Perceptual Characterization of a Tactile Display for Live Electronic Music Performance

Designing a Vibrotactile Notification Tool for the CIRMMT Live Electronics Framework (CLEF)

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Abstract

This study was conducted to assess physical and perceptual properties of a tactile display for a vibrotactile notification system within the CIRMMT Live Electronics Framework (CLEF), a Max-based modular environment for composition and performance of live electronic music. The tactile display was composed of two rotating eccentric mass actuators driven by a PWM signal generated from an Arduino microcontroller. Physical measurements using an accelerometer were carried out in order to estimate intensity and spectral peak frequency as function of duty cycle of the PWM signal. In addition, three user-based studies were conducted to estimate perceptual vibrotactile absolute threshold, differential threshold and temporal differential threshold. Obtained results provided us with precise guidelines that facilitate the design of perceptually robust vibrotactile stimuli for our tactile application. A set of eight simple tactons (vibrotactile icons) was defined, whereafter an absolute identification test was conducted in order to estimate mean tacton recognition rates. Results were promising; mean tacton recognition rate was found to be 74 %. Based on all findings described above, a Max-based prototype used for exploration of tactile stimuli was developed. The prototype contained a library of tactile notification presets to be loaded into CLEF, along with a simple tacton editor for design of customized tactile events.
Referat

Perceptuell karakterisering av en taktill display för
musik som involverar elektronisk generering och
processering av ljud i realtid

Syftet med denna studie var att undersöka fysiska och perceptuella
egenskaper hos en taktill display som designats för att presentera taktill
notifikationssignaler till användare av CIRMMT Live Electronics
Framework (CLEF), en Max-baserad modulär miljö för komposition
och framförande av musikstycken som involverar Live Electronics. Li-
ve Electronics är ett begrepp som innefattar elektronik som används för
att generera, processera eller modifiera ljud i realtid. Den taktilla display
som användes i denna studie var uppbryggd av två roterande excentris-
ka massor, drivna av en pulsbreddsmodulerad signal som genereras av
en Arduino mikrokontroller. Accelerometermätningar och tre använd-
arbaserade studier genomfördes för att undersöka följande: intensitet
och spektral toppfrekvens som funktion av pulskvot, sensorisk tröskel
och intensitetsdiskriminering mellan presenterade stimuli, samt JND i
millisekunder för två efterföljande taktilla stimuli. Erhållna resultat ana-
lyserades varefter riktlinjer för design av perceptuellt robusta signaler
för vår taktilla display sattes upp. I slutfasen av studien designades åtta
taktilla signaler, varefter en användarbaserad studie genomfördes för att
uppskatta hur lätta dessa signaler var att identifiera. En genomsnittlig
identifikationsnivå på 74 % kunde noteras. Baserat på ovan beskrivna
resultat utvecklades slutligen en taktill modulprototyp i form av ett bibli-
oteck av fördefinierade taktilla stimuli. Denna prototyp inkluderande även
en funktion som gav användaren möjlighet att designa och skräddarsy
egna taktilla signaler.
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Acronyms

AC Alternating Current 11
ADSR Attack Decay Sustain Release 12
CIRMMT The Centre for Interdisciplinary Research in Music Media and Technology 1
CLEF The CIRMMT Live Electronics Framework 1
DC Direct Current 11
DMIs Digital Musical Instruments 7
DSP Digital Signal Processing 6
GUI Graphical User Interface 18
JND Just Noticeable Difference 9
MIDI Musical Instrument Digital Interface 4
OSC Open Sound Control 6
PWM Pulse Width Modulation 11
Chapter 1

Introduction

This section gives a short introduction to the problem domain and defines the purpose of the study.

1.1 Overview

In a preliminary study by Schumacher et al. (2013), a tactile notification tool for CLEF (the CIRMMT\textsuperscript{1} Live Electronics Framework)\textsuperscript{2} was presented. The tactile display used in this study was composed of two vibrating actuators and a software control module seamlessly integrated into a Max\textsuperscript{3} environment. The tactile module was designed to allow performers and composer to take advantage of haptic feedback in the context of live-electronics performance. The aim in the current study is to investigate characteristics of the vibrating disk motors used in the tactile display mentioned above and to provide guidelines that facilitate the development of a more coherent and meaningful vibrotactile notification system for CLEF.

1.2 Purpose

The purpose of this study was to investigate the following research question: \textit{In terms of actuator signals, how should a vibrotactile display for live-electronics performance be designed in order to ensure perceptually robust identification and discrimination between vibrotactile stimuli?}

1.3 Problem Statement

Haptic feedback has been proven to be fundamental in the process of “embodiment” of a musical instrument and an integral part of musical interaction. Despite this,

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\textsuperscript{1}The Centre for Interdisciplinary Research in Music Media and Technology, housed at the Schulich School of Music at McGill University, Montréal.

\textsuperscript{2}http://clef.sf.net

\textsuperscript{3}www.cycling74.com
live-electronics systems seldom provide the musician with any haptic feedback. On the contrary, performers often find themselves in a sort of “limbo” where they, for a certain amount of time, receive no feedback about the internal state of the electronic system. By introducing tactile cues in the context of live-electronics performance, the “action-perception loop” between performer and live-electronics system can be closed, resulting in a tighter interaction, more similar to the one existing between a normal instrument and a musician. (Schumacher et al., 2013)

1.4 Motivation

One of the limitations of the previous work carried out by Schumacher et al. (2013) was the lack of characterization of the vibrating actuators that were used in the tactile display. The aim of the current study is to fill this gap, thereby enabling design of perceptually robust actuation signals. Findings from the current study may not only be relevant for musicians and composers using CLEF, but also for other projects where the same type of actuators are used to provide vibrotactile feedback during a performance: namely the CIRMMT Student Award funded project Using haptic notifications for polyrhythmic / metric synchronization in ensemble performance. In this project, vibrotactile metronomes will be used in an ensemble performance with a saxophone quartet.

1.5 Project Objectives

The main objectives of the project are:

- To investigate which type of messages that could be communicated to a musician through the haptic channel in the context of live-electronics performance.
- To investigate the physical characteristics of the vibrating disk motors used in the tactile display for CLEF.
- To investigate the perceptual characteristics of the vibrating disk motors used in the tactile display for CLEF.
- To design a “vocabulary/library” of tactile cues, i.e. a set of tactons, that can be used for information display in live-electronics performance.
- To investigate if the designed tactons are perceptually differentiable.
- To develop a prototype with tactile notification presets (including tactons) to be loaded into CLEF.
- To provide straightforward guidelines for the development and improvement of the tactile module for CLEF.

4http://www.cirmmt.org/research/support/student/student-award-recipients14-15
5http://www.quasar4.com
1.6 Project Scope

Since several factors, e.g. experimental design, contact area, choice of actuator and body locus may affect threshold levels obtained in perceptual tactile experiments (Verillo, 1963; Cholewiak et al., 2001; Weber, 1834; Choi and Kuchenbecker, 2013), the experiments conducted in this study were designed with the explicit aim of characterizing the specific set-up used in our vibrotactile application. The results obtained can thus not be generalized to other set-ups or tactile displays to any larger extent. Although the topic of mapping is briefly discussed in this report, the development of mapping strategies for CLEF variables to vibrotactile stimuli is not an integral part of this study.
Chapter 2

Literature Review

This section introduces the theoretical framework linked to the study and presents an introduction to previous work within the field.

2.1 Background

Realtime processing of musical data and sound during a performance, i.e. the use of live electronics for mixed music, is common practice in contemporary music performance. Various input devices such as MIDI foot pedals or switches may be used in order to allow the performer to control realtime processing of live generated music or to trigger musical events. An important concern for both musicians and system designers in this context is to facilitate the interaction between instrumentalist and the live-electronics system (Schumacher et al., 2013; McNutt, 2004).

As opposed to performances involving only acoustic instruments, live-electronics performance is often characterized by a lack of feedback concerning the current state of the system producing the music. Different attempts have been made to facilitate the interaction between performer and live-electronics system, for example by adding on-stage visual feedback about articulated actions (Michailidis and Bullock, 2011). Another approach, as suggested by Schumacher et al. (2013), is to exploit the haptic modality as an alternative channel for information display. The study described in this report is a continuation of the project cited above, aiming to investigate the perceptual and physical characteristics of the actuators used in the vibrotactile display developed by Schumacher et al. (2013).

2.2 Mixed Works

In electronic music, the term “mixed works” signifies pieces that combine live performance of one or several acoustic instruments with sounds that are produced, created or reproduced electronically. Today, there are typically two main types of mixed works: pieces with fixed electronic media and pieces with live electronics. In a performance with fixed media, the musician is accompanied by a fixed pre-recorded
accompaniment such as a CD, a tape or sound file on a computer. In performances with live electronics, the electronic music is not fixed, meaning that sounds are created or manipulated electronically in real time along with the acoustic sounds. (de Oliveira Rocha, 2008)

2.2.1 Live-Electronics Performance

Regardless of the complexity of the electronics used, performance with computers may be considered a form of interaction between musician and electronics (Belet, 2003). In modern performances for mixed works for acoustic instruments and live electronics, it is common to make use of computers and software, such as Max/MSP. Pre-recorded sounds, real-time processing of sounds produced by acoustic instruments as well as synthesis of new sounds can be combined during a single performance (de Oliveira Rocha, 2008). Electronic music input devices, MIDI devices, interfaces and pedals such as sustain pedals and expression pedals are examples of input sources that could be used (Michailidis and Bullock, 2011). Since live-electronics performance is highly dependent on interaction between performer and electronics, these type of performances are often called interactive performance (de Oliveira Rocha, 2008). Despite the past years rapid technological and computational advancements, composition for a performer and a fixed accompaniment, e.g. a CD, is still the most common combination of live performance and electronics. In these contexts, the connection between live and recorded parts is an important part of the musical performance.(McNutt, 2004)

2.2.2 The Lack of Feedback in Live-Electronics Performance

The relationship between an instrumentalist and the acoustic instrument is bidirectional (Chafe, 1993). An instrument reacts to the energy received from the musician by producing both audible and tactile feedback. In contrast to the interaction with an acoustic instrument, moderns electronic musical input devices, instruments and interfaces do usually not provide sufficient haptic feedback to the performer. A gap is therefore created in the sensory experience when performing with electronic devices. By decoupling the gestural controller and sound producing units into two separate components, the haptic feedback loop between performer and vibrating parts of the instrument is broken. (Birnbaum and Wanderley, 2007; Giordano et al., 2012) This may introduce problems and create insecurity for the musician during a live-electronics performance, since the performer is often left without feedback in terms of immediate response to the action performed and the internal state of the electronics system (Schumacher et al., 2013; Michailidis and Bullock, 2011).

Different attempts have been made in order to improve the situation described above, for example by adding auditory or visual displays, introducing a technician that takes care of the technological part of the performance, or by providing auditory metronome click tracks through headphones. Such approaches may however be distracting and increase the cognitive workload of the performer, who is already
engaged in reading a score, listening to sounds or synchronising to other musicians. 
(Schumacher et al., 2013)

\subsection*{2.2.3 CLEF}

The CIRMMT Live Electronics Framework (CLEF) is a Max-based modular software framework for live electronics, developed by Marlon Schumacher at the Music Technology Department at McGill University. CLEF follows a structural design and allows for users to rapidly create complex signal processing, algorithms and control data. The framework is directed towards composers and musicians; it is implemented natively in Max and does therefore not rely on any external programming frameworks or software libraries.

The framework is designed using the Model-View-Controller paradigm and relies on multiple technologies for messaging and management of storage. Communication in CLEF is handled over a shared message bus using a syntax in the Open Sound Control (OSC) format (see Wright et al. (2003)). The environment can also be remotely controlled via the OSC messages, for example through custom graphical user-interfaces and OSC-enabled input devices. Storage of data is handled via Max dictionaries and the \texttt{pattr} system. The architecture of CLEF is based on three different components; an infrastructure for hosting 1) Modules, a score system structured into 2) Events and Cues, and a graphical interface providing 3) Views containing Widgets. A screenshot of the graphical user interface of CLEF, i.e. the view containing a number of widgets, can be seen in Figure 2.1.

A Module is an abstraction that encapsulates a specific functionality. Modules form the processing core of CLEF and chain together, generating data and processing incoming audio and control messages. The modules are selected at the beginning of the creation of a CLEF project and act as a pool of resources that can be accessed through the shared message bus. When instantiated, modules are loaded into the environment and assigned a unique address, whereafter their namespace is registered and signal in- and outputs are connected through a global routing matrix.

Events are a set of instructions for the modules and the router. This is somewhat similar to the page of a musical score. Events are designed as Max patchers, which can be customized and designed freely containing a set of instructions that may include changes to routings or module parameters. Users can program different Events that generate sounds and data algorithmically, control other events, respond to changes in the environment and so on. Example of graphical widgets that can be dropped into events are breakpoint-function-editors and Digital Signal Processing (DSP)-routing widgets. Finally, the creation of a CLEF project involves creating a list of Cues. The cue list assigns each cue to an event, which are then triggered in a specific order. The cue list is a flexible way of organizing, and re-structuring, a sequence of musical Events.

\footnote{http://cycling74.com/docs/max5/refpages/max-ref/pattr.html}
2.3. HAPTICS

The concept of haptics is an umbrella term referring to both kinesthetic and tactile sensation. Kinesthetic sense, also entitled proprioceptive sense, enables humans to perceive positions, movements and forces of one’s body. The tactile sense, the cutaneous sense, enables humans to perceive object properties through the skin. In haptics, tactile rendering involves processes associated with reproduction and modeling of physical stimuli that induce tactile sensation. One example of this is the vibrational feedback provided on touch screens. Kinesthetic rendering encompasses creation of force feedback that induce kinesthetic sensation, i.e. movement and force of one’s body. (Choi and Kuchenbecker, 2013)

In the musical domain, haptic feedback involves the creation of forces which resist the movements of a musical performer. Such forces are used to produce a feeling of interaction with virtual objects and surfaces, or to simulate a required effort in a physical interaction with a musical instrument. (Marshall, 2008) A wide range of studies focus on the use of haptic feedback for musical interfaces, and how this could address the problem of decoupling between control and sound generation in modern Digital Musical Instruments (DMIs). Haptic feedback has lately become a factor in the design of new instruments (MacLean, 2000; Giordano and Wanderley, 2013). The use of haptic and especially tactile technology within the musical domain is however not limited to DMIs (Giordano and Wanderley, 2013). Devices capable of providing tactile feedback have been used in learning interfaces for musical education, displays for hearing impaired and notification tools for live performances (Giordano and Wanderley, 2011; Karam et al., 2009; Schumacher et al., 2013).
2.3.1 Tactile Perception

The term tactile perception refers to perception mediated by variations in cutaneous stimulations (Loomis and Lederman, 1986). Tactile perception operates through a network of cutaneous receptors of the human skin and is responsible for a number of different sensations such as temperature, pressure, texture, orientation and vibration (Giordano and Wanderley, 2013).

The Four-Channel Theory

A basic knowledge of the fundamentals of vibrotactile perception is a necessity when designing vibrotactile displays and applications. Tactile perception is complex, and its neurophysiology is still under active research (Choi and Kuchenbecker, 2013). One of the most established theories concerning vibrotactile perception is The Four-Channel Theory; glabrous (non-hairy) skin contains four different types of sensory cells (mechanoreceptors) that can detect skin deformation. The four touch-sensing channels differ in the type of mechanical stimuli to which they respond (Choi and Kuchenbecker, 2013) and each one of them is sensory to different specific features in a tactile stimulus (Johnson, 2001). The following mechanoreceptor categories have been identified:

- Pacinian corpuscles (FA II)
- Meissner corpuscles (FA I)
- Ruffini endings (SA I)
- Merkel disk (SA II)

These sensory cells are connected to two types of nerve fibers; the Fast Affarent (FA) family and the Slow Affarent family (SA). FA fibers involve Meissner (FA I) and Pacinian (FA II) nerve endings, whereas SA fibers are connected to Merkel (SA I) and Ruffini (SA I) end-organs. The behaviour of Pacinian cells in particular is similar to the way the auditory system reacts to a stimulus (Makous et al., 1995), suggesting that the FA II channel is the channel to be mainly exploited for the mediation of musical vibrotactile events (Birnbaum and Wanderley, 2007). In general, the FA I and FA II are considered to be the channels responsible for vibration sensation (Choi and Kuchenbecker, 2013).

After the end of tactile stimulation, FA fibers cease to respond rapidly, whereas SA fibers may continue to respond over a longer period of time. This property is an important characteristic of the skin which is called the adaptation property. Since this property of the human skin may influence the sensory magnitude of a vibration, reducing the risk for adaptation is something that needs to be considered in design of tactile interfaces. (Verillo and Gescheider, 1992)
2.3. HAPTICS

2.3.2 Vibrotactile Parameters

In order to produce vibrotactile feedback we require mechanical actuators that can produce vibrations whose frequencies and amplitudes are within the range of human tactile sensation (Marshall, 2008). Below follows a brief introduction to the vibrotactile parameters that we have to consider when designing a vibrotactile display.

Frequency Response

The frequency response of non-hairy skin when excited by a tactuator is usually characterized by a u-shaped form, with a frequency span ranging from 40 Hz to 1000 Hz and peak sensitivity around 250 Hz. The sensation versus magnitude curves relating perceived intensity to tactile stimulus frequency presented by Verillo and Gescheider (1992) are very similar to the Fletcher-Munson curves for auditory perception (MacLean, 2000; Giordano and Wanderley, 2013). As for the Fletcher-Munson curves, such equal sensation magnitude graphs give information about how intense a vibrotactile signal must be at any give frequency to equal the subjective magnitude of a tone at any other frequency (Verillo and Gescheider, 1992).

Intensity

The sensitivity to a physical stimuli is often represented via the absolute detection threshold. This is the weakest stimulus intensity that allows humans to perceive a stimulus in a robust manner. (Gescheider, 1997) Absolute thresholds are are affected by numerous factors, e.g. body site (locus), contact area, stimulus duration, stimulus waveform, contact force, skin temperature, age etc. (Jones and Lederman, 2006) Moreover, absolute thresholds of vibrotactile stimuli strongly depend on vibration frequency. The different perception channels are therefore characterized by frequency-dependent absolute thresholds. The channel with the lowest threshold will decide the overall absolute threshold. (Choi and Kuchenbecker, 2013)

Once the lowest level at which a stimulus is perceptually detectable is known, it is important to investigate if users can distinguish between different vibrotactile cues having different intensities. The capability to do so is quantified by the Just Noticeable Difference (JND), also called the discrimination threshold. The JND in intensity is the smallest intensity difference that leads to reliable discrimination. Difference thresholds depend on the strength of the reference stimulus, and the JND is thus often represented by a Weber fraction, which is the ratio of the difference threshold to a reference level. According to the Weber law (Gescheider, 1997), Weber fractions usually tend to remain constant regardless of the reference level for the same kind of stimuli. For vibration intensity, Weber fractions have been found to cluster around 10-30 %.

According to Choi and Kuchenbecker (2013), at least 20 % to 30 % of a difference in amplitude is necessary for robust discrimination between vibrotactile stimuli in practical applications (i.e. Weber fractions around a ratio of 1.1 to 1.3). Moreover,
it is worth mentioning that the actual number of identifiable stimuli is restricted also by other perceptual and cognitive factors connected to information transmission (Tan et al., 2010). It has been suggested by van Erp (2002) that not more than four different levels should be used between detection and comfort-pain threshold when designing vibrotactile stimuli.

**Time and Rhythm**

It is important to investigate how good users are when it comes to judging timing in the context of vibrotactile cues. In general, human tactile perception is considered to have high temporal acuity (Choi and Kuchenbecker, 2013), ranging somewhere between that of vision and audition (Jones and Lederman, 2006). Pulses with a time gap as small as 5 ms can be detected by human skin (Goldstein, 2002). Temporal variations can be achieved in vibrotactile signals by changing the amplitude over time, i.e. by modifying the signal’s envelope, thereby creating a sensation of rhythm (Choi and Kuchenbecker, 2013). Studies have shown that the sense of touch performs surprisingly well when it comes to rhythm recognition (Kosonen and Raisamo, 2006; Jokiniemi et al., 2008; Brown et al., 2005). Regarding tactile rhythm perception, humans are quite sensitive to differences, possessing high discrimination and recognition abilities (van Erp and Spapé, 2003; Swerdfeger and Fernquist, 2009).

**Spatial locus**

Actuator density and location is an important parameter when designing multiple elements tactile displays. Spatial discriminability has traditionally been measured using a two-point threshold, i.e. the shortest distance needed for two simultaneously applied stimuli to be reliably perceived as distinct. Measured thresholds of spatial acuity differ significantly across the body, since different skin areas are characterized by different mechanoreceptor densities. (Choi and Kuchenbecker, 2013)

In the current study, a positioning on the back of the torso was chosen. Localization in this region is best at the spine and navel (Cholewiak et al., 2004) and the threshold for localizing vibrotactile stimuli on the back is 11 mm (Eskildsen et al., 1969). Although not as sensitive in terms of tactile perception as the hands and fingertips, there are other advantages to developing a tactile display for the back of the torso. One advantage, as pointed out by Piateski and Jones (2005), is that the large area of the torso enables us to accommodate twice as much information compared to if the fingertips would have been used. Moreover, actuators spread out over the large surface of the back of the torso may compensate for the decreased skin sensitivity, introducing spatial locus as an additional parameter for tactile information display (Jones and Lederman, 2006).
2.3. HAPTICS

2.3.3 Vibrotactile Actuators

A wide variety of actuators producing oscillating movements that can be perceived by the human skin are available on the market today. The different actuators vary in size, cost, type and freedom of control. Examples of different actuators are loudspeaker actuators, motor actuators, piezo disc actuators and solenoids. Several characteristics should be considered when deciding which actuators to use, such as mechanical characteristics (e.g. frequency response and resolution, amplitude response and amplitude range) and control characteristics (e.g. technical specifications involving the number of control variables; control signal, amplitude control, frequency control, waveform control and spectral control). (Marshall, 2008; Choi and Kuchenbecker, 2013)

In general, motor and solenoid actuators offer much less control than AC signal driven actuators such as loudspeaker actuators and piezo discs (Marshall, 2008). The actuators used in this study are rotating eccentric masses. These vibrating motors are commonly used in mobile phones and vibrotactile game controllers. The frequency and amplitude of the vibration for these type of actuators vary proportionally to the speed of the motor’s rotation. The amplitude and frequency are thus linked; higher input levels will naturally produce both higher frequency and higher amplitude and the actuators do not offer control of spectral content. The motors are controlled by modulating an applied DC voltage, a Pulse Width Modulation (PWM) signal, which is indirectly linked to the intensity of the vibration. (Marshall, 2008) PWM is a technique where the duty cycle of a square wave is modulated to encode a specific analog signal level. At any given instant of time, the full DC supply is either fully on or fully off. A low duty cycle will correspond to low power, since the power is off for most of the time. Duty cycles are commonly expressed in percent, where 100 % is fully on. (Barr, 2001)

Figure 2.2: The actuator used in this study.
CHAPTER 2. LITERATURE REVIEW

2.3.4 Tactons

Tactons are tactile structured messages, i.e. tactile icons, designed to communicate information through the haptic channel. Information can be encoded into tactons through parameters of cutaneous perception. The properties which can be manipulated are similar to those of auditory icons or earcons (defined by Gaver (1986)), such as frequency and intensity. However, the parameters available will vary depending on the type of actuator that is used (Brewster and Brown, 2004).

Tacton design

Little is yet known about how to efficiently design tactons (Brown et al., 2005). However, the design approaches can be considered to be somewhat similar those adopted in earcon design. As for the case with auditory icons, it is important to design tactons in such a manner that they can be differentiated by users. Moreover, it is essential to make sure that the tactile signals are salient. The initial step of tacton design therefore involves investigating how vibrotactile icons should be designed in order to be perceptually robust. When such initial design considerations have been done, the next step is of the design process is to decide how to map information to representations. As mentioned by van Erp (2002), information could be encoded in the following tactile parameters: subjective magnitude, frequency, location or temporal patterns.

Encoding Information in Tactons

Assuming that the process of designing tactons is similar to the process of designing auditory earcons, one could adopt some of the design approaches as defined by Blattner et al. (1989). One suggestion would to adopt a similar design paradigm as the one suggested in above cited source; short motifs could be used to represent simple actions or objects, and these motifs could then be combined together in different ways to represent more complex messages and concepts. A similar analogy has been discussed by Enriquez et al. (2006), where a haptic phoneme is defined as a small unit of a constructed haptic signal to which a meaning can be assigned. The haptic phonemes can in turn be combined serially or in parallel to form words or haptic icons, holding more elaborate meanings.

As mentioned by Gunther (2001), different tactile stimuli could be produced by combining tactile duration with alterations in the envelope of a vibration. According to the analogy of letters and words mentioned above, it may be proposed that basic tactons could be defined in terms of simple ADSR envelopes, and that these envelopes then could be combined together into more complex tactile messages or rhythms.
2.4 TACTILE FEEDBACK IN LIVE-ELECTRONICS PERFORMANCE

Tacton Recognition and Learnability

Recognition rates for tactons produced via the type of actuator used in our current study has previous been investigated by Brown and Kaaresoja (2006). Results were promising when presenting tactons with a phone vibration motor; when tactons encoded two pieces of information (type and priority of the signal) in rhythm and intensity, recognition rates of 72% were obtained. Brown et al. (2005) also identified rhythm as a successful parameter in tacton design in another previous study, where recognition rates of over 90% were obtained when three different rhythms were used. Rhythm, or tempo, and intensity may therefore easily be identified as two important parameters for information encoding.

The mapping between vibrotactile stimuli and encoded information of a tacton is abstract. This means that there is no intuitive connection between perceived stimulus and the information that this stimulus represents. As a result, the meaning of every single tacton needs to be learnt. In a study by Enriquez et al. (2006) it was found that a set of 12 haptic stimuli could be perceptually distinguished for arbitrarily chosen stimulus-meaning pairs. Users could consistently recall an association between a haptic stimulus and an arbitrary meaning assigned to it when a 9 phoneme haptic set was used. In another study by Chan et al. (2005) it was found that a set of 7 tactile stimuli with abstract labels could be identified with a 95% accuracy in the absence of workload and when a learning time of less than three minutes had preceded the experiment. These results indicate that humans are able to learn arbitrary abstract mappings between tactons and meanings.

2.4 Tactile Feedback in Live-Electronics Performance

2.4.1 Related Work

The role of haptic and tactile feedback in the context of musical interaction has been investigated in numerous studies throughout the years. Tactile actuation technology has been widely adopted in the design of Digital Musical Instruments (DMIs) and researchers have identified which tactile cues that can be sensed by performers while playing traditional musical instruments (Chafe, 1993; Puckette and Settel, 1993; Giordano et al., 2012; Marshall and Wanderley, 2006; Birnbaum and Wanderley, 2007). A taxonomy of tactile feedback for musical interaction in which three major categories could be identified was suggested by Giordano and Wanderley (2013). The taxonomy divided tactile feedback into the following three categories: tactile notification, tactile translation and tactile synthesis.

Tactile feedback has already been used in order to convey information regarding the performer’s direct action on the system in the context of live-electronics performance. In a study by Michailidis and Bullock (2011), small vibrating motors were used to give musicians valuable information regarding successful triggering of effects in a live-electronics performance with an augmented trumpet. In McDonald et al. (2009), a wireless haptic interface was used to coordinate performers in
free-improvisational performances. The interface, Vibrobyte, allowed a composer to send haptic signals to performers and performers to haptically affect each other. Attempts to generalize the concepts of vibrotactile notification and feedback for live-electronics performance were made in the study by Schumacher et al. (2013), discussed below.

**Vibrotactile Notification for Live Electronics Performance: A Prototype System**

A tactile synthesis framework, or tactile module, designed to provide performers with information concerning the internal state of the CLEF framework was introduced in the previously cited study by Schumacher et al. (2013). The tactile module was capable of displaying not only immediate feedback in response to specific commands from the user to the system, but also more abstract parameters not directly linked to the user-system control flow, e.g. score-related information such as tempo changes. The tactile display consisted of two vibrating actuators (rotating eccentric masses) placed on the back of the torso of the musician. The module prototype was implemented as a synthesis module which could be seamlessly integrated in live-electronics projects and controlled through the global messaging system provided by CLEF. The parameters of the tactile module could be accessed through the OSC namespace and controlled either explicitly or implicitly, i.e. as a function of other variables in the environment. The conceptual structure of the tactile module, i.e. the tactuator, can be seen in Figure 2.3. A screenshot showing the graphical user interface of the tactile notification module and the pattr client window showing its namespace can be seen in Figure 2.4.

Results from evaluations of the tactile display indicated that the haptic modality was a promising communication channel for conveying musically relevant information, and that tactile notifications could effectively become a parameter included among other musical parameters in scores for pieces for live electronics. Further improvements on the tactile module have been made since the initial study by Schumacher et al. (2013). Along with other changes, a vibrotactile metronome module has been added to the functionality.
2.4. TACTILE FEEDBACK IN LIVE-ELECTRONICS PERFORMANCE

Figure 2.3: Structure of a tactuator CLEF module.

Figure 2.4: Screenshot of the tactile notification module GUI and client *pattr* client window.
Chapter 3

Methodology

This section gives justification for the choice of methods and discusses the methodology’s limitations.

3.1 Procedure

The following points outline the project procedure:

- Analysis of mixed works for live electronics
- Physical characterization of the tactile display
- Perceptual characterization of the tactile display
- Design of a set of tactons: defining a group of basic tactile building blocks
- Evaluation of the designed set of tactons
- Development of a prototype: designing tactile notification presets that can be loaded into CLEF
- Summary of results: setting up guidelines for the design of actuator signals for CLEF

3.2 Analysis of mixed works for Live Electronics

For any study that involves a design process, it is important to first define the scope of the project in terms of design goals, before moving on to the next phase of the project. In order to define the design goals of this project, and to determine which type of information that might be relevant to communicate to the musician during a live-electronics performance, a number of other mixed works for live electronics\(^1\) were studied. Especially the mixed work *Wooden Stars* by Goef Holbrook was analyzed (de Oliveira Rocha, 2008) in order to get an insight into the pitfalls involved in live-electronics performance. Moreover, a literature study on the topic (see e.g.

\(^{1}\)Following the listening list of the course MUCO540 Advanced Digital Studio Composition 1 at McGill University. See full list here: [http://www.music.mcgill.ca/~marlon/MUCO541/2013/Listening_List.htm](http://www.music.mcgill.ca/~marlon/MUCO541/2013/Listening_List.htm)
3.3. PHYSICAL CHARACTERIZATION OF THE TACTILE DISPLAY

McNutt (2004); de Oliveira Rocha (2008)) was carried out in order to gain deeper understanding of the problem domain and the potential needs of the musical performer in these contexts. The outcome of this part of the study was the definition of a set of message types that may be conveyed to the musician through the haptic channel during live-electronics performance. The definition of these message types will facilitate future design of mapping strategies between musical cues and tactile events.

3.3 Physical Characterization of the Tactile Display

3.3.1 The Tactile Display

The actuators used in this project were two VPM2 flat rotating eccentric masses from Solarbotics Ltd\(^2\). The actuator was driven using a ULN2803A\(^3\) IC unit as motor driver. This was connected to an Arduino Uno board generating a Pulse Width Modulation (PWM) signal. The PWM duty cycle (with available values ranging from 0 to 1) is the only parameter which can be controlled by the user.

For the experimental set-up, two vibrating disk motors driven using PWM output from the Arduino Uno board were placed on the torso of the subject using a velcro band. A positioning on the back of the torso was chosen since such a set-up will not hinder the performer’s musical expressivity or movement. The actuators were placed symmetrically about the spine. The software used in the experiments was coded in Max and the communication between the host computer and Arduino board was achieved using the Firmata\(^4\) protocol.

![The vibrotactile display.](image1.png)

![Two actuators are placed inside the red piece of fabric.](image2.png)

Figure 3.1: The hardware prototype.

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\(^2\)https://solarbotics.com/download.php?file=159e

\(^3\)http://pdf.datasheetcatalog.com/datasheet/SGSThomsonMicroelectronics/mXssxrt.pdf

\(^4\)http://www.firmata.org/
3.3.2 Accelerometer Measurements

The data collected at 192 kHz using the accelerometer attached to the actuator allowed us to investigate several characteristics of the specific vibrating motors chosen for the project. A PCB 352C23\(^5\) 1-axis accelerometer was used. The accelerometer was fixed on the top face of the actuator using a small piece of Petro Wax\(^6\). The actuator vibration for ten discrete PWM duty cycle values (0.1 to 1.0) were measured to assess the actual amplitude of vibration (average power) and average peak amplitude frequency at each step. Average peak amplitude was defined as a weighted average of the most significant frequency peaks found in the spectrum. Average power was expressed in dB, with maximum amplitude (0 dB) used as reference power. The analyses were performed up to 1000 Hz in the original spectrum, which is the upper limit for tactile perception. Moreover, the ramp-up (i.e. the time to reach the peak vibration amplitude) and ramp-down (i.e. the time from full amplitude of the PWM signal to the moment where the noise floor in the accelerometer signal was reached) were measured.

![Figure 3.2: The experimental set-up for the accelerometer measurements.](image)

3.4 Perceptual Experiments

In order to design a meaningful vibrotactile notification system for CLEF, it is of great importance to first ascertain what is perceptually significant in terms of actuator signals. Three experiments were designed to estimate: vibrotactile absolute threshold, vibrotactile differential threshold and vibrotactile temporal threshold. To ensure good experimental design and comprehensible user interfaces, the perceptual experiments were designed in an iterative manner. Before conducting the final perceptual experiments, pilot studies with other lab members were carried out. Several adjustments were made after initial pilot studies. It was found that the subjects needed to wear headphones with masking noise in order not to be biased by auditory cues from the vibrating motors. Moreover, some of the interfaces had to be modified; GUIs were redesigned, and in some cases the GUIs were replaced by external keyboards in order to improve comfort.

The vibrotactile stimuli used in the experiments had a length of 500 ms and were switched on and off immediately; the PWM duty cycle was set to go directly

\(^5\)http://www.pcb.com/Products.aspx?m=352C23
from 0 to 1 for the attack and 1 to 0 for the release respectively. To reduce the risk for biased responses caused by auditory cues, the subjects wore headphones with a low level of pink noise during the entire experiment. The level of the noise was adjusted so as to mask the sound produced by the vibrating motors for the highest duty cycle level.

All subjects signed an informed consent form that was approved by the McGill University Research Ethics Board before participating in the experiments. Some of the participants participated in several of the perceptual experiments, some only in a single experiment. Before each perceptual experiment, the instructor (i.e. the author) gave a short introduction and description of the task. The instructor was present during all experiments to answer questions and provide help, if needed.

3.4.1 Vibrotactile Absolute Threshold

The vibrotactile absolute threshold is the lowest intensity level, i.e. the lowest duty cycle, at which a vibrotactile stimulus can be detected. A standard method of constant stimuli was used in order to estimate vibrotactile absolute threshold. A total of 8 subjects (4 men and 4 women, 21-31 yrs) participated in the experiment. A set of 5 equally spaced stimulus intensities, corresponding to duty cycles of the PWM ranging from 0.1 to 0.5, was chosen. Each stimulus level was repeated six times in a randomized order, thereby giving a total of 30 stimuli. The length of each stimulus was set to 500 ms. In order to reduce the risk for adaptation effects, i.e. a decrease in the sensory magnitude of a stimulus (Verillo and Gescheider, 1992; Gunther and O’Modhrain, 2003), 5 stimuli were presented on the left actuator, whereafter 5 were presented on the right actuator. As noted by van Erp (2002), the time to recover from a decrease in sensory magnitude (the recovery time) is about half the time for adaptation. A pause of the same length as the vibrational pattern was introduced after each shift of actuator, in order to ensure a sufficient recovery time.

The subject was asked to press the space-bar of an external keyboard every time (s)he could perceive a stimulus. The proportion of detected stimuli was annotated for each stimulus intensity. Vibrotactile absolute threshold was defined as the point where the proportion of detected stimuli was above 50 %.

3.4.2 Vibrotactile Differential Threshold

The vibrotactile differential threshold corresponds to the change in duty cycle at which an increase in a detected stimulus can be detected. A two-alternative forced-choice experiment (2AFC) for “same” or “different” discrimination was used in order to approximate the difference in vibrotactile stimulus intensity level needed for the subject to perceive two stimuli as having different intensities. The aim was to investigate which difference in duty cycle that was required in order to ensure robust discrimination.
CHAPTER 3. METHODOLOGY

A total of 10 subjects (5 men and 5 women, 21-31 yrs) participated in the experiment. Some of the participants had also participated in the absolute threshold experiment described above. A number of 81 stimulus pairs of various intensity levels were presented in a randomized order. Each stimulus pair consisted of two vibrotactile pulses of a length of 500 ms, separated by a pause of randomized length (750 to 1500 ms). The 81 stimulus pairs consisted of all possible combinations of duty cycles within the perceptual threshold, i.e. 0.2-1.0 (lower level set after the absolute threshold test), separated with a step size of 0.1. This gave a total of $9^2 = 81$ stimulus pairs, where 9 pairs were combinations of the same intensity and 72 were pairs with different intensities.

A total of 5 stimulus pairs were presented on the left actuator, whereafter a pause for recovery was introduced in order to reduce the risk of adaptation effects. The active actuator then changed from the left to the right side and the pattern of 5 stimuli continued. The vibrotactile pattern of 5 stimuli was approximated to take around 15 seconds in average. A pause of 15 seconds was thus introduced between each shift of actuator, enabling a total recovery time of 30 seconds.

The subject was asked whether (s)he could detect a difference in stimulus intensity between the two vibrotactile pulses by pressing one of two assigned keys labeled “same” or “different” on an external keyboard. The subject had 4.5 seconds to answer before next stimulus was presented. If no answer was recorded for one stimulus pair the answer was set automatically to “same”, since it was assumed that a too long response time indicated that it was hard to decide whether the stimuli were actually different, thereby indicating that they were probably interpreted as being very similar.

Results collected from the experiment were analyzed using a logistic regression model. The obtained results provided guidelines concerning required difference in stimulus intensity for robust perceptual discrimination.

3.4.3 Vibrotactile Temporal Threshold

The vibrotactile temporal threshold, i.e. the gap detection threshold, is time needed for two vibrotactile stimuli presented after each other to be perceived as two separate succeeding pulses. A 1-up-1-down forced choice fixed-size staircase (FSS) discrimination test was used in order to estimate gap detection threshold for two vibrotactile stimuli presented after each other. A total of 10 subjects participated in the experiment (5 men and 5 women, 21-38 yrs).

Two vibrotactile stimuli (of 500 ms) separated by a short pause were presented to the subject. The subject was asked whether (s)he could detect one stimulus or two stimuli. The GUI presented to the participants can be seen in Figure 3.3. If the subject could detect one stimulus, the pause between the succeeding stimuli was increased with one step-size. If the subject could detect two stimuli, the pause was decreased with one step-size. The size of the upward step was chosen to be three times the size of the downward step, as suggested by Kaernbach (1991) and García-Pérez (1998). Step-size was set to 10 ms up and 3.33 ms down.
3.5. TACTON DESIGN

The start value of the pause between two stimuli was chosen after a preliminary series of experiments on the author, where a range of 15 pauses between stimuli ranging from 0 to 150 ms were presented in a random order using pulses of 200, 400, 600 and 800 ms respectively. Annotations of whether one or two stimuli could be detected were done. The test was carried out for duty cycles of 0.5 and 1.0. Results from this initial phase indicated that temporal threshold should fall within 0 to 40 ms. The initial pause between the stimuli was thus set to 50 ms, in order to ensure a time time difference above the perceptual threshold.

The one-up-one-down forced choice staircase discrimination test was carried out for all duty cycles ranging from 0.2 (which was found to be the absolute threshold, see Section 4.3.1) to 1.0, with a step-size 0.2. After each staircase a pause of 60 seconds was provided and the active actuator was changed, in order to reduce the risk for adaptation effects. The staircase continued until 11 response-changes, i.e. when the change of direction in subject response (one or two perceived pulses) had changed 11 times.

The time threshold was defined as the average of the steps yielded in every change of direction, with the first change of direction discarded. In other words, the average was computed for 10 reversals.

3.5 Tacton Design

The first step when creating a set of tactons is to identify the parameters of vibration that can be used to encode information (Hoggan and Brewster, 2007). Therefore, the perceptual and physical experiments had to be conducted before the design of the tactons. Following the results from the perceptual experiments, a set of tactons were designed in order function as basic building blocks for information display.
3.5.1 Defining a Set of Tactile Building Blocks

When it comes to absolute identification of stimuli, the span of absolute judgement and the span of immediate memory impose severe constraints on the amount of information that we are able to remember. As early as in 1956, Miller presented results that indicated that the short time memory has a limited capacity of storing 7 items at a time, plus or minus 2. Therefore, no more than 8 tactons were used as basic building blocks for information display. Each of the 8 tactons was defined by a unique ADSR envelope. In terms of duty cycles, the tactons all had a range of 0.2 to 1.0.

A rough approximation of temporal dimensions of the tactons was first found by adjusting the ADSR-envelopes for a locus on the fingertips of the author. The tactons were then tested on the back of the torso and adjusted if needed. A pilot experiment with the 8 defined ADSR envelopes was conducted with one participant, whereafter further adjustments were made to fine-tune the envelopes. The purpose of the fine-tuning of the vibration envelopes was to produce stimuli that were perceptually as far away from each other as possible.

3.5.2 Development of a Prototype - Defining a Vibrotactile Library

Following the analysis of the experimental results and the definition of tactile building blocks, a Max patch serving as a library of vibrotactile cues (“tactile presets”) was developed. The purpose of this prototype was to give the user a possibility to try out different tactons and to experiment with different mappings between tactile and musical cues. The prototype was developed as an external Max-patch which could be used in combination with the tactile module for CLEF already developed by Schumacher et al. (2013).

3.6 Evaluation of Tactons

The purpose of this experiment was to optimize the set of tactons and to evaluate the user’s ability to identify the tactons described in the previous section.

3.6.1 Tacton Identification

Five participants (4 men, 1 woman, 27-35 yrs) participated in the experiment. Due to time constraints, the subjects were all students or PhDs at the McGill Music Technology Department. Most of the participants had therefore already had some previous exposure to haptic feedback prior to the study. The same tactile display as in the previously described perceptual tests was used, and the presented stimuli alternated between left and right side. The experiment was encoded in Max, sending OSC messages to the vibrotactile module through the CLEF message bus. Each tacton could thus be defined as an event that was triggered by a bang in an external Max patch.
3.6. EVALUATION OF TACTONS

A total of 8 tactons were used in the experiment. Headphones presenting masking pink noise were worn during the entire experiment, so that auditory cues from the actuators could not be used to identify the tactons. Descriptive names were used to represent the tactons since this was considered to reduce learning time. The experiment was divided into three different phases. In the first phase, the Learning Phase, the subjects were instructed to learn the names associated with the 8 vibrotactile stimuli. The participants were presented with a GUI (see Figure 3.4) that enabled them to play back the 8 tactons as many times as they wanted by clicking on the name of each tacton. Subjects were allowed to use 5 minutes for this phase but could proceed to the next phase after trying out each stimulus at least 3 times.

![GUI for the evaluation experiment.](image)

In the second phase of the experiment, the Practice Phase, subjects got a chance to practice before the actual evaluation phase the Test Phase. 9 tactons were presented to the subject in a randomized order, giving 9 trials. After each stimulus, the participant was asked to identify the tacton, indicating their response by selecting one of the buttons configured as in Figure 3.4. No time limit was imposed on the participants and no feedback regarding correctness of the response was provided during the experiment. The stimuli order was randomized across subjects. After the 9 trials, the subject was allowed to proceed to the next phase of the experiment.

A pause of 30 s was provided between the second and third phase of the experiment. In the final phase of the experiment, the subject’s ability to identify the tactons was tested. A set of 64 stimuli was presented to the subjects, who identified the tactons by selecting the corresponding labeled button. Each tacton was presented 8 times for a total of 64 trials in a randomized order, with the constraint
that a pause of 30 s was introduced after each set of 16 trials. The participant was allowed to play each tacton twice, by pushing a button entitled “play again”. Several aspects of the participant’s performance were measured, see summary in Table 3.1.

<table>
<thead>
<tr>
<th>Measured Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning time</td>
<td>time used in phase 1</td>
</tr>
<tr>
<td>Practice time</td>
<td>time used in phase 2</td>
</tr>
<tr>
<td>Test time</td>
<td>time used in phase 3</td>
</tr>
<tr>
<td>Answering time</td>
<td>time from presented stimuli until answer</td>
</tr>
<tr>
<td>Identification rate</td>
<td>number of correctly identified tactons</td>
</tr>
</tbody>
</table>

Table 3.1: Measured aspects of the participant’s performance.

### 3.7 Methodological Critique

In this study, the research question was investigated through physical experiments, pilot experiments involving other lab members and perceptual user studies. Mostly quantitative methods were used, although some more qualitative approaches were adopted in the initial stages of the design of the perceptual experiments. The design of the tacton library was conducted with an exploratory and qualitative focus, aiming to give insight into how vibrotactile stimuli could be designed for the particular context of musical performance.

#### 3.7.1 Sample Selection

Since the experimental design was improved after initial tests and pilots, it is likely that the obtained results are somewhat reliable, although the time constraints of the survey naturally resulted in a relatively small sample size. As for the perceptual experiments, a sample size of 8-10 subjects was used, giving a sufficient number of observations to carry out statistical analysis on collected results. For the final evaluation of the tactons, it would have been preferable to run the experiment for a larger number of participants. Nevertheless, the total number of observations for each tacton was still 40 trials. Although many of the subjects who participated in the final evaluation test were musicians or participants who had had some musical training, it would have been preferable to run the tests on participants who had experience of live-electronics performance.

Regarding the background of the participants in the experimental studies, it is worth noting that the total number of subjects that were affiliated with the Music Technology Area at McGill University was 12, and the number of external subjects with no experience from the field of music technology was 6. Many of the subjects participated in multiple of the perceptual tests and the evaluation, which might have had an influence on the results. The total age range was 21 to 38 years. Since sensory perception can be affected by age, this may also have influenced the results.
3.7. METHODOLOGICAL CRITIQUE

3.7.2 Validity

Validity involves how successful research is in achieving what it sets out to achieve and if a causal link can be made between variables. As for the physical experiments with the accelerometer, the measurements provided data related to the physical characterization of the actuators. For the perceptual experiments, results related physical correlates to perceptual ones, and the causal link is therefore somewhat intuitive. Pilot experiments carried out in the beginning of the design process ensured that the questions that subjects had to answer were well defined and well drafted. In this sense, pilot tests reduced the risk that collected data was influenced by misunderstandings of the task or a confusing set-up. Due to the relative complexity of the stimulus set in the final tacton evaluation experiment, it is hard to draw conclusions regarding correlations between physical and perceptual entities. However, we may still draw conclusions about the perceptual robustness of discrimination of the stimuli.

3.7.3 Reliability

Reliability is the replicability of the research and the accuracy of the research techniques used. The results obtained in this study are likely to be somewhat replicable, although the results from future investigations of vibrotactile perception might of course deviate somewhat from the results presented in this study, depending on experimental design and sample selection. Nevertheless, research methods adopted in this study were designed to reduce the impacts of such factors. In general, it is hard to achieve similar results for experiments involving sensory perception since both experimental set-up and individual differences among subjects, such as gender and age, may heavily influence the results. It is also possible that familiarity with vibrotactile stimuli may influence obtained results.

When it comes to the definition of the vibrotactile message types defined in Section 4.1.1, more quantitative methods for category classification could have been used, however due to this study’s limited time frame this was not part of the scope of this project.

3.7.4 Generalizability

Findings from the experiments carried out in this study are specific to the particular set-up, i.e. to this particular vibrotactile display. The findings should not be generalized to any other set-up with a different spatial locus or vibrotactile actuator. Another reason why results from this study should not be generalized is the relatively small sample size used. However, results presented in this study might still be of interest in projects where the same type of vibrating disk motors are used.
Chapter 4

Results

This chapter summarises the results from the experiments and describes the design process for the development of a library of tactons for CLEF.

4.1 Analysis of Mixed Works for Live-Electronics

Analyses of multiple compositions, as well as a literature review, were carried out. The main focus was put on the piece Wooden Stars by Geof Holbrook (de Oliveira Rocha, 2008). This piece is composed for percussion and electronics, and allows triggering, stop and sustain of several audio files (fixed media) through a Max patch.

In Wooden Stars, effects of acceleration and deceleration are explored. The piece involves fixed media, but the piece is nevertheless characterized by a high level of interactivity. Electronic parts are controlled by a Max patch, allowing the performer to trigger, stop and sustain multiple audio files by pressing a specific pedal. In total, the piece has 51 triggers (stop, start of audio files etc.) which can be activated by pushing a pedal. A Max patch provides the performer with means of synchronisation by displaying a timer that enables the performer to keep in synch with events indicated in the score and displaying the waveforms of the pre-recorded audio files. A cursor progressing through the audio file helps the performer to keep accelerandos and ritardandos in sync with the fixed media. To conclude, synchronisation is a key concept in the piece. (de Oliveira Rocha, 2008)

Conclusions from the analysis of the musical cues and annotations of events that should be triggered according to the transcription of Wooden Stars resulted in a list of different messages that may be needed in the interaction between technology and musician in the context of live-electronics performance. After sorting this set of messages, they were divided into four different sub-categories, depending on their message type. One may suggest that the design goal of the vibrotactile module for CLEF should be to enable encoding of the following message types in the vibrotactile dimension:

- Feedback messages
4.1. ANALYSIS OF MIXED WORKS FOR LIVE-ELECTRONICS

- Synchronization and coordination messages
- Notification messages
- Background and ambient messages

4.1.1 Message Types

Feedback Messages

These messages relate to how the system responds to actions performed by the musician. In other words, this category represents all the messages that are the result of an action performed by the musician. The following list illustrates some examples of messages that go within this category:

- Confirmations of successful start or stop upon an action, e.g. message confirming that a button press has been performed to start playing fixed media.
- Confirmation of successful switching between parameters or program states.
- Confirmation of successful negotiation of prosthetic devices, e.g. activation or deactivation of microphones, loudspeakers, pedals, sensors etc.
- Confirmations from other musicians, used during a collaborative performance involving multiple musicians.
- Continuous feedback during an action (compare to the force-feedback provided by a knob on a mixer), e.g. in circumstances when live-signal processing is used for effects involving overdubbing, spatialization filters, delays and so on.
- Continuous feedback of stereo effects and virtual placement of sound sources.

Synchronization and Coordination Messages

This category includes all messages that should prepare the musician for a future event that is mediated in the score of the musical piece, i.e. messages that inform the user what is happening in the interaction beyond the point of what the user is currently doing. Such messages may improve the coordination and synchronization of a performance. Examples of such messages follow below:

- Countdowns to musical events and actions, involving indications of where to start or stop an action. This is the type of information that would usually be mediated through a musical score or communicated by a conductor.
- Indications of tempo, meter changes, or messages concerning expressive qualities such as dynamics and articulation.
- Synchronization messages from other members of the ensemble in a collaborative performance.
- Synchronization messages concerning the interaction between musician and fixed media.
CHAPTER 4. RESULTS

Notification Messages

This category involves messages related to the technical set-up and the live-electronics system used during the performance. These messages report the current state of a system, independent of the actions of the musician. Therefore, these messages do not depend on any actual interaction with the performer. Examples of such messages are:

- Alert and error messages, e.g. warning messages communicating that there is a risk for feedback or that an access has been denied to an electronic device, or a low battery level of a device.

Background and ambient messages

The final category consists of messages that are to be conveyed in the background of the interaction. This could for example be subtle effects such as continuous signals, ongoing metronome click-tracks or other more immersive, low-amplitude, messages that can be used to affect the overall experience of the user.

4.2 Physical Characterization of the Tactile Display

4.2.1 Accelerometer Measurements

Ramp-up time required for the motor to go from zero to full amplitude was lower than 15 ms for discrete duty cycle levels ranging from 0.1 to 1.0. The ramp-down time ranged from 400 to 610 ms for duty cycles of 0.2-1.0 (the time for a duty cycle of 0.1 could not be consistently measured due to low signal-to-noise ratio). A summary of ramp-down times for every PWM value ($X_0$) can be found in Table 4.1.

<table>
<thead>
<tr>
<th>Duty cycle $X_0$</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>t (ms)</td>
<td>400</td>
<td>490</td>
<td>540</td>
<td>580</td>
<td>580</td>
<td>580</td>
<td>600</td>
<td>610</td>
<td>610</td>
</tr>
</tbody>
</table>

Table 4.1: Ramp-down times for different duty cycles.

As seen in the table, a duty cycle of 0.2 resulted in a 400 ms ramp-down. However, since results from the vibrotactile absolute threshold experiment suggested that duty cycles below 0.2 are below perceptual threshold (see Section 4.3.1), we can consider the longest relevant ramp-down time for the actuators to be approximately 200 ms (ideally one can subtract the 400 ms of ramp-down time corresponding to 0.2 amplitude from all measured ramp-down times, since what happens in those 400 ms is not perceivable). It has to be remarked that these values might be influenced by our experimental set-up where the actuator was placed on a table, and that results might change when the actuator is in contact with a user’s skin.
4.2. PHYSICAL CHARACTERIZATION OF THE TACTILE DISPLAY

Figure 4.1 and 4.2 clearly show that both amplitude and frequency are correlated with the PWM duty cycle and cannot be directly controlled with this specific type of actuator. As seen in both figures, the relationships are not linear. Frequencies show a clear tendency to stabilise around 350 Hz for the higher end of the duty cycle range (for duty cycles larger than 0.5). The frequency range varies from 140 to 380 Hz. The sensitivity peak, i.e. the frequency that lowers the threshold of perception the most, can be found around 250 Hz for tactile perception (Verillo and Gescheider, 1992). The sensitivity peak’s corresponding duty cycle, annotated with a red dotted line in Figure 4.1, can be found somewhere between 0.3 and 0.4.

![Figure 4.1: Average peak amplitude frequency at each discrete PWM duty cycle step from 0.2 to 1. The average peak amplitude is a weighted average of the most significant frequency peaks found in the spectrum. The red dotted line corresponds to the tactile sensitivity peak frequency.](image)

![Figure 4.2: Average power level at each discrete PWM duty cycle step from 0.2 to 1, expressed in dB, with maximum amplitude (0 dB) used as reference power.](image)
4.3 Perceptual Characterization of the Tactile Display

4.3.1 Vