crank, respectively.

4. The Splorer Modular System

Splorer is a custom built set of musical interfaces, which were designed and implemented with the goal of measuring the aforementioned differences. Splorer consists of two modular parts: a *resonator controller* and an *excitation controller* - see Figure 2. The two parts can be connected to form one overall interface - see figure 3. By creating two *resonator controllers* and three *excitation controllers* it is possible to combine your way to 6 unique interfaces to test on. These interfaces are used to control two different physical models (giving a total of 12 unique musical instruments to test on).

By testing the interfaces in these 12 different combinations it should be possible to first of all minimize uncertainties connected to external variables when comparing the knobs and sliders. Secondly it should be possible to identify which other variables influence the overall impression and performance of the instruments.

In order to conduct the tests as close to the natural environment of an electronic musician as possible the interfaces were designed to give the impression of real "commercial" hardware synthesizers. The design was kept as consistent as possible for the different controllers in order to minimize uncontrollable variables connected to visual impressions.

4.0.1. Knobs and Sliders

Two different *resonator controllers* were implemented. One implemented three knobs, and one implemented three sliders - see figure 2. The sensors were interfaced with Max/MSP [1] using Arduino Diecimila [2] data acquisition boards.

4.0.2. Surface, Crank and 2D Slider

Each of the three *excitation controllers* implemented three input devices. Common for all three was that one of these

[1] http://cycling74.com
[2] http://arduino.cc/en/Main/ArduinoBoardDiecimila

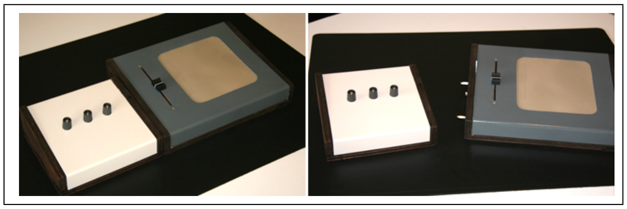

Figure 3. The excitation controller (grey) can be attached to the resonator controller (white). This gives the user the impression of playing one single instrument, while transmitting the sensor data from the excitation controller to the Arduino placed only in the resonator controller.

input devices was a slider. Additionally the *Surface* implemented a 2-dimensional touch pad. The *Crank* implemented a crank, which could be adjusted in and out for an extra parameter. The *2D Slider* implemented two sliders placed orthogonally to each other - though being semantically equal to the trackpad, the controls of the 2D slider are separable, where the trackpad's are integral [9]. See figure 2.

The *excitation controller* and the *resonator controller* are connected to each other in order to strengthen the user's impression of playing one single instrument- see figure 3.

4.0.3. Flute and Friction

Two different sound synthesis models were implemented. The flute model implements two digital waveguides and a simple non-linear exciter [16]. The friction model implements three digital waveguides and a non-linear exciter [1]. Both are borrowed from a previous project and only slightly modified to suit this study [2]. The controller mapping for each model was kept as equal as possible for the resonator part. The excitation mapping was made so that the user had to keep moving in order to sustain sound [3]. According to [8] this can enhance the feeling of playing "an actual instrument".

4.1. Test Subjects

In order to be able to apply the results of this study to the specific target group (electronic musicians) it was very important that the test subjects were chosen carefully.

Two experts were interviewed with regards to suggesting relevant candidates. One is the owner of a respected Danish electronic record label and the other is an editor of the leading electronic music program on the Danish National Radio. Three main criteria were given to the experts: 1)The candidates need to compose their own music. 2)They need to have released at least one record. 3)They need to fit into the overall category of electronic music. The first two criteria made sure that the test subjects were experienced and established artists. The third ensured that they fit into the target group of electronic musicians.

With this information around 40 musicians were found, around 30 were contacted. Hereof 20 musicians were tested in the end.

5. Method

The actual test contained two major parts. The first part was a questionnaire which was used to establish the musical background of the test subjects. This should ensure that they were indeed part of the target group. This was followed by an interview regarding the typical work processes of the electronic musician/composer. The interview will not be elaborated in this paper.

The second part was the actual usability test. Each test subject had to carry out three identical tests - testing three different unique instruments. With 20 test subjects that gave a total of 60 tests. Having to test 12 unique instruments we were able to achieve 5 repetitions for each.

Each test took approximately 20 minutes and consisted of 3 parts:

5.1. A free play and explore session

Firstly the user had approximately 7 minutes to play around with the instrument as he or she wished in order to get an impression of the overall instrument. This was used to simulate the natural way in which a musician would try out a new instrument for the first time.

5.2. Musical tasks

The test subjects were first asked to listen to four samples (we call them *reference sounds*) all created using a software version of the sound synthesis model. Each sample (approx. 10 seconds) represented different timbral changes [4]. The test subjects then had 3 minutes to imitate each *reference sound* using the instrument at hand. This resulted in 4 sound samples from each test subject for each unique instrument - or 4×5=20 samples for each unique instrument.

The samples were rated by how well they resembled the *reference sounds* on a Likert scale from 1-5 (1 being not at all, and 5 being an exact resemblance). The author and an impartial sound engineer rated all sounds not knowing which sound went with which interface/test subject. The average between these two ratings was used to calculate the final sound rating of each sample. In order to find the specific sample rating for each unique instrument, first an average of each of the 5 test subject's sounds was found, giving four sound ratings (one for each of the four reference sounds). An average between these four was then calculated giving one specific score for each of the 12 unique instruments.

5.3. Questionnaire

Test subjects finally filled in a quantitative questionnaire about the perceived difficulty of the task (has not been used for this paper) and the impression of the overall instrument.

[3] go to http://media.aau.dk/∼stg/splorer to see mapping details

[4] go to http://media.aau.dk/∼stg/splorer to listen to the reference sounds

They were asked to rate the overall instruments on a Likert scale from 1-5 (strongly disagree, disagree, neither or, agree, strongly agree) on *accurate control, intuitive control, inspiring, frustrating, nice feel, predictable, whether it gave them musical ideas, felt like an acoustic instrument, used for composition, used for live performance, time to master* and finally *overall likeability*. The different rating criteria were chosen in order to asses features important to traditional HCI evaluation along with features associated with the proposed framework of creativity and exploration. The subjects had the option of writing comments for explaining their answers - these have been used to reflect on the results.

Finally a log of observations during the test was compiled (containing also comments from the test subjects during the test). These observations have mostly been used to gather early/spontaneous impressions of the instruments / interfaces / synthesis models. The observations were used together with the comments for reflecting upon results.

The test was performed 3 times by each test subject, each time with a different unique instrument (combination of *resonator control / excitation control / sound synthesis model*). The combinations were picked randomly making sure that each test subject tried each of the two resonator controllers, each of the three excitation controllers and each of the two sound synthesis models. The order of the combinations was also randomized making sure that for example friction / sliders / crank was not the first to be tested every time.

5.4. Setup

The sound synthesis models were implemented as externals in Max/MSP 5 running on a 2.4 GHz Intel MacBook Pro with 4 GB 667 MHz SDRAM (Mac OS 10.5.6). This was connected to a PreSonus Firebox firewire sound card. Speakers varied, as each test was performed in each of the test subject's own studios - again in order to mimic the real world scenario, as can be seen in Figure 1.

The *reference sounds* used for the imitation task were played from a separate computer. This way the test subjects were able to playback the samples at will, while the test conductor is free to monitor the test using the sound synthesis computer. The *reference sounds* were played back in Quicktime on a 1.5 GHz G4 PowerBook 12" with 1.25 GB SDRAM (Mac OS 10.4.11) with a built in sound card using Beyerdynamic DT 770 headphones.

6. Results

6.1. Test Subjects

20 musicians were tested - 2 female / 18 male. Ages ranged from 20 to 45 with an average of 29.6. 70% were attending or had attended a conservatory for electronic music. The average amount of records sold for the test subjects was 5513 ranging from 0 to around 50000. Five subjects reported that they had sold 0 albums - however, they were all found experienced enough to be regarded for the task based part of the test - interviews and comments were discarded. They reported using an average of 21 hours a week playing/making music. 55% knew what physical modeling was, implying that they would be quite unbiased when evaluating the instruments.

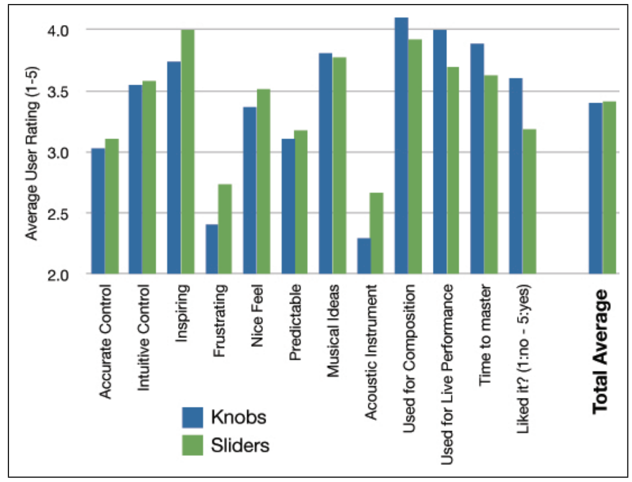

Figure 4. There were no significant differences between user ratings of knobs and sliders.

6.2. Knobs or Sliders?

Surprisingly the questionnaire revealed no significant difference in ratings between knobs and sliders, as can be seen in Figure 4. Slight differences between the two exist- but the quantitative data did not reveal them as significant ($p > 0.05$ in all the comparisons). *Sample ratings* suggest that the sliders were slightly easier to control. However, the difference was not substantial enough to make it conclusive.

There were reported differences in the comments of the test subjects. However they were quite ambiguous. Some said that the sliders provided more control, while others said that the knobs were easier to adjust accurately. Factors that might have distorted the results are most likely found in the quality of the actual sensors. Although an effort was made to make the quality of the two devices equal, there seemed to be different preferences among the test-subjects as to what constitutes high quality - especially when it came to sliders. The amount of passive haptic feedback provided by the resistance of the mechanical parts of the slider seemed crucial when evaluating its quality.

6.3. 2D Slider, Crank or Surface?

The crank received the most positive commentary feedback of the three excitation controllers. Comparing *sample ratings* for the different excitation controllers also indicates that the Crank provided the best control of the sound synthesis models. The crank was rated highest when it came to *intuitive control, inspiring, feel, musical ideas*, and *likeability*. It was also rated least *frustrating* as can be seen in Figure 5.

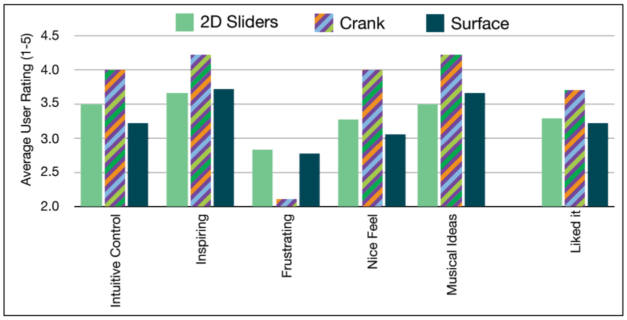

Figure 5. The Crank excitation controller was rated highest in intuitive control, inspiring, feel, musical ideas and likeability compared to 2D Slider and Surface controllers. It was also rated least frustrating.

The 2D slider and the Surface were rated surprisingly equal. The only considerable difference was found in *accurate control*, where 2D slider scored the highest.

The crank definitely had an upper hand in the sense that it is an unused controller for electronic music. Subjects seemed to have an initial impression that the crank was funny resulting in rather low expectations. This was followed by a feeling of "pleasantly surprised" after having tried it. Many expressed: "I would never have thought a crank would work that well for this kind of music". The lower ratings of the 2D slider were most likely due to a combination of the test subjects feeling too restricted in their movements and the controller lacking novelty. As for the Surface, the sensory part of the interface did not live up to the standards the musicians have come to expect from a touch sensitive pad. They had to press too hard to produce sustainable output.

There were very different opinions about the fact that the users had to keep the excitation controller in constant movement in order to produce sound. Some said it felt intuitive and like a real instrument while other reported that too much focus had to be on "keeping the sound going" to really focus on playing/controlling/adjusting the sound - this might have to do with the normal practice of most electronic musicians, where they utilize some sort of automation to keep the sound going, while being free to alter/explore the more timbral parameters of their system. An extended practice time could of course help avoid this.

6.4. The Sound Synthesis Models

The most considerable differences was found between the two sound synthesis models. The friction model was the clear favorite when analyzing the *comments*. Additionally the friction model was rated highest in *inspiring, feel, musical ideas, used for composition*, and *likeability*. However it was rated lowest in *intuitive, predictable* and *accuracy*. See figure 6.

Sample ratings showed that the flute sounds were better imitated than the friction sounds. There seems to be inverted proportionality between how creatively inspiring the sound

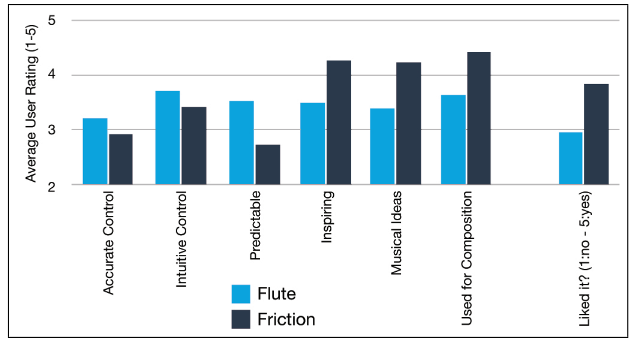

Figure 6. The friction mode was rated highest in inspiring, feel, musical ideas, used for composition and likeability

synthesis model is and how accurate, intuitive and probably most of all predictable it is. This is somewhat equal to results found in [13]. Of course, if one was to design an accurate, intuitive and predictable musical instrument directed towards electronic musicians, he or she would not necessarily fail in making it creatively inspiring. But maybe unpredictability could be a criteria that enhances creative exploration. Further research is needed to be able to confirm such a relationship.

7. Discussion

Although subjects reported having preferences for one or the other surprisingly, no significant difference was found between knobs and sliders. Further research is needed but comments seem to reveal that differences are tightly bound to tradition, habits and routines. Had the knobs and sliders been tested on well known interfaces, which are strongly bound to tradition in regards to choice of input devices (like mixers or envelope controllers), the results would most likely differ.

Interesting differences arose between other influencing variables. They revealed that in order to design novel musical instruments, which afford creativity and exploration, one can't necessarily make the controls as accurate or as predictable as possible - also indicated in [3]. It definitely shows that testing for traditional HCI features alone will not be enough to evaluate the success of interfaces in this highly complex world of (electronic) music.

It was interesting (though maybe not surprising) how important the sound synthesis model is compared to the interface. The somewhat inverse proportionality between intuitiveness, predictability, accuracy and the affordance of creativity and exploration was an interesting observation. The constraints of the interface should not be clear to the point that it becomes predictable. Predictability is a feature that according to this research must be avoided - which makes the quest for "intuitive interfaces" tricky. One must be careful not to mistake predictability for intuitiveness.

The most concerning issues with the methodology were issues of time. The mere fact that the musicians did not have more time to explore the instruments may have distorted the results. It is difficult to avoid the effect of novelty in such a short amount of time. A 20-30 minutes test seems sufficient when testing for traditional usability factors. But in order to asses factors like creative and exploratory affordances tests must be conducted over longer periods. These "softer" factors closely related to the *third wave* [11] and "HQI/HQS" [5] are more difficult to asses. Future research will investigate a more qualitative approach where fewer musicians "borrow" Splorer instruments for longer periods of time in order to get closer to a real world scenario. This could be carried out like in [7] where three subjects were tested over ten different sessions.

Should the same task-based method be used again, the reference sounds should be more intriguing for test subjects. Some participants said that the tasks were somewhat boring compared to the capabilities of the instruments. This definitely has an influence on trying to create a real world scenario. Having musicians from the target group create the reference sounds could lead to better results.

A larger sample will also minimize uncertainties caused by other uncontrolled variables. However this is one of the major problems of gathering solid quantitative data in this field. Reliable test subjects are relatively few and therefor difficult to recruit. Another solution would be to limit the variables - however, extremely simple test scenarios are perhaps too far from the real environment of the electronic musicians to produce valid results.

8. Conclusion

A low level interface evaluation has been presented. The use of knobs compared to sliders for novel musical instruments directed specifically for electronic musicians was evaluated. No significant differences were found between the two. However, different preferences were reported suggesting differences to do with tradition, habits and routine.

The methods used here can serve as inspiration when investigating creative and exploratory affordances - especially when dealing with the relatively complex electronic musicians, the majority of which also compose music. By focussing on the users it is possible to come close to real world scenarios in controlled environments. Evaluating few elements (knobs and sliders) under varying circumstances also produces more valid results. Circumstances can of course vary a lot more than in this test, so further research is needed to establish a more complete picture.

9. Acknowledgments

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Paper IV

From Idea to Realization - Understanding the Compositional Processes of Electronic Musicians

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Abstract. This paper presents a study of the compositional process of creating electronic music. 18 electronic musicians were interviewed with focus on discussing their compositional approach, how ideas were realized, and how musical tools were utilized throughout the process. Results show that the process changes significantly from the beginning of the compositional process to the end. Freedom and control are not always keywords for designing successful musical tools. Participants reported that many creative ideas arise by not being fully in control, not being able to predict the outcome, or restricting or deliberately creating challenges for ones-self.

1 Introduction

The motivation for this study was to investigate the interaction connected to the creation of electronic music in a compositional setting. In order to do so the work processes of today's electronic musicians have been examined. Traditionally there are two overall approaches to composing electronic music. In one approach the composer starts out with a clear goal or idea of how the end result will be. He or she might create a detailed plan of how to realize the idea. The composer then brings the idea to life using tools and skills at hand. In the other approach the composer is inspired in an exploratory sense by a selection of sound material or available technologies and from there experiment to finally form a resulting piece [8].

This latter approach forms a research framework used also in [2, 1] which examines the control of physical models from a user centered creative exploratory perspective. The framework regards the user as an *explorer* of musical affordances. The ecological [4] framework used in among others [7] takes a similar approach.

The research presented here focusses on understanding how exploratory interaction plays a role in the creation of electronic music in praxis. Would it for instance be possible to encourage such exploratory interaction by design? Or in other words, would it be possible to design a musical interface, which affords creative exploration?

We were interested in how musicians conceive their ideas for new musical pieces. What is the nature of a new idea? An idea for a melody, a mood, a beat or perhaps a whole piece or album? How close is the resulting piece to the initial ideas and how do musicians interact with the tools at hand to explore these ideas? Finally we were interested in understanding in which situations (and perhaps with which tools) musicians perceive themselves as being creative or exploratory. Answering these questions necessitated asking electronic musicians about there typical work process when creating music.

The qualitative methods used in this study have been inspired by related studies within electronic music. In [6] a qualitative internet survey was conducted in order to understand the relationship between musician and musical tools. [9] suggests a method for evaluating interview data adopted from HCI studies, and finally [5] uses interviews methods proposed in [10] for evaluation of a novel interface. Their method for analyzing the interview data resembles to a large extent the methods used here.

2 Methods

2.1 The Test Subjects

Well established electronic musicians were carefully selected as test subjects by consulting two experts: An owner of a respected Danish electronic record label and an editor of the leading electronic music program on the Danish National Radio. Three main criteria were given to the experts: 1) The candidates need to compose their own music. 2) They need to have released at least one record. 3) They need to fit into the overall category of electronic music. Around 40 musicians were selected, 30 were contacted and in the end 18 participated in the study.

2.2 The Study

The study consisted of three overall parts. First the test subjects filled in a qualitative questionnaire after which a semi-structured interview was conducted. Finally they were asked to perform a series of musical tasks (these are not described in this paper - see [3] for more details).

2.2.1 The Questionnaire

The questionnaire was used to establish the musical background of the test subjects and to find out how they themselves would describe the musical tools they used for compositional processes. They were asked to classify their compositions based on genre, approach, goals, ideas, etc.. They were then asked what kind of software/hardware they used, and to critique that software/hardware.

2.2.2 The Interview

The interviews were individual semi-structured with a duration of approximately 15 minutes each. They were guided by the interviewer, who asked additional questions to keep the test subjects' focus on discussing the process of working on a piece of electronic music. The questions were based on three overall themes. These themes were:

1. *"What is the most typical work process for you when composing a piece of music?"*
2. *"In which situations do you find yourself most creative when creating music?"*
3. *"In which situations do you find yourself exploring when creating music?"*

Interviews were recorded using a dictaphone and transcribed for data analysis. The transcriptions then underwent a filtering process divided into several stages. First each transcription was deducted into key statements and interesting quotes for each of the three areas (corresponding to the three overall guiding questions). The nine most relevant of these statements were extracted (three from each area) to produce a final document. If a transcription contained more than nine interesting statements, they also made it into the final document.

These overall statements were then compared, contrasted and evaluated.

3 Results

18 participants were interviewed - 2 females and 16 males. Ages ranged from 20 to 45 with an average of 29.6. 70% were attending or had attended a conservatory for electronic music. The average amount of records sold for the test subjects was 5.513 ranging from 0 to around 50.000. Unfortunately 5 of the 18 subjects reported having sold 0 records, however, they were all found experienced enough to participate.

3.1 Results of the Questionnaires

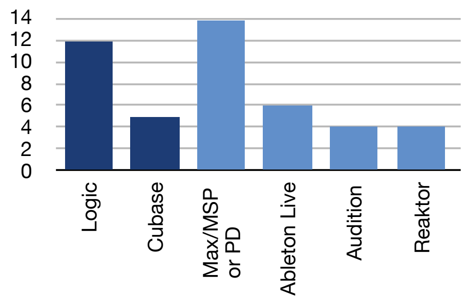

Figure 1: Out of 18 subjects, 12 used Logic as their main DAW, 5 used Cubase. Other commonalities included Max/MSP, PD, Ableton Live, Audition, and Reaktor.

17 of the 18 subjects used either Logic or Cubase as their main DAW[1]. As additional software most used Max/MSP or PD - this could however be biased because the majority of 70% of the subjects that were or had attended a conservatory had received lessons in Max/MSP. Other commonalities included Ableton Live, Audition[2], and Reaktor - see figure 1. When it came to hardware tools there were no significant commonalities. A few had MPCs of different kinds, MIDI controllers/keyboards and vintage analogue synthesizers. Answers also included some hardware audio effects, compressors and pre-amps.

When critique was given of subjects' software/hardware tools, four common statements emerged. Four subjects expressed the desire for more physical interaction. Four wrote that the software was often too linear - both the process and the actual end result demanded more nonlinear tools. Three subjects wrote that there was a lot of especially software out there that had too many options/possibilities - this could kill creativity. Finally three subjects were concerned with the hassle connected to setting up hardware (took up too much space, too many cables etc.).

Asking subjects to classify their compositions produced some interesting answers regarding especially their approach to making music. 15 were classified as having an extremely experimental approach. The last

[1] Digital Work Station
[2] Audition is former known as Cool Edit

three were still experimental, but had somehow found a niche or a certain way of approaching composition every time. 12 persons explicitly expressed that their approach involved letting themselves be guided by the musical tools at hand.

3.2 Results of the Interviews

3.2.1 Overall Process

Results of the interview data analysis revealed that most subjects prefer exploring with tools at hand until stumbling upon an idea or simply gathering enough sonic material to form into a piece. They rarely have a concrete idea about the finished piece until very late in the process - and as most subjects stated: "The idea can then still change dramatically." One participant described the process as how he imagined an abstract painter would work, creating a sort of collage of colors until a form arises, which is then pursued.

Many expressed the need to go from this extremely exploratory mode into a more pragmatic mode in order to be able to finish compositions. It seemed that the exploratory or experimental mode mostly deals with getting ideas and producing interesting sound material. It is a highly non-linear process of breaking away from current ideas to pursue new ideas and experiment with different approaches. Once an idea has matured enough, or enough sound material has been collected, an editing mode acts as a transition to the more pragmatic mode. Of course there is always room for new ideas throughout the editing and pragmatic mode.

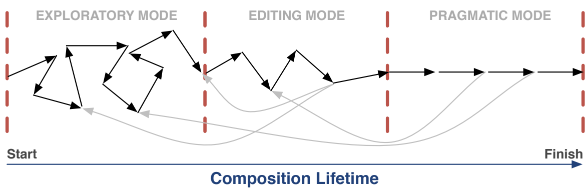

Figure 2: The compositional process can be divided into three modes. An exploratory mode, an editing mode and a pragmatic mode.

3.2.2 The Explorer and the Worker

One (representative) subject explained how he found himself working in two different modes, the explorer and the worker. How they take over from each other usually differs. Here are two examples:

1. The explorer starts and when there is enough material, the worker takes over and puts it all together creating the form.
2. The worker makes a nice synthesizer and then the explorer discovers that it fits with something else and putting it there and there makes a piece.

Hence, the worker and the explorer can both start and finish the process.

3.2.3 The Initial Idea to finished composition

When do you get an idea? What is the nature of the idea? How long does the idea last? Most said that ideas change a lot depending on how they interact with their tools. Many express the desire to be better at getting directly from idea to sound - but then the same subjects also underline the productive creative consequences of not really knowing what will happen when turning that knob or connecting these two wires.

All subjects described the early process of gathering sonic material as being very exploratory. "Playing around", "go with the flow", "deliberately try to loose control", "trial and error", "work without thinking", were statements describing the exploratory search for new sound material. This corresponds well to the results of the questionnaires. Ideas may spark the process, but the ideas are mostly of technical nature or describing moods, overall themes or philosophical phenomena. Also, these overall ideas most often change during the compositional process.

3.2.4 Unpredictable versus Intuitive

12 of the 18 subjects said that they let the machine(musical tools) have a say in the outcome of their work. One put it like this: "There are two members in my little band. One is me and my ideas, the other is me not being so fast with the knobs, which means I accidentally do something other than what I intended - and then we compromise." It seems that musicians like when a tool has "a life of its own".

16 of 18 said that finding themselves in too much control can kill the creative process. Most prefer tools that they don't understand fully, tools that are unpredictable in some way, or tools that they can use in unintended ways. Especially systems that you can pass sound through were popular because each element can be very limited, and even though you get to know the tools well you can always patch things up in new ways.

Approximately half of the test subjects explained in greater technical detail about their music making process - and almost all of them said that using a tool to do things that that tool was not intended to do created the most interesting results. One said that it is often something that essentially sounds bad combined with something nice that creates the most interesting results.

Intuitive predictable tools, which provide users with full control are still needed. It seems that the closer they come to the final stages of finishing the composition, the more they need accurate control.

3.2.5 Creativity

When asked about in which situations they found themselves most creative, most subjects (14 of 18) said explicitly that they were most creative at a specific time of day, in a certain location or alone or with other musicians. These are quite external factors that they either actively try to control or in hindsight had realized nearly always produced good results.

3.2.6 The Challenge

15 out of the 18 subjects said that they feel more creative when they don't fully understand something. A deliberate work process is putting themselves in situations that are challenging.

3.2.7 Boundaries vs. Freedom

Most subjects set boundaries, rules, dogmas, limiting their options in order to guide or challenge the creative process. When the answers described concrete tools, those tools would mostly be limited in functionality. Freedom is wanted in an overall sense but even when being totally free musicians want help for making decisions. Rules are made up to guide the creative process - but the freedom is there to suddenly change rules / directions / tools etc.

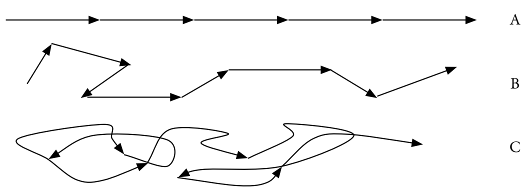

Figure 3: Workflow can be divided into three different processes. A) represents the very linear approach with minimum exploration. B) represents the exploratory approach but where each exploration is contained within some sort of linear boundary. C) represents the extremely exploratory approach where everything is possible at all times.

Figure 3 represents three different forms of workflow. A) represents a one-dimensional rigid process, which could represent the process of getting an idea, and knowing exactly how to materialize it. B) represents a two-dimensional more free process where each step is rather limited - represents the process of exploring possibilities within fixed boundaries, but still having the freedom to change direction at any time. C) represents a totally free process where everything is possible at all times.

The majority of the test subjects express that the most creative process can be found somewhere between B and C.

Figure 4 shows a different representation of B and C. The left part represents working within boundaries but still having the overall freedom to explore something else - an approach preferred by the majority of the test subjects. The right part represents working with total freedom without boundaries.

It is important here to mention that a few test subjects however, said that they were most creative working with the "everything is possible" approach of for instance Logic, Cubase or even Max/MSP, which is closer to the right part of figure 4.

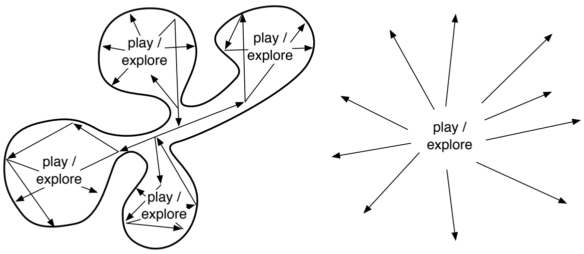

Figure 4: On the left: Illustrates freedom with boundaries. On the right: Represents total freedom.

4 Design Proposals

The following are a set of design proposals, which might encourage exploratory interaction. They are not strict principles for design of new musical tools - they might not even be achievable. They are more reflections, which might serve as inspiration for future research:

1. Design for unintended use.
2. Design for a balance between an intuitive tool and an unpredictable tool - this could also be achieved by modes, or a setting of how predictable the interface should be.
3. Restrict the possibilities of the musical tool.
4. Make the tool compatible with everything else.
5. Give the tool a possibility of passing sound through it.

5 Quotes

Lastly there were a few interesting quotes that fit in to a more overall understanding of the relationship between the electronic musician and his compositional tools:

About freedom / boundaries: "It's like when asking whether you like hardware or software. It is the interplay between the two that is interesting."

About deliberately loosing control: "You're always standing on the cliff of intellectual trying to dive off into the artistic."

"Nirvana is when you think: "Wow, did I make that?""

About why to set up challenges: "... when I play acoustic piano, I always find myself playing the same kind of melodies."

"I love to squeeze a plugin beyond its capabilities - that is when surprising things happens."

"I never really become good at something. I always feel like I almost know what I'm doing. Otherwise things begin to get boring."

6 Conclusion and Discussion

18 interviews of electronic musicians were conducted in order to understand the compositional process of creating electronic music. Special focus was put on understanding how musical tools played a part in this process and how creative ideas arose, were carried out, and materialized using these tools.

Participants seem to prefer working in a free exploratory mode early on in the compositional process. They explore new ideas by trying to break boundaries, interact with musical tools differently than intended, connecting tools in new ways, setup restricting rules and create challenges for themselves. Ideas are not at all fixed/concrete in this mode.

The closer the composition is to finalization, the more rigid the process most often becomes. New ideas can always arise of course, but the participants have the need for working more pragmatically to be able to finish the composition.

This research depicts some of the challenges of designing new musical tools for creating electronic music. Designers should be aware of *when* in the compositional process the tool is needed. This determines (too some extent) the desired interaction and thus how intuitive and how predictable the tool should be. It also seems that restricting the tools to few capabilities, while still being compatible with other systems) affords creativity, and is especially desirable in the early explorational stage of the compositional process.

It is very much the interplay between the ideas of the musician and the slightly unpredictable feedback from the musical tool that encourages new ideas to be sparked.

7 Acknowledgements

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Paper V

PHOXES - MODULAR ELECTRONIC MUSIC INSTRUMENTS BASED ON PHYSICAL MODELING SOUND SYNTHESIS

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ABSTRACT

This paper describes the development of a set of electronic music instruments (PHOXES), which are based on physical modeling sound synthesis. The instruments are modular, meaning that they can be combined with each other in various ways in order to create richer systems, challenging both the control and perception, and thereby also the sonic potential of the models. A method for evaluating the PHOXES has been explored in the form of a pre-test where a test subject borrowed the instrument for a period of 10 days. The longer test period makes way for a more nuanced qualitative evaluation of how such instruments might be integrated into workflows of real world users.

1. INTRODUCTION

The PHOXES (Physical Boxes) are a set of musical instruments, which are based on physical modeling sound synthesis. They were developed in order to investigate how high level exploratory control structures have an impact on the sonic potential of physical models.

1.1 Exploring Physical Modeling

Traditionally the goal when developing physical models has been to accurately simulate the physical mechanisms, which produce sound in the real world. When controlling these models the goal has often been to achieve the same nuanced input capabilities as one would have when playing real acoustic instruments striving for an enhanced expressivity or intimacy.

This research deals with the ongoing investigation into how control structures for physical modeling sound synthesis, can enhance the explorability and thereby the creative potential of the technique. One goal is to understand how physical modeling can be controlled in order to accommodate the work processes of the end user (for us the experimental electronic musician). The focus is not on expressivity or intimacy of musical controllers, but on enhancing their exploratory and creative potential (note that these are not apposed to each other as a higher level of intimacy can also lead to a higher degree of exploration [1]).

Figure 1. The PHOXES system is modular and currently implements four different modules each implementing a different physical model and a different excitation controller. *Upper from left: friction PHOX and particle PHOX. Lower from left: drum PHOX and tube PHOX.*

We believe that physical modeling bears with it an obvious potential to maintain the balance between intuitive control and that certain amount of complexity that is needed in order facilitate the exploratory processes, which are so important for supporting creativity. Within creativity support tools research this balance is referred to as *Low threshold, high ceiling, and wide walls* [2].

One way of creating a low threshold can be to design input devices, which are built upon traditional acoustic instruments. Controls will not only be familiar, there will also be a great amount of users, who have already spent years on refining expert playing techniques. In developing the PHOXES we have worked in the opposite direction by leveraging on input devices and control structures found in commercial electronic music instruments, merging them with alternate input devices specifically suited towards the physical models.

2. PHOXES

Each PHOX is an instrument on its own implementing a physical model, an excitation controller and four knobs for adjusting various model parameters (mostly resonator parameters). The excitation controller lets the user inject energy into the physical model by performing musical gestures, which intuitively relate to that model. For instance the tube PHOX implements a flute controller for exciting a turbulence model. The user receives visual feedback in the form of exact control values on an LCD screen mounted on each PHOX.

Each PHOX works as a musical instrument on its own, but the PHOXES are modular, meaning that two or more PHOXES can be combined in various ways to produce sonically richer systems. Although each physical model is still fixed this lets the user explore the models in a totally different and more abstract way. Each PHOX still upholds an intuitive perception of how the sound is produced, because of the perceived causality inherent in the physical modeling technique. But when they are combined this perceived causality is challenged, altering both the gesture space provided by the PHOXES and the sonic potential of the models. How this is handled is described later in Section 2.5.

The goal when developing the PHOXES was to create a flexible system that while keeping each physical model fixed (not letting the user assemble their own physical model as seen in for example [3]), the users are able to combine the different models in various ways thereby achieving a different exploration of the sonic possibilities made available by each model. This section will describe the design and implementation of the PHOXES - in particular the physical models used, the choice of control devices (including how they were built) and the mapping strategies for developing the modular system.

2.1 Physical Models

Each of the individual PHOXES implements a different physical model, each representing a different physical modeling technique. They vary in complexity, sonic fidelity and physicality (which type of excitation gesture they naturally propose). The four PHOXES (as seen in Figure 1) and the physical models on which they are based are:

- **tube PHOX** - implements a *turbulence model* with a simple nonlinear exciter [4] and a one-dimensional waveguide resonator [5].
- **particle PHOX** - implements a *particle model* with a stochastic excitation based on Physically Informed Sonic Modeling (PhISM) by Perry Cook [6].
- **friction PHOX** - implements a *friction model* with a complex nonlinear exciter [7] and a one-dimensional waveguide resonator.
- **drum PHOX** - implements two identical *drum models* each with a simple nonlinear exciter and a two-dimensional waveguide resonator [8].

2.2 Physical Devices

As described in Section 1.1 the PHOXES have been inspired by commercial electronic music instruments. It was important that the eventual test environment was as natural for the test subjects as possible, which is also why the PHOXES were designed with a look and feel that were convincing enough to resemble real commercial hardware synthesizers. The PHOXES could have been presented

Figure 2. The flute controller is implemented using an amplified low pressure sensor mounted to the end of a tube, which the user blows into.

(and perhaps partially controlled) in a software environment, but it was important for us to put emphasis on the physical devices as standalone instruments - even though they are not. Finally, it was crucial that they were robust and durable enough to make a long term evaluation possible.

Each of the four PHOXES is implemented using a PhidgetTextLCD with PhidgetInterfaceKit 8/8/8 [1], which provides 8 analog inputs, 8 digital inputs, 8 digital outputs, and a 2-line by 20-character LCD screen. This makes it possible to control mapping settings, control settings, and display settings in a customized menu system directly on each of the instruments. The instruments connect to the computer via USB and communication, sound synthesis and mapping is handled directly from Max/MSP. The system has been tested on a MacBook Pro with 2.4 GHz Intel Core 2 Duo processor and 4GB 667 MHz DDR2 SDRAM - Mac OSX 10.5.8.

2.3 Excitation Controllers

Each PHOX implements a different excitation controller, which naturally relates to the physical model of that PHOX. The excitation controllers are as follows:

2.3.1 tube PHOX Excitation Control - Flute

The tube PHOX implements a flute controller, which by default controls the turbulence model. The flute controller implements an amplified low pressure sensor [2], which is attached to a tube that the user blows into - see Figure 2. The pressure sensor is very responsive and is sensitive enough for detecting very small differences in air pressure produced by the blowing gesture and because the signal is amplified it connects directly into the Phidget interface [3]. The air pressure is mapped to the input energy into the physical model.

2.3.2 particle PHOX Excitation Control - Crank

The particle PHOX implements a crank as its default excitation controller - see Figure 3. The crank is attached to a

[1] from http://phidgets.com
[2] the 1INCH-D-4V from All Sensors
[3] could also be an Arduino or CUI interface or the likes

Figure 3. The crank is used as excitation controller for the particle PHOX. It is attached to a multi-turn rotational potentiometer.

Figure 4. The friction PHOX implements a ribbon sensor, which lets the user slide his or finger back and forth over the surface to create energy.

multi-turn rotational potentiometer [4] and the rotational velocity of the potentiometer is mapped to the input energy of the physical model - the probability of a particle hit in the case of the particle PHOX.

2.3.3 friction PHOX Excitation Control - Slide Surface

The friction excitation controller is implemented using a ribbon sensor (a soft potentiometer [5]) - see Figure 4. The user slides his or her finger back and forth on the surface to create energy. The velocity of the motion is mapped to the input energy of the physical model.

2.3.4 drum PHOX Excitation Control - Drum Triggers

The excitation controller for the drum PHOX consists of two drum triggers built from piezo transducers [6] - see Figure 5. The transducer produces a voltage when struck - this is thresholded to detect a hit and peak detected to determine the velocity of the hit.

2.4 Model Parameter Controls

Each PHOX also implements four knobs, which let the users control selected parameters of the physical model. For instance one is able to adjust how long the tube is, or how dampened the particles collide. Physically, they are controlled by simple knobs (potentiometers), which help establish the look of the PHOXES by aesthetically connecting them to more traditional electronic instruments or controllers. They present a familiar control surface, which lowers the threshold for electronic musicians initially learning the instruments and finally, because they are the same on each PHOX, they help to perceptually connect the different PHOXES into one system.

[4] Model 357 from Vishay
[5] SoftPot from Spectra Symbol
[6] KPSG100 from Kingstate

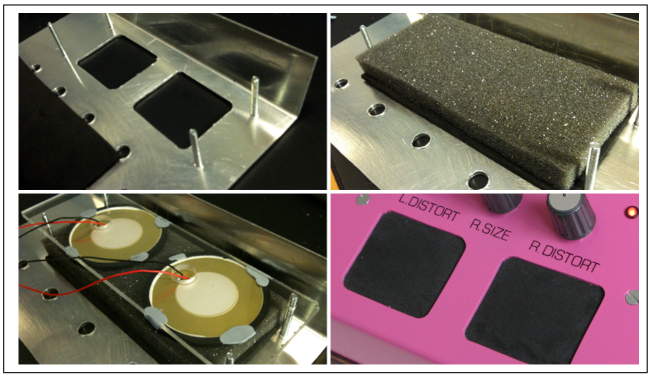

Figure 5. The drum PHOX implements two drum triggers, which were implemented by mounting two piezoelectric discs under two layers of foam.

The following is an overview of which model parameters are controllable. Parameters for the tube PHOX are *tube length 1, tube length 2, vibrato*, and *flute airyness)*. Parameters for the particle PHOX are *fundamental frequency, approximate frequency of four partials, amount of randomization of partial frequencies*, and *bandwidth of the partials*. Parameters for the friction PHOX are *frequency 1, frequency 2, downward force*, and *roughness (randomness of force and amount of noise)*. Finally, parameters for the drum PHOX are *left drum size, left drum frequency distortion, right drum size*, and *right drum frequency distortion*.

2.5 Modularity

2.5.1 Exploration of excitation gestures

By default each PHOX has a dedicated controller, which is intended to presents a natural intuitive relationship between excitation gesture and model. This helps the user to get a first intuitive impression of the model's control possibilities. However, the user can also choose to control the physical model using the excitation controller imbedded in any of the other PHOXES. For instance instead of exciting the friction model of the friction PHOX using the *slide surface* one is able to use the *crank*. This lets the user explore different playing styles by performing different excitation gestures - thereby hopefully achieving a deeper exploration of the sonic potential of the physical models.

The flexibility of the PHOXES system entails an implementation challenge because each PHOX must uphold a meaningful relationship between input gesture and the sound being produced no matter what type of excitation gesture. The idea is to use *energy* as the common denominator as each model relies on energy in order to be excited. But how that energy mechanically relates to each model must be defined. The challenge becomes particularly interesting when shifting between continuous excitation gestures (e.g. blowing into the flute controller) and instantaneous excitation gestures (e.g. tapping/striking the drum trigger). A number of different possible mapping solutions were considered, but we chose to map the energy of a drum hit to an energy envelope, which has a peak proportional to the hit velocity and which decays in energy again proportional to the hit velocity (linear decay lasting between 200 and 500 ms.). This means that when using the drum triggers to excite for instance the turbulence model, the amount of air pressure (exciting the turbulence model) will be enveloped according to the hit velocity of the drum.

For mapping a continuous gesture (e.g. rotating the crank) to a model that normally is excited by instantaneous gestures (tapping/striking the drum trigger) a similar challenge occurs. We have chosen to let the instantaneous gesture take shape as a scraping mechanism, which creates small instantaneous excitations we can use for exciting the drum. How frequent the excitations occur and their individual velocities depend on the velocity of the continuous gesture.

2.5.2 Controlling one physical model with another

Energy into the physical model of a PHOX need not come from an excitation controller. The system makes it possible for the user to drive the physical model using the output sound from a different model - similar to [9]. This means that for instance the turbulence model, which by default is excited with a certain amount of white noise (proportional to how hard the user blows), can be excited by the output sound from e.g. the drum model. This is done by substituting the white noise with the audio output from the drum model. It thus becomes the drum sound, which drives the turbulence model. The result is a sort of fusion between the two models, where the turbulence model acts as a sort of audio effect, which is used to color the drum sound.

Earlier research has shown that interesting timbres from one model can be transferred to another model, and models, which users rate as boring can become interesting when combined in this fashion with other models - (even with each other) [10]. The PHOXES extend this idea by making it possible to combine many models at the same time (for instance use the crank of the particle PHOX to excite the turbulence model of the tube PHOX then letting the resulting audio signal excite the friction PHOX and so on and so forth).

Because the user is able to excite one PHOX with audio output from a different PHOX, each model must have a way of taking audio as input and somehow substituting that with the energy input of the model.

For complete details regarding mapping go to `http://media.aau.dk/~stg/phoxes/`.

3. PRE-TEST

In order to explore a suitable method for evaluating the PHOXES a pre-test was conducted. Carrying out any formal evaluation of these kinds of instrumental systems in the rather complex environment of creative music making has proven to be quite challenging. Different evaluation methods have been proposed for evaluation of musical interfaces inspired by methodologies found in the field of Human Computer Interaction (HCI) [11, 12]. For this pre-test we wanted to explore methodologies related not so much to the performance or usability of the system (how well the user is able to perform specific tasks) but more the overall experience with the system dealing with softer hedonic qualities [13, 14, 15] - for instance how well the user identifies with the instruments, whether they are inspiring to work with or how well the system supports musical exploration.

Most formal evaluations of musical interfaces are carried out under circumstances far from the natural environment of the electronic musician, which may be adequate for various specific usability issues [16]. But we believe that this makes it difficult to evaluate factors of more qualitative nature. Earlier research [17] has also suggested that tests need to be carried out over longer periods of time, which is especially enforced when evaluating more complex systems.

The pre-test was carried out using one male test person who is an experienced experimental electronic musician. He has extensive experience with both traditional acoustic instruments (mostly percussion instruments) and with various electronic instruments as both a composer and a performer. The test took place over a period of 10 days where the test-subject borrowed the PHOXES. The test was very free as the test person did not receive any instruction as to any specific tasks to perform during the 10 days. The test subject was instructed to treat the instruments as he would any new musical device that came into his possession.

In order to asses the implications of the longer test period, first impressions were noted by having the test subject fill in a questionnaire after having played around with the PHOXES for approximately one hour. The questionnaire was comprised of two forms: One was the AttrakDiff[7] hedonic / pragmatic evaluation form also used in [13], which lets the user rate the system based on a series of opposite/bipolar word-pairs relating to hedonistic and pragmatic qualities of interactive systems. The other was a semi-quantitative Likert-scale style evaluation form that lets the user rate each individual PHOX and the overall system in regards to features more closely related to the specific area of physical modeling based electronic instruments - such as whether the instruments provided sonic diversity, or felt like a real acoustic instrument. The same questionnaire was filled out after the 10 days test period. Finally an open interview was conducted to gather qualitative statements about how the test-subject worked with the PHOXES, whether that changed throughout the test-period and which issues arose during the test-period.

4. RESULTS AND DISCUSSION

The main focus when evaluating the data collected in the pre-test was on the methodological approach, and specifically on what kind of system improvements have to be made if this kind of evaluation method is to succeed on a greater scale. However, the results of the evaluation have been included to provide an initial idea of the perceived qualities of the PHOXES system. Note that they are totally subjective and inconclusive as only one test subject participated in the test.

The results indicate that the test subject was highly motivated and stimulated by the PHOXES system (Hedonic Quality - Stimulation) and found them having a high per-

[7] http://www.attrakdiff.de

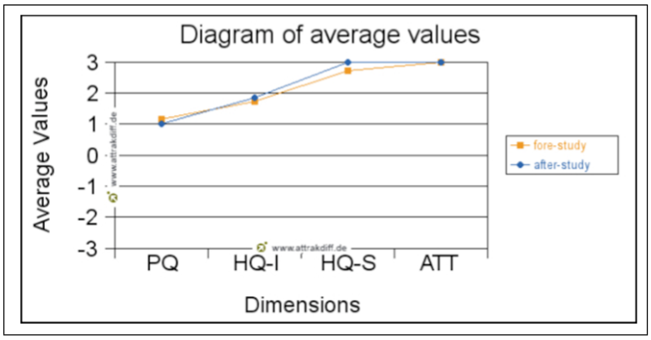

Figure 6. Results of the AttrakDiff evaluation. The following dimensions are evaluated: Pragmatic Quality (PQ), Hedonic Quality - Identity (HQ-I), Hedonic Quality - Stimulation (HQ-S) and Attractiveness (ATT). Fore study corresponds to first impressions and after study corresponds to the final evaluation.

ceived quality (Attractiveness). The subject's identification with the system was above average (Hedonic Quality - Identity) - as so was the perceived usability (Pragmatic Quality).

Surprisingly the perceived hedonic and pragmatic qualities stayed more or less unaltered when comparing answers from the first impressions evaluation and the final evaluation after the 10 days - See Figure 6.

Problems with the PHOXES in regards to the relatively uncontrollable test scenario were found in the computational cost of the physical models. The DSP CPU load would limit the test subject as he integrated the PHOXES into larger sequences/multitrack recordings in his preferred digital audio workstation (Ableton Live). This was quite unfortunate, as it is important for us to examine how the PHOXES are able to integrate into the work flow of eventual future test subjects in order to evaluate their exploratory qualities. Apart from cleaning up the code (Max/MSP patch and externals) making it run more smoothly, a solution could be to keep the processing on a separate dedicated machine. On the positive side, the physical interfaces were easy to setup and physically durable enough for the 10 days test period.

There was a problem that the test subject did not get to explore parts of the modular system. As the test subject put it; he didn't get to the advanced settings. It is difficult to say whether the system was too complicated, whether the system was not presented intuitively enough, or whether the test period might have been too short. The subject might also have been too focussed on improving playing skills, focussing on the interplay between controllers and models, and not so much on the combining of models. On one hand more time or explicit tasks could be given to the participants in order to get them to focus on certain parts of the system. On the other hand it is valuable to see how different uses of the system might arise by absence of specific tasks.

We were pleased to experience that the PHOXES system was robust enough to handle 10 days of use without our interference. For future testing we will improve the PHOXES in accordance with the improvements described above. We will continue to explore the methodological approach, including a longer test period and more task oriented restrictions to parts of the evaluation period.

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Paper VI

Longitudinal Evaluation of the Integration of Digital Musical Instruments into Existing Compositional Work Processes

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Abstract. This paper explores a longitudinal approach in the qualitative evaluation of a set of digital musical instruments, which were developed with a focus on creativity and exploration. The instruments were lent to three commercial electronic musicians/composers for a duration of 4 weeks. Free exploration periods and a compositional task evaluated using semi-structured show and tell sessions revealed that the context of use had a major influence on how the instruments were experienced by the test persons. Central issues revolved around the learning/adoption process, and around the importance of playability, explorability, and connectivity.

1 Introduction

The experience of playing a musical instrument or working with a musical tool is a product of many complex factors. Carrying out formal evaluation of those experiences thus poses numerous challenges. This article deals with the exploration of these challenges by presenting the design and evaluation of a set of instruments—the PHOXES, which were developed within an exploratory framework for physical modeling (Gelineck & Serafin, 2010b) with the primary focus on the user experience. The initial goal has been to design a musical tool that is stimulating and can thus extend the creative potential of the physical models on which the tool is based. The focus has been on the importance of explorability, balance between freedom and constraints, the users ability to identify with the instrument, on connectivity and modularity.

When evaluating these instruments we explore a holistic approach, involving case study evaluations that take place over longer periods of time—a so-called longitudinal approach, inspired by recent movements within Human Computer Interaction (HCI) (Poppe, Rienks, & Dijk, 2007; Kaye, 2007). More formal HCI-inspired evaluation schemes have gained interest within the field of New Interfaces for Musical Expression (NIME), also those which take a holistic in-depth approach. However, thus far the methods have only focussed on short exploratory sessions where musicians elaborate freely on what one may call *first impressions* (Kiefer, Collins, & Fitzpatrick, 2008; Stowell, Plumbley, & Bryan-Kinns, 2008). Short evaluation sessions (1-2 hours long) can definitely be very powerful in understanding many aspects of a new musical tool, but there are issues that longitudinal approaches are better at uncovering. Examples include evaluation of of learning curves, integration into existing work processes, experiences of real use, and the effects of novelty (i.e. a novel interface might spark an interest in the beginning purely because it is perceived as novel, but once the initial "wow" factor has faded, so too might the experience of using the interface). In this study we evaluate the PHOXES using a methodology that let real world users borrow the musical instruments over a longer period of time. The goal is to evaluate the creative and exploratory qualities of the PHOXES by understanding how they are integrated in existing work processes of professional electronic musicians.

Initially, the exploratory framework for developing the PHOXES is shortly presented. We then reflect on different possible evaluation methods and related work arguing why this qualitative longitudinal approach has been taken. The development and evaluation of the PHOXES is presented and finally, we reflect on some future perspectives for qualitative longitudinal evaluation methods within the field.

2 Exploratory Framework for physical modeling

Within the field of NIME, design directives/guidelines and conceptual frameworks have been presented to help structure the different approaches to research and development of musical interfaces (Overholt, 2009; P. Cook, 2009; Fels, Gadd, & Mulder, 2002). The conceptual framework presented in earlier work by the authors (Gelineck & Serafin, 2010b) outlines 7 design directives for developing musical systems for exploratory control of physical models. The directives are: (1) balance sonic diversity and plausibility of the model; (2) experiment with the energy that drives the model; (3) control physical models with physical gestures; (4) make the user work; (5) encourage exploration of sound parameters and exploration of gestures; (6) experiment with the interplay between instantaneous and continuous instrumental gestures; and (7) make the system modular.

The approach addresses the importance of a musical tool's ability to support creative idea generation and creative work processes by facilitating *exploration*—one of the key issues within the field of Creativity Support Tools (Shneiderman et al., 2006). A central part of creative activity is *exploring* new possibilities, and we argue that musical instruments can be designed to facilitate this exploration (to encourage the user to keep searching for new ways of using the tool).

The framework suggests that physical modeling sound synthesis lends itself well to exploration on different levels—sonic, physical and conceptual—without compromising intuitiveness because of its inherent perceived causality. As also outlined in (Johnston, Candy, & Edmonds, 2008), physical modeling based instruments may relieve musicians from creating mental maps of the relationship between the sound they wish to produce and abstract synthesis parameters, because there exists an intuitive understanding of the relationship between physical processes and the produced sound.

The framework also focusses on the physicality of the interaction involved in playing and exploring a physical modeling based instrument. The ability to explore different musical gestures can extend the sonic properties of the models themselves. We can experiment with the conceptual understanding of the system by giving the user different possibilities of physically interacting with it. Because cognition is largely embodied (Wilson, 2002) we can extend the perception of the sonic capabilities of the models by extending the physical interaction capabilities.

Finally the framework focusses on the importance of making the system modular. Constraints can help guide the creative process. But the freedom to explore undiscovered possibilities is also central to creativity. It is not always clear whether to focus on one or the other when trying to promote creativity (Gelineck & Serafin, 2009a; Gurevich, Stapleton, & Marquez-Borbon, 2010; Burnard & Younker, 2002). A modular approach is a powerful way of achieving the balance between constraints and freedom. Each module may impose creative boundaries while the system as a whole provides the freedom for creative exploration. Coughlan and Johnson (2006, 2007) argue that the balance can be achieved by letting users themselves control the constraints of the system. In this way, the constraints are kept helping not only to learn the system, but also to guide the creative flow on a low level, while freedom is obtained on a higher level by being able to alter the constraints at will. By applying a scaffolding approach the user is initially helped to understand the constraints of a system after which these constraints can be extended or even broken.

3 User Experience Evaluation of Musical instruments

Within recent years the field of NIME has looked to the field of HCI for developing more systematic and rigorous methodologies for evaluation (Wanderley & Orio, 2002; Marshall, Hartshorn, Wanderley, & Levitin, 2009). Most efforts towards more formal evaluation schemes deal with task based evaluation of usability factors—such as the ability to keep rhythmic timing, to play notes on a musical scale or to modulate simple synthesis sounds. Tasks could be to create simplified compositions, to follow a beat, to hit notes within a given timeframe or to replicate certain musical motifs. Breaking down the activity of playing a musical instrument into smaller activities (tasks) can help understand for example, which gestures may provide the most accurate control when manipulating certain musical parameters. However, an interactive system or interface that is intuitive, has a high degree of usability and produces good results in task based evaluation sessions may fail if it does not motivate the user, or if the user cannot connect to it on a personal level. Here understanding the *experience* of using the instrument is essential. This is difficult to do using task based methods. As Stowell, Robertson, Bryan-Kinns, and Plumbley (2009) argues, alternative methods are needed for evaluating the essentially subjective experiences of interaction. The need for more holistic approaches to evaluation is greatly acknowledge within HCI, where a paradigm shift seems to be underway—the so-called *third wave* (Bødker, 2006; Harrison, Art, Tatar, & Sengers, 2007) of HCI.

When moving the focus of evaluation from task-oriented usability studies onto a more holistic approach where attitude, context, time, etc. become important, we move away from the goal of quantifiable data to more holistic descriptive data. The approach targets a multitude of different dimensions (or qualitative interaction factors (Springett, 2009)) that all interact to form the overall experience. The initial goal is to detect and describe these dimensions after which causality can be explored. Here a bottom up approach is used based on grounded theory (Corbin & Strauss, 2008)—a methodology widely used in social sciences—where theory emerges from rich qualitative empirical data. When gathering data the *process* of interaction becomes central, not the *outcome*.

When striving for rich descriptions of user experiences the context (who, what, where, when, why (Abowd & Mynatt, 2000)) in which the experience occurs becomes central. Interaction is not just dependent on the user and the system but also largely influenced by the context in which the interaction takes place. Context can be taken into account on many levels, by carefully considering for whom the tool is intended, whether the tool is to be used in a live situation, whether it is collaborative, mobile, compositional, etc.. Recent movements within HCI recommend evaluating user experience in scenarios as close to the real world context that the tool is intended for as possible (testing on end-users, in their own surroundings, within existing work practices, etc.) (Wiberg, 2005; Shneiderman, 2007; Stowell et al., 2009) and evaluation approaches in natural environments are getting more and more used, especially within fields of HCI where traditional interaction paradigms are being contended (as ubiquitous and persuasive computing (O'Hara, Glancy, & Robertshaw, 2008; Dalsgaard, Skov, & Thomassen, 2007)).

3.1 The Longitudinal Approach

There are two main reasons for choosing a longitudinal approach. The first is to be able to monitor changes over time. Elements that change could be the overall use, user's attitude towards the instrument, user's playing technique, user's conception of possibilities with the instrument, etc. An approach could be to conduct a controlled lab study where test participants were invited to participate in sessions that occurred on a timely basis over a course of weeks or months. At each session the participant would perform the same task and the improvements over time would be assessed.

The second reason for choosing a longitudinal approach is to explore what happens when the instrument is integrated into a real world context. This is very hard to do in a controlled lab study. When dealing with experience—and in our case also creativity—because it is so subjective, it is crucial that the test subjects are given freedom to asses the tools that are to be evaluated on their own time and in their own surroundings (Collins, 2005). A previous study by the authors (Gelineck & Serafin, 2009a) also shows that many electronic musicians find themselves most creative at certain times of day or in specific locations, which does not suit the lab experiment.

In developing the methodology for this study we have mostly been interested in integration into real world scenarios, keeping in mind that changes over time play an important role. We find it remarkable that almost all qualitative evaluations of NIMEs are carried out inviting test subjects to explore the instruments for a maximum of 2-3 hours. Of course, a lot can be derived from carrying out these first impression evaluations of musical instruments, and we acknowledge that longitudinal evaluations are more demanding in time and cost. Even though, we feel that in the attempts at developing more structured holistic evaluation of NIMEs there is an unbalance between the short-time lab based approaches and the longitudinal situational or context dependent approaches.

As mentioned above different methods exist within longitudinal evaluation. This also applies to the data collection. The goal is to get as accurate a representation as possible of the user's experience when using the tool within a real world context. Constant observation can be used to obtain detailed descriptions of users working with the tool, however this method is not only extremely time consuming, both in the data collection phase and in the analysis of the data. More importantly, it may interfere with the user's often quite private space and personal way of working, creating an uneasy atmosphere that does not reflect a natural setting. Another method is having users write logs of their daily activities or receive notifications (using for instance a pager) at random times during the day asking them to note down what they are doing and how they feel at the moment of the page. In (Collins, 2005) a composer was followed over the course of three years. The user was equipped with a tape recorder hooked up to a microphone *and* to the sound board. The user was then asked to retrospectively explain what had happened immediately after a compositional activity while having the possibility of playing back parts of the composition in order to explain or emphasize certain compositional thoughts. At the same time MIDI data was collected and verification interviews would elaborate on the emerging data. Analysis of this "thick" data resulted in a hypothetical highly recursive process model of the compositional process where model stages were described by Collins as "richly context-driven solution spaces"—as opposed to "problem spaces". In (Nuhn, Eaglestone, Ford, Moore, & Brown, 2002) electroacoustic composers' work was analyzed by using a triangulation method involving a one day compositional task, observation, verbalization, interviews and gathering of multi-source computer data. Nuhn et al. emphasizes the importance of the familiar setup for the creative process and stresses the non-linear divergent manner in which the electroacoustic composers work with their software tools.

We propose a retrospective 'show and tell' semi structured interview technique that gives the test subject total freedom to use the instrument over a course of weeks after which an interview is conducted to gather the perceived experience of the test subject. The interview is set in the subject's normal work environment, and subjects are encouraged to not only elaborate on how they have been using the system, but also show different playing techniques, playback relevant audio recordings, account for specific compositional approaches related to the system, illustrate typical forms of interaction and show specific integrations with other tools. The interviewer has a selection of issues that are to be enlightened, but not in any given order. It is important to let the subject elaborate freely on how the system has been used, after which additional questioning can be initiated.

The technique resembles the 'think aloud' protocol (Ericsson & Simon, 1993), that has been widely used in within HCI evaluation. However, previous work has suggested that the technique is too distracting from the musical interaction preventing the user from being naturally immersed into the musical context (Kiefer et al., 2008; O′Modhrain, 2011). Modified versions of the technique have been used by Johnston et al. (2008) and Stowell et al. (2009) to deal with this issue. In (Stowell et al., 2009) for instance, users were asked to report on how they felt using the system immediately after interacting with it. Our approach is more retrospective, meaning that we loose the very immediate and spontaneous thoughts of the subjects as they interact with the system. However, by having the users not only talk about their experiences retrospectively but also show physically what they are reporting, it is our hope that we can evoke some of those immediate perceptual responses.

The evaluation methodology pursued above is implemented in the evaluation of the PHOXES instruments. Before going into detail with the actual evaluation, a short description of the their functionality is presented, including details regarding various issues related to their design.

4 The PHOXES

The PHOXES are a modular set of physical modeling based digital musical instruments. The goal when developing the instruments has been to explore the framework presented earlier (Gelineck & Serafin, 2010b). We used the design directives and experiences gained from that study to develop instruments that are targeted at temporary electronic musicians. In the following we account for design decisions and discuss various implementation issues that has lead to the PHOXES in their current form.

The PHOXES consist of four different physical interfaces that each control a separate physical model. Each PHOX implements four controller knobs for adjusting model parameters, an excitation controller used to inject energy into the model, and an LCD screen with two buttons implementing a menu system for manipulation of mapping and tonality settings. When developing the four physical models the focus has been on exploration, sonic diversity and plausibility (to which extent the sound is perceived as having been produced in a physical manner), as opposed to accuracy or faithfulness (to which extent a sound resembles that of a real world instrument). It was interesting for us to explore general models, using the intuitive causal qualities of physical modeling as a platform, but giving the user the capabilities of exploring them beyond natural physical boundaries. The four implemented models are:

- a *turbulence model* that implements two tubes connected in parallel. The excitation mechanism is modeled implementing a simple nonlinear exciter (P. Cook, 1992). The resonator implements two one-dimensional waveguides (Smith, 1992). The user is able to adjust the length of the two tubes, a vibrato achieved by modulating the length of the tubes, and the airiness. The default excitation controller is a wind-controller implementing an amplified low pressure sensor[1] attached to the end of a plastic tube that the user blows into to produce energy.
- a *particle model* that implements a modal synthesis model with a stochastic excitation mechanism based on Physically Informed Sonic Modeling (PhISM) by Perry Cook (P. R. Cook, 1997). The user is able to adjust a main frequency (controlling the fundamental frequency), harmonic frequency (controlling 4 distributed partials), amount of tone, and the randomness of frequency of the partials. The default excitation controller is a crank implemented by connecting it to a multi-turn rotational potentiometer[2]. The rotational velocity of the crank determines the produced energy.
- a *friction model* that implements a one-dimensional waveguide resonator with a complex nonlinear exciter (Avanzini, Serafin, & Rocchesso, 2002). The user is able to adjust a main frequency, harmonic frequency, downward force, and roughness. The default excitation controller im-

[1] 40PC Series Miniature Signal Conditioned Pressure Sensor from Honeywell

[2] Model 357 from Vishay

plements a ribbon sensor (a soft potentiometer[3]). The user slides a finger horizontally across the surface of the ribbon sensor. The velocity of the movement determines the produced energy.

- two identical *drum models* each implementing a two-dimensional waveguide resonator with a simple nonlinear exciter (Duyne & Smith, 1993). Adjustable parameters are right and left membrane size, and right and left size distortion (the amount of membrane size-distortion during a hit). The default controller consists of two drum pads each implementing a force sensitive resistor[4]. The user taps the drum pad with a certain velocity using his or her fingers to produce energy.

The physical models are programmed as Max/MSP externals which are then manipulated in the Max/MSP environment. Sensor data is acquired by an Arduino Board[5] inside each PHOX and sent via USB to the computer running Max/MSP. A powered USB HUB was used to power the Arduinos as they drew more current than provided by the onboard USB ports of the computer. Max/MSP receives only the sensor data, and takes care of all mapping and audio processing. It sends audio to the sound card of the computer and text data to the LCD screens for visual feedback on mapping and tonality settings (described later). The user can decide how many PHOXES to connect at any given time—everything is handled inside Max/MSP.

Each of the PHOXES can be played individually, which lets users explore the model in a relatively straightforward constrained manner. The intended focus will be on playing technique (mastering especially the excitation controller and interdependencies of the parameter controls) as well as exploring the capabilities and boundaries of the synthesis model in itself. Three of the PHOXES rely on continuous excitation gestures (flute, slide surface, crank), while one takes instantaneous gesture input (drum pads).

Additionally, the user can choose an excitation controller from any of the PHOXES to give energy to any other PHOX (even multiple PHOXES can receive energy from the same excitation controller). This lets the user explore the physical relationship between gesture and model. For instance, blowing onto a drum gives a whole different feel and sound than tapping it.

Finally, the sound produced by playing one PHOX can also be used to exert energy into another. In this way the PHOX doesn't receive physical energy from a user performing a gesture with a controller. It takes a sound signal as energy input, mapping that to the excitation of the underlying model. The goal is to conceptually turn the PHOX into a kind of audio effect, which completely alters the model's perceived properties, while still upholding the intuitive causality inherent in the model. Sound from an external sound source can also be used to inject energy into a PHOX—this adds to the connectivity of the system, extending its exploratory capabilities.

The idea of the PHOXES has been to extend the already modular approach of the PHYSMISM (Böttcher, Gelineck, & Serafin, 2007; Gelineck & Serafin, 2010b). The user can now explore the physical models individually, play the same model using various input devices, play multiple models at the same time using the same input device or combine multiple PHOXES, letting the sound from one PHOX drive the next and so on and so forth.

For more on development, mapping-strategies, etc. go to `http://media.aau.dk/ stg/phoxes`

4.1 Pre-testing the PHOXES

A pre-test was carried out in order to get a first impression of the exploratory qualities of the PHOXES (Gelineck & Serafin, 2010a) and to explore the longitudinal approach from a methodological and technical perspective. What kind of results could we expect? What problems could arise when lending a set of prototypes to an electronic musician for a longer period of time? And finally, which issues could be improved in order to improve the functionality of the PHOXES for the formal evaluation.

An electronic musician borrowed the PHOXES for 10 days. The AttrakDiff evaluation form[6] was filled out in the beginning and end of the test period. The form is used to evaluate the perceived hedonic and pragmatic qualities of interactive products. It uses a semantic difference scale, asking participants to rate a system using pairs of bipolar adjectives. At the end of the test period a semi-structured interview was carried out.

The pretest showed promising results, however there were two important issues that arose that we were able to deal with before the more formal evaluation of the PHOXES. One was the length of the test period. It seemed that 10 days was not long enough to get a to explore them fully. The test subject did not get to explore the combination feature of the PHOXES system very much. Consequently, the test period has been prolonged, and the evaluation is now split up into three periods—explained later in section 5. The other issue had to do with computational cost. The models were being run on the test person's own laptop, which meant that when playing the PHOXES there was not much

[3]SoftPot from Spectra Symbol
[4]402 FSR from Interlink
[5]Arduino Duemilanove

[6]http://www.attrakDiff.de

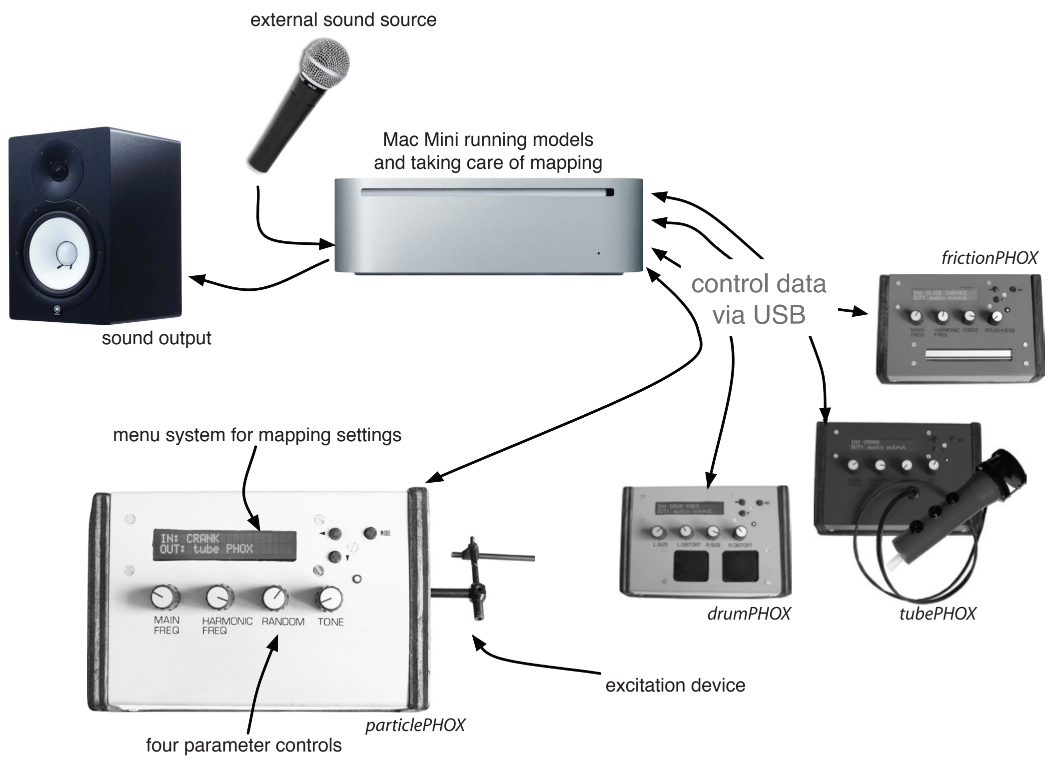

Figure 1: The PHOXES send control data to a computer via USB. The computer is running Max/MSP, which takes care of all mapping and audio processing. The user can then use the audio output from the computer in any desired way, and use the audio input of the computer to interact with the PHOXES.

CPU left to do other things on that laptop. One of the major goals of the evaluation, was to understand how the PHOXES would be integrated into the existing compositional work practices of the test subject. The CPU limitation opposed this goal as the test subject was restricted in the use of his laptop computer, which he normally used for running larger sessions in a Digital Audio Workstation (DAW), functioning as his main compositional tool. The PHOXES now run on a secondary machine (Mac Mini, Intel Core 2 Duo 2.4 GHz, 2GB RAM). This way the PHOXES system has only a line out (for the output of the PHOXES) and a line in (for using external audio to drive the PHOXES). Minor issues regarding the responsiveness of the drum pads was also improved based on the pre-test. An overview of the final setup is presented in Figure 1.

5 Evaluation of the PHOXES

The main goal of the evaluation was to understand the creative and exploratory qualities of the proposed system by focussing on how the PHOXES are integrated in real world working processes of professional electronic musicians in a compositional setting. The evaluation was carried out by letting three professional commercial musicians borrow the PHOXES, each for a duration of 4 weeks. Three sets of the PHOXES were produced so the evaluations could be carried out in parallel reducing the overall duration of the whole evaluation period. Evaluations took place in November and December of 2010. The presented methodology takes a multidimensional in-depth approach using questionnaire, longitudinal free exploration, a longitudinal compositional task, and semi structured 'show and tell' interviews - see section 5.2 page 7.

5.1 Test subjects

The musicians were purposely selected by consulting with an expert in the field of electronic music in Denmark, with five main criteria in mind. The musicians needed to; (1) regard themselves as electronic musicians, (2) have had at least one commercial record released, (3) be currently active, (4) have some sort of experimental approach to their music making and (5) differ somewhat from each other (in order to explore differences in use of the PHOXES).

5.1.1 Test person A

The first test person is 24 years old and the least experienced of the three. He has been working with music professionally for 2 years and has only just released his first EP (also making appearances on compilations and remix albums). His approach is very much centered around making music using his laptop working mainly with software synthesizers controlled via Logic[7] as his main DAW. He has a lot of focus on melody, harmony and structure. He has limited experience with hardware and considers himself part of the screen generation (GUI based music) defining his music as House, HipHop and Techno.

5.1.2 Test person B

The second test person is 34 years old and has worked professionally for 14 years. He works a lot with hardware (analogue synthesizers, modular synthesizers, sequencers, DIY equipment). A major part of composition for him is to spend longer periods of time working with making sketches, exploring various approaches, equipment, structures, etc.. These then at some point distill into actual compositions. During the evaluation he was working with a new piece of equipment[8] in such a sketching phase. He uses mainly Ableton Live[9] for sketching and Nuendo[10] for productions. His approach to making music is very much inspired by trying to break down conventional forms found in commercial synthesizers. As he states "synthesizers often malfunction in an unusual way, but are also able to surprise". He is not concerned with notes/tonality, but more with timbre and structure.

5.1.3 Test person C

The third test person is 46 years old. He is also the most experienced having worked professionally for 25 years. He uses a lot of both with hardware and software in his music and also incorporates acoustic instruments as he is an experienced drummer who also plays guitar and electric bass. He defines his own music as Indie or Electronica. Lastly, he emphasizes that his main goal is to make music (as opposed to playing with / exploring devices).

5.2 Method

The 4 week test period was divided into three phases depicted in Figure 2. During the first two weeks the test persons were totally free to use the PHOXES as they pleased, during the third week the subjects were semi-bound to a compositional task, while keeping the last week free again. The pre-test showed that being totally free in the evaluation period produced some feedback that is very close to a real world situation, but also that there were parts of the system that were not explored. Asking the test subjects to perform a compositional task during the third week was meant

[7] http://www.apple.com/logicstudio/logicpro/
[8] The MachineDrum by Elektron
[9] http://www.ableton.com/live
[10] http://www.steinberg.net/en/products/nuendo.html

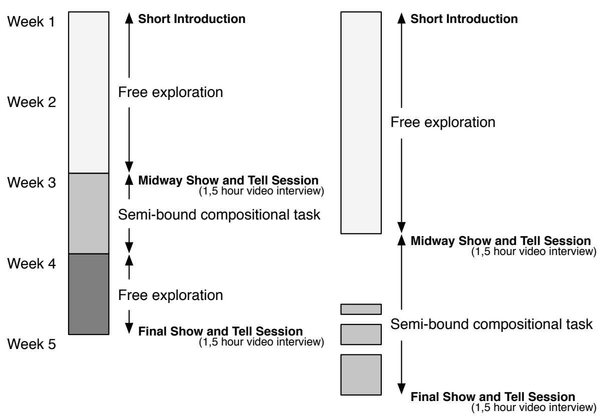

Figure 2: On the right: The intended test period (followed by test person A). On the left: How the test period turned out in practice for test persons B and C. Notice how the entire period after the midway show and tell session for test persons B and C were devoted to the compositional task.

to force them to work with required parts of the system, making them aware of the full capabilities of the system. The task involved producing a piece of music, with the following constraints; (1) all PHOXES must be used in some way, (2) all excitation controllers must be used in some way, (3) how you use the PHOXES including which other instruments/tools you use is up to you, and (4) the piece must represent you as an artist.

Freeing the test subjects in the fourth week it was our hope that they would explore those capabilities within their own context. Mainly because of unfortunate external factors, test persons B and C not only had to use more than the 4 weeks for the evaluation but also did not find time to use the PHOXES after having completed the compositional task.

At the first meeting, the PHOXES system was briefly introduced. Here it was important to explain the features of the PHOXES system in an unbiased manner being sure not to suggest specific ways of working with them. The most important explanation was on setting up the system, explaining the different models, explaining the modular feature and the tonality control. The test subjects were then told to treat the PHOXES as if they were their own, and to use them at will for two weeks. We did not impose restrictions in regards to how many hours they were required to use them. It was totally up to them.

After the first two weeks an individual midway show and tell session was carried out in the test subjects own studio. This was mainly to explore how feedback given by the test subject would change between the midway and final evaluation. The session was carried out using a semi structured interview guide, instructing the test person to elaborate on how he had been using the PHOXES throughout the two weeks, while showing specific playing techniques or illustrating in which compositions they were used. Being a semi structured interview the interviewer had a set of issues that the interview was to illuminate, but not in any given order. The overall issues were: *sonic properties, playing techniques, individual/in-combination, with other tools, motivation, unintended use, collaboration, live vs. studio* and *technical issues*.

After four weeks an identical show and tell session was carried out (see figure 2). When the final session was finished the test subjects were furthermore asked to reflect on the evaluation procedure—Was the evaluation method invasive in any way? What did the compositional task do for them? Was there enough time for exploring the system fully? Would it have been sufficient with a shorter test period?

5.3 Analysis

Throughout the analysis phase it is important to keep aware of the objectivity and validity of how the data is analyzed. By structuring the analysis into different stages it is possible to enhance the validity while still being conscious of the illusion of objectivity. There is no truly objective way of analyzing this kind of qualitative subjective data, but there are ways of striving for objectivity. Most importantly, it is crucial to clarify the deductive process of extracting the results from the raw interview data.

5.3.1 Analysis of video data

The video data from the show and tell interviews was first transcribed also noting down all relevant actions and sounds for later analysis. The transcription then underwent a filtering process where statements/actions were first coded and then recoded. The codings used were partly derived from initial areas of interest but also from revisiting notes taken during the interviews. These were important as they would illuminate areas of interests that were interesting for the interviewer at the time of the interview. Finally codings would arise from the data during the coding process. These actions and statements were grouped together, after which they could be compared and contrasted in order to identify central patterns or issues.

6 Results

When analyzing the data a set of key issues emerged that will serve as a way of structuring the presentation of findings. These were *the influence of technical issues, exploring in context, learning process, sound, modularity, playability, MIDI, The composition* and *studio vs. live.*

The interview and observation data revealed that overall there was a considerable difference in how much or how well the PHOXES were integrated into the existing workflow of the three test persons. All three found them challenging to integrate naturally into their normal work flow, but while *person A* was very positive towards the PHOXES and used them to a great extent throughout the test period (he used them approximately every other day, and also incorporated them in a large part of his own productions), *persons B and C* were more reluctant only using the PHOXES to a moderate extent (only 5-7 sessions each throughout the four week test period). While acknowledging that the difference was unfortunately due partly to external factors (sickness, snow, Christmas), the main discussion below will delve into the reasons for this quite distinct difference.

A large part of the data illuminated issues that were not necessary specific for the PHOXES. Interesting issues regarding learning, context and explorability in general have been included to illustrate their importance to the methodology.

6.1 The influence of technical issues

Two of the test persons experienced technical difficulties while starting up the PHOXES (there was a flaw in the initiation of the PHOXES, which meant that they had to restart them two to three times before they worked properly. This was most likely caused by instabilities of controlling four Arduinos through the same USB port.) It turned out that these issues would have a great influence not only on the extent to which the PHOXES were used during the test period but more importantly on how motivated the test persons were to integrate them into their usual workflow.

Test person C specifically said that so much effort to start them up probably influenced his overall perception of the PHOXES and had resulted in him not using them as much. Under the midway show and tell session, test person B said that he had trouble with the drumPHOX being buggy at startup. During the remaining two weeks he had simply disabled it making the PHOXES initiate smoothly. Test person A, who did not have any issues with initiation had used them extensively and had even taken them to a colleague's studio for a collaborative session.

6.2 Exploring in Context - integration

Throughout the evaluation it became evident that the test persons did not evaluate the PHOXES as traditional standalone instruments, but more on how they related to the context in which they were used. Focus was not only put on how they were specifically integrated with other musical tools, but also how they supported the musical approaches of the test persons and how they worked in relation to musical features both on a low level (harmony, feel, melodies, chords, etc.) and on a higher compositional level (timing, breaks, suspense, ambient background, etc.).

Test person A specifically said that he had not regarded them as a solo instrument, but that he never does when it comes to synthesizers. He explained how instruments (mainly referring to synthesizers) always sound differently when they are played on their own and when they enter the composition. The most important issue is how they relate to the composition. In another example test person C explained how he was mostly interested in making music, not exploring the instrument as such:

> *"...others are probably interested in instruments in a way that they can keep searching, but I use them for making music..."*

In other words, they were quite focussed on the music they were producing (whether it was a piece, a beat or a sketch of some sort), and it was the music and how the PHOXES could support it that was explored more than it was the instrument as such. Test person C went on to explain how he never fully learns a synthesizer because he is so pre-occupied with the music:

> *"..and that's why I never really learn the synthesizers fully, because I just play with them until I have something I can use and then I hurry on to something else.."*

When asked about exploration in general all three test persons reported on how the exploration would happen on an unconscious level as a feedback loop between ones self, ones ideas, and the tools one uses. For instance exploration was described by test person B to be a very chaotic process of trying many different things and then all of sudden being able to put everything together:

> *"It's just like that... then you collect some samples, then you have... these machines boiling... that sounds good... then you record that and then.. you keep it in that box and keep some beats in another box.. and then.. I don't know how you achieve that overview that makes you think, okay, now*

> *I have enough... now I can put things together.."*

Another example is where test person A elaborates on how a concrete idea has fed off the capabilities of PHOXES:

> *"It goes both ways.. I have some music that I want to make and then these [the PHOXES] make it possible to do some things, but then you discover new things.. I would never have made this [plays back a beat made with drumPHOX], that is something that this [drumPHOX] has inspired me to.. the good thing is, that I would never have that rhythm without these pads, then it would just have said boom, boom, boom [more periodic]... not hand-played.. so yes they are, but you have to have them for a while.. to get to know them.. and then they give you ideas..."*

All test persons emphasized that they regarded the PHOXES more as sound generators than actual synthesizers, as the PHOXES would produce sound that could be used as a basis for something else (for example use friction noise as a basis for subtractive synthesis).

Almost all recordings of the PHOXES were either heavily edited or applied with audio effects. In fact it was completely natural for the test persons to apply the PHOXES with some audio effect by default. When asked to show how they had played the PHOXES they would start a beat, add a reverb effect or compressor before actually playing. Sometimes just subtle effects like reverb and compression where used, but most of the time effects were applied extensively in post processing. Here is an example of person C explaining what he has done in the composition:

> Person C: *"yes, here are only sounds from them [PHOXES]... and then a lot of plugins, right.."*
> Inteviewer: *"But there is more or less some sort of effect or something on all of them..?"*
> Person C: *"yes, that's what I always use... delay and compression and EQ, reverb, distortion and those kind of things.."*
> Inteviewer: *"yes.. so it is completely standard that you normally use all that on everything you..."*
> Person C: *"yes, that is what I do... I take some sounds, and then I do something to them... either I play on a software synth in here, right [in Logic]... so something like this [a software synthesizer]... that can do lots of things... um... or I play on an outboard synth with MIDI [points at a large outboard synthesizer], and then when I get the sound in, then I do something to it so it comes alive... and that is all those plugins that you can apply..."*

The large amount of time used on processing was emphasized strongly during the show and tell sessions. In general, when asked to show how they had been using the PHOXES the test persons ended up using much longer time tweaking sounds, applying effects or editing passages than actually playing the PHOXES, which illustrates well how they have been used throughout the evaluation period. Test person A explains how he used the PHOXES in a track in one of his compositions:

> *"... you can see that I have recorded it and then I have found a start point and an end point and then it just runs backwards and then I have pitch shifted it 9 semitones up.. almost an octave... then it sounds completely different, and then cut it up... in my sampler... this one [Battery]... that's what I put everything into..."*

Another example of the importance of context was illustrated by the difference in how person B explored the PHOXES throughout the evaluation period. During the first two weeks he only used the PHOXES together with his DrumMachine, which he used in a very fixed structured manner (making small 2 bar loops that worked as a sort of sketching). This meant that he would concentrate on very short PHOXES sounds, really exploring the micro aspects of the various timbres. Later on when working on the compositional task he used Ableton Live, which lead to a much more general exploration of the sonic capabilities of the PHOXES.

Finally context could also be regarded from a higher level compositional perspective. For instance test person A put a lot of emphasis on how he would utilize certain features of the PHOXES to build up towards a break, or set the mood:

> *"...it can work as an introduction to something new when you turn up the "harmonic"... listen.. [plays the particlePHOX while adjusting the "harmonic frequency"].. there, then it dives... yes, and then... [plays it again]... it's quite cool when it's been like, rhythmical, and then all of a sudden there is free passage..."*

6.3 The Learning Process

When discussing how the PHOXES were initially learnt it became apparent that they went through several phases of exploration. The test persons all described how they initially explored the PHOXES on their own (with no background track, beat and no applied audio effects). They would start working their way more or less systematically through the different parameters of the PHOXES to get a first impression of the system's capabilities. Note that for instance person B said that he had no systematic approach to learning them, that he just let himself be guided by the parameters and sound, falling into a certain flow. However, when asked to show this exploration he was quite systematic especially in adjusting parameters, most likely on an unconscious level.

While exploring the PHOXES on their own was an important first step for the test persons, they would very quickly (within the first 10-20 minutes) try to put the PHOXES into context. As test person A put it:

> *"...there isn't really anything that motivates me to turn this knob, if there isn't an underlying chord it can play together with... otherwise you will just sit and play some lame 'doudoudoudoudou'... ... it is the chords that create euphoria or melancholia in a track, you can't just create that ... they are also monophonic [referring to the PHOXES] ... so you have to have some underlying chords. I mean, if I am to sit and try this out then I have to have a passage of two to three, maximum four chords."*

Most examples of exploration using the PHOXES happened in two forms - both integrated somehow in a musical context. One form included short explorations creating short snippets of sound generated quickly while working with a looped beat of some sort. They would want to add something to the beat, quickly turn to a PHOX, try a few times to add something interesting, then turn to the beat editing the recording to fit a groove. This process was very guided by the beat/passage and included a lot of very immediate trial and error work, exploring many different (mostly software) tools within a short period of time. There were examples throughout the show and tell sessions of the test persons being so immersed in this exploratory process that they seemed to loose track of the conversation. This seems to indicate some form of flow resulting from a combination of creative challenge, motivation and skill of the composer, and capabilities of the tool.

In the other form of exploration they would record longer passages (5-20 minutes) where they played more freely along to a longer passage or a loop. They would then return to the recording, identifying useful passages that they could either remember having played or that surfaced upon re-listening (for instance by scrolling through the sample by adjusting small sample start-points).

Finally, after having grown more accustomed to the capabilities of the PHOXES they would be used in an actual composition when needed. Test person A emphasized the difference between exploring new instruments in context and actually integrating them into a piece, saying that he only really started to integrate them into the pieces after knowing them better. Test person C also explained how after a short exploration of a new tool, he would generally put it aside until he found a need for it in a composition.

> *... then I would use 15 minutes on finding out what they could do and then I would leave them there until one day where I needed them... I wouldn't want to sit an play with anything that wasn't going to be used somehow..."*

This final stage was naturally reached by test person A but was kind of forced onto test persons B and C by the compositional task.

Figure 3 illustrates the learning process involved in adopting the PHOXES including the different forms of exploration suggested from this evaluation. First the exploration is mostly systematic (very short initial period), then integrated into a musical form of some sort for further understanding of capabilities (longer period). The instruments might be put on hold, discarded for a while or forgotten until an occasion arises that demands or suggests their use in a specific composition. On a general level stages 2, 3 and 4 do not follow a strict sequential form as ideas can emerge early in exploration process that leads directly to a specific use in a composition. Furthermore, the specific use in composition may spark an idea for a certain exploration of some of the extended capabilities.

6.4 Sound

Another key issue that arose from the show and tell sessions were related to the sound of the PHOXES. The test persons seemed to agree that the sound of all the PHOXES belonged to the same timbral space, either sounding analogue with an interesting digital edge or sounding digital with an analogue edge. For instance test person A played back some of his other compositions pointing out where he would like to exchange certain elements with PHOXES sounds to give the track an analogue edge.

All test persons reported the PHOXES as being more free or abstract than other synthesizers, which made them more demanding to work with. Especially test person B who normally feeds off trying to break the constraints of more commercial hardware found it challenging because as he put it "the PHOXES are already broken".

Otherwise the test persons were more focussed on exploring subtle variations in the sound, mostly tran-

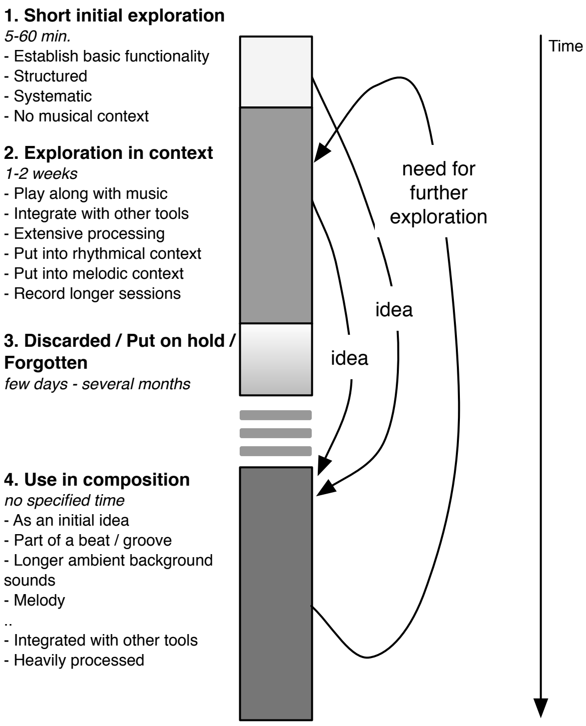

Figure 3: The learning process involved in adopting and integrating the PHOXES into composition would go through several stages of exploration. Time periods for each stage are suggested to illustrate their temporal relation.

sients, sampling them and using them in a rhythmical context. Interestingly, many interesting subtleties were produced as a result of the challenging control (See section 6.6 page 13 for more control issues). The most representative example of this was how test person B based his composition (for the compositional task) on a subtle little sound that occurred just as the frictionPHOX would be excited before it reached a stable state. These sort of unintended sounds were a large part of what the test persons generally sought after in their exploratory and compositional process.

When describing specific sounds of each PHOX the test persons would relate them to how they worked well or not in the context of their music or their approach. For instance the friction sound was reported to be good for ambient noise (for instance side-chained with the master channel of the DAW) or having interesting timbres that could be cut up and used rhythmically. Test person C for instance said that the frictionPHOX had many interesting timbres but that it was hard to integrate into his music.

Another timbral issue was whether or not the sound was easy to fit into the mix (for instance how well it blended with the bass track). Two of the test persons mentioned that most of the PHOXES' sounds were quite dominant in the timbre space of the compositions. This was regarded both as a positive and a negative property.

6.5 The Modular Approach

Apart from one specific case, the modularity of the PHOXES seemed not to have been fully explored by the test persons during the evaluation. At the midway show and tell session all subjects showed how they had experimented with combining the different PHOXES. However, only test person A turned out to have used the modular feature in composition. He found a combination that explored the interplay between the instantaneous and continuous excitation by having the audio output from the drumPHOX serve as energy input to the frictionPHOX. He specifically used the combination to open and close the friction noise by manipulating the size of the drum—a small drum will have a short highly dampened sound that when sent to the frictionPHOX creates a short focussed noise burst, while a large drum will have a sound with a longer envelope creating a wider less focussed friction noise. In this way he could play this combination by hitting the drum patterns in a rhythmical manner while manipulating the envelope of the friction noise burst by only manipulating the size of the drums.

When elaborating on how the test persons used the PHOXES it seemed that they had understood the general concept of the modular approach. However, when asked specific questions (for instance about the differences between using excitation controllers and audio output to exert energy into a model) they generally showed that they hadn't understood it fully. There seemed to be an interpretation that pointed to the modular feature being nice, fun, inspiring, but in practice the persons tended to stick to playing the PHOXES individually.

One reason given by test person C could be the cumbersome menu system:

> *"...it feels more like an instrument when it's there right away right... and usually engineers that make synthesizers have a hard time understanding that it can be a problem, but it is when one has to be creative."*

Another reason could simply be that there is so much focus on making music that they are not occupied with going deeper into the instrument, if they already have something that works. All three test persons mentioned that they will seldom use the full potential of a musical tool or instrument.

Finally factors regarding the evaluation process could also have been influential. The test persons did not have time to explore the PHOXES deeper or the task of handing in a composition overshadowed the task of exploring the instrument. This is one of the consequences of striving for a realistic evaluation setup by making the evaluation process so free for the test persons - there will be features that are not explored and thus can not be evaluated.

6.6 Playability

An important issue that emerged from the show and tell sessions was the issue of playability, its role for a synthesizer in general and how the PHOXES lacked/enabled playability in different ways. Various different definitions of playability can be found in the literature (P. Cook, 2001; Serafin, Smith, & Woodhouse, 1999; O/Modhrain, 2011). The playability was expressed by the test persons as something that resembled the control and feel of an acoustic instrument or somehow helped ease the immediate play of the PHOXES (in contrast to working with the instrument in an editing/mixing situation).

There seemed to be a general consensus that the PHOXES were quite hard to control. This was mostly experienced as a lack of ability to control melodic and rhythmical structure, to recreate certain interesting timbres or as too much of latency when using the excitation controllers. Test person A's solution was to record sounds into a sampler in order to achieve additional control. This for instance made it possible for him to play melodies on a keyboard by mapping samples to the different keys. Person C was very critical towards this lack of control, arguing that it took away the immediate/spontaneous playability that is so important when playing music. He argued that the PHOXES had too much focus on exploration of timbre alone and that without having better control of notes, melody, harmony and rhythmical structure they generally lacked playability.

Test person B was not preoccupied with notes and melody at all, but also emphasized the lack of control mostly in one's ability to reproduce a certain timbre, especially on the frictionPHOX. However, he showed that it was indeed possible to work expressively with the frictionPHOX when illustrating how he had exploited the unintentional sound (see section6.4) that later would serve as a basis for the compositional task.

General issues that lowered the playability of the PHOXES included the aforementioned lack of control, cumbersome menu system, lack of MIDI support and tedious setup. Finally, there were latency issues with both the drumPads and the SlideSurface that made it difficult to play accurate rhythmical patterns in real-time. Not surprisingly, it was test person C, who is also an experienced drummer, that was most critical towards the drum pads.

Generally the tubePHOX and the particlePHOX were more played as traditional instruments (observation showed more expressive play, and subjects reported them as being easier to control). The tubePHOX as individual instrument was more predictable and initially not as interesting as the other PHOXES, but as test person B remarked the tubePHOX had "opened up" over time and he enjoyed the ability the flute gave him to control three parameters simultaneously. Interestingly person B had played the French horn as a child and was by far the test person to play most expressively on the flute controller.

A high amount of playability was reported for especially the particlePHOX, which generally was the most preferred of the PHOXES, especially within the first two weeks of evaluation (this was perhaps not surprising (Gelineck & Serafin, 2009b)). Reasons given included the timbral qualities, the tonality, the organic feel, the interplay between accurate control (crank) and randomness/"life of its own" (stochastic excitation), and the truly continuos physical gesture. Interestingly, the crank was not preferred for controlling other PHOXES, which emphasizes the importance of the stochastic excitation for the heightened playability of the particlePHOX. It seemed that there was a certain threshold for when the randomness in regards to control would go from "feeling like an acoustic instrument" and supporting expressivity and exploration to lowering the perceived playability. Test person C said that he likes unpredictability and random variation because it can really suggest alternative musical directions, but also that the PHOXES needed to have less random variation or provide better control over the randomness. This corresponds well to (O′Modhrain, 2011), in which it is argued that unpredictability must be reliable. Interestingly, one of the subjects said during the final evaluation that he had grown tired of the sound of the particlePHOX and had focussed on working with the other PHOXES instead.

6.7 MIDI / Notes

The issue of whether the PHOXES should have supported MIDI was a considerable issue for two of the test persons. When describing why MIDI would have improved their experience with the PHOXES they emphasized three overall areas:

1. *MIDI In* would provide more accurate control of the synthesis engine, by either letting them program/edit sequences for making fast rhythmical patterns or for more control in a live situation, or by using their favorite MIDI control interface (for instance test person C was very critical towards the drum pads on the drumPHOX). If he had been able to control the excitation of the drumPHOX using his own MIDI drum pads, he would have used it much more. Generally test person C found it hard to incorporate the PHOXES into his normal workflow because of the minimal control of notes (both in the way that he had to dig through menus to find the right key, and the control using a knob, that made it impossible to jump between non-consecutive notes in real time). He emphasized again and again that *MIDI in* would have made a huge difference for him. While test person A said that controlling the PHOXES with a MIDI sequence would have helped him by for instance freeing a hand to perform other functions or by being able to play melodies on a keyboard, he found a way to work with the PHOXES ending up feeding off the constrained physicality of what he called *"hand play"* (see fourth quote in section 6.2 page 10).
2. *MIDI Out* would have made it possible to control or modulate other synthesizers with the excitation devices—for instance test person C would have liked to take the natural gesture control of the crank and use it to also control other elements:

   > *... but the fun part could be if you could let it control different parameters of a synthesizer... the filter, modulate the filter or something else... that could be fun... "*

   He would also have been able to add a keyboard to control notes while controlling actual excitation with the crank:

   > *... and this [particlePHOX] should have some keyboards, some keys, right... it could be fun if it had a keyboard... that one [particlePHOX]... then I would sit and invent melodies, then I think songs would start on that barrel organ there, where you would sit and play a little tune with one hand while turning this [the crank] with the other hand..."*

3. It would have been interesting to explore polyphony in regards to the PHOXES. As mentioned earlier a great deal of exploring a new digital musical instrument is putting it into a musical context. Polyphony would have made it easier to explore harmony, mood, feel, etc. while playing the PHOXES without a musical context (a beat or a loop playing in the background)

6.8 The Composition

The compositional task was approached surprisingly similar by the different test subjects. All test persons had an initial idea established throughout the free exploration period of how to use the PHOXES in the composition. Test person A used the combination of drumPHOX and frictionPHOX mentioned earlier as a point of departure, while test person B used the unintentional sound of the frictionPHOX mentioned earlier. Test person C used some earlier recordings and explored the tonality of the particlePHOX as his starting point. They would all initially use time building an overall structure for the composition based on their initial starting points. Then at some point they would all use the PHOXES to record a longer session, and then afterwards go back and look for interesting sounds, that could be incorporated (as mentioned in section 6.3). Interestingly, when asked to play those recordings the test persons would discover sounds, that they had wanted to use at the time but had forgotten.

All though they were totally free to use whatever external sound (sounds not made using the PHOXES) they wanted, they all took it upon themselves to use almost only PHOXES sounds. Two of the test subjects used a few beats from elsewhere while the third subject only used PHOXES sounds. As seen before (Nuhn et al., 2002; Gelineck & Serafin, 2009a) composers often set up constraints or challenges for themselves in this way to spark the creativity process.

Again, the modular capabilities of the PHOXES were hardly used at all. The particlePHOX and frictionPHOX were both used in longer passages as ambient background sounds, otherwise most PHOXES sounds were used rhythmically and heavily processed (EQ, pitch-shifting, compressor, reverb, tremolo, cutting up samples, etc..).

6.9 Studio vs. Live

While all three test persons agreed that the PHOXES were interesting to use in a compositional setting, they also agreed that in their current form they would not be suitable for live use. Here accurate and immediate control is crucial (presets, MIDI, no menus, etc.). Person B emphasized that there was a big difference between what gear he used live and in the studio.

> *".. maybe a free jazz musician or others would think that they are fun to take with them on stage, but for me, they are not controllable enough.... but then that makes it fun in the studio, right.. because you don't bring the most controllable machines with you in the studio, because they are not the ones that open up and like give you new sound material.. "*

Test persons A and C said that minor unpredictable variations are fine for live purposes if they are subtle. For instance person C said that it would be interesting to use the stochastic excitation with the crank to control subtle audio effects live because of the natural organic feel of the crank (also mentioned in section 6.7). However, he would never bring a crank on stage because it would look silly. He recommended a jog wheel as seen on most DJ CD-players or on the Arc[11] for the continuous excitation feel. The slideSurface would also work live with less latency, however the friction model was too difficult to control in a live context.

7 Discussion

In this article we have presented a set of modular electronic/digital music instruments, that have been designed to support creativity and exploration. The idea has been to develop the overall system focussing on the following issues: Explorability, balance between constraints and freedom, personal identification with the instrument, connectivity, modularity, physicality of exploration, and sonic diversity.

A set of four modular digital musical instruments (the PHOXES) were developed each implementing a different physical model. Each module implemented a separate excitation controller that let the user exert energy into the model. Additionally by letting the user combine the different PHOXES in several ways it was the goal to maximize explorability by providing freedom in the combination of each constrained module.

The PHOXES were evaluated in a compositional setting using an in-depth holistic approach were three experienced commercial electronic musicians borrowed the PHOXES over a period of four weeks being almost totally free to use them as desired - a compositional task was given towards the end of the test period. Two "show and tell" sessions were used to gather information about the test persons' experience with using the PHOXES. The goal was to evaluate the experience of playing the PHOXES by understanding how they would be integrated into real world contexts.

The importance of context became evident as everything regarding the PHOXES would be evaluated in relation to the context in which it was used. This was evident both in the way that the PHOXES were addressed (talked about), how they were played during the show and tell sessions, how they were criticized, and how the use of the PHOXES changed depending on the tools that they were used with. For instance it was observed that more time was spent adjusting effects, editing sounds, cutting, etc. than actually playing the PHOXES. While we suggest that this is a quite typical way of working with new tools, it could also be due to limitations of the PHOXES - the lowered playability caused by especially the difficult tonal control or lack of MIDI support might have forced the test subjects to spend much time working with their familiar tools in order to extract the desired functionality out of the PHOXES. Additionally all test persons said that they would probably approach the PHOXES in a completely different way if they were to evaluate them in 6 months (different tools, approaches, compositional goals, etc. would influence how they were used).

While the PHOXES were developed to support creative exploration by striking a balance between constraints and freedom, they seemed to be too constrained in their connectivity. MIDI support would have made a considerable difference for at least two of the test persons, but it is difficult to distinguish whether improved control (especially on a note-level and rhythmical level) would have made MIDI support less important. While the test persons inherently had a very high focus on timbral aspects, experimentation, and post processing, they were still surprisingly aware of the importance of immediate playability of an instrument for creative exploration. The PHOXES seemed to put too much focus on timbral exploration, neglecting the playability that is so important for immediate embodied experience of making music.

Unfortunately and interestingly, the modularity that has been so important in the development of the PHOXES was only seriously utilized by one of the test

[11] http://monome.org/articles/2011/01/14/arc/

persons. This also meant that the exploration of the physical interaction with the different models was difficult to evaluate. The perceived causality inherent in the physical models (described earlier in section 4 page 4) was not powerful enough to provide the test persons with a clear mental model of the PHOXES. More attention definitely needs to be directed towards making the combination of different PHOXES more intuitive. It might also be that the test persons disregarded the menu system early on because it took such a substantial amount of cognitive resources away from the most central activity that is making music.

It is interesting, though maybe not surprising, that the test persons set up constraints for themselves during the compositional task. On a general level this kind of behavior makes it difficult to evaluate whether creative inspiration might be due to the constraints of the task or due to the qualities of instrument being evaluated.

This study suggests that the less experienced musician (test person A) found it easier to embrace the PHOXES, using them to a large extent. While it might seem that test persons B and C are more traditional and less experimental in their way of making music, this is hardly the case. We believe that it is the amount of experience of the musicians and the fact that they have developed stronger preferences towards certain issues (playability, MIDI, work-flow, etc.) that has made them more critical in general towards the PHOXES. They are still regarded as experimental, but it is important to emphasize that an experimental approach is still an approach that might be bound by certain norms or usual work processes. In other words an experimental musician still has a way of structuring ideas, a way of working with musical tools, preferences towards certain approaches, etc.. These must be catered for either by making the tool more flexible or developing it for a more specific target group.

The longitudinal methodological approach to the evaluation turned out to beneficial in a number of ways. First of all the test persons all said that the free exploration period was important for them to get to know the PHOXES in the same way that they would normally get to know a new digital musical instrument. They also said that the process had been very natural and they had felt quite free to work creatively with the PHOXES. Even the compositional task had been familiar as they are used to deadlines for finishing compositions in their daily work. External factors and technical issues unfortunately may have distorted the naturalness of the approach and that is definitely an issue to take seriously in these kinds of low-controllable test environments.

While we were not provided with any immediate user experiences as everything was reported retrospectively, the show and tell sessions seemed to be quite powerful in how the "show" part would force the subjects to reflect more carefully about their experiences. There were several instances were test persons would show something differently, recall issues they had forgot about or change their mind because they had to physically show what they meant - both regarding interaction with the PHOXES and with their other tools. Subjects would exhibit positive experiences with parts of the instrument that they had discarded or been critical towards while showing which parts did not work, or they did not like. Not only does this sort of method increase the validity of the methodology, it might also show interesting differences between what is normally experienced in the now, and how those experiences are recalled. Recent movements within HCI suggest that even though memory may not be consistent with actual experience it is still valid (Norman, 2009; Karapanos, Martens, & Hassenzahl, 2010).

This study has illustrated the importance of context in regards to evaluation of complex factors to do with music making, creativity and exploration. The presented methodology is a contribution to the evolving demand for new methods that take into account the experience of using musical interfaces over longer periods of time. It might be interesting in the future to explore methodologies that have more multi-dimensional approaches to evaluation of musical instruments (Nuhn et al., 2002; Collins, 2005) or additional ways of dealing with the problem of retrospective assessment—for instance the iScale or the Analytical Scale proposed by (Karapanos et al., 2010). Furthermore it would be interesting to see the merging of more traditional usability evaluation and holistic experience evaluation as there are many ways that these two approaches would be able to feed off each other. An obvious example is extracting concepts that emerge from these more subjective holistic evaluations and evaluate them under more controlled settings. But one could also take results found in quantitative usability evaluations and study them in various real world contexts. In particular within new interfaces for musical expression (NIME) there seems to be a great potential in approaching the design and evaluation from this more experience driven perspective.

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Co-author statement in connection with submission of PhD thesis

With reference to Ministerial Order no. 18 of 14 January 2008 regarding the PhD Degree § 12, article 4, statements from each author about the PhD student's part in the shared work must be included in case the thesis is based on already published or submitted papers.

Paper title: A quantitative evaluation of the differences between knobs and sliders.

Place of publication: Proceedings of the International Conference on New Interfaces for Musical Expression, 2009.

List of authors: Steven Gelineck, Stefania Serafin

PhD student: Steven Gelineck

Contribution (short description of
the authors' contribution to the article, text): The major part of the work was carried out by author S. Gelineck. Co-author S. Serafin participated in the statistical analysis and in editing of the script.

Signature, PhD student

Signature, co-author

Co-author statement in connection with submission of PhD thesis

With reference to Ministerial Order no. 18 of 14 January 2008 regarding the PhD Degree § 12, article 4, statements from each author about the PhD student's part in the shared work must be included in case the thesis is based on already published or submitted papers.

Paper title: From idea to realization - understanding the compositional processes of electronic musicians.

Place of publication: Proceedings of the Audio Mostly Conference, 2009

List of authors: Steven Gelineck, Stefania Serafin

PhD student: Steven Gelineck

Contribution (short description of
the authors' contribution to the article, text): The major part of the work was carried out by author S. Gelineck. Co-author S. Serafin participated in the editing of the script.

Signature, PhD student

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Co-author statement in connection with submission of PhD thesis

With reference to Ministerial Order no. 18 of 14 January 2008 regarding the PhD Degree § 12, article 4, statements from each author about the PhD student's part in the shared work must be included in case the thesis is based on already published or submitted papers.

Paper title: Phoxes - modular electronic music instruments based on physical modeling sound synthesis.

Place of publication: Proceedings of the 7th Sound and Music Computing Conference, 2010

List of authors: Steven Gelineck, Stefania Serafin

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Contribution (short description of
the authors' contribution to the article, text): The major part of the work was carried out by author S. Gelineck. Co-author S. Serafin participated in the editing of the script.

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Co-author statement in connection with submission of PhD thesis

With reference to Ministerial Order no. 18 of 14 January 2008 regarding the PhD Degree § 12, article 4, statements from each author about the PhD student's part in the shared work must be included in case the thesis is based on already published or submitted papers.

Paper title: Longitudinal Evaluation of the Integration of Digital Musical Instruments into Existing Compositional Work Processes

Place of publication: Submitted for publication in Journal of New Music Research, 2011

List of authors: Steven Gelineck, Stefania Serafin

PhD student: Steven Gelineck

Contribution (short description of
the authors' contribution to the article, text): The major part of the work was carried out by author S. Gelineck. Co-author S. Serafin participated in the editing of the script.

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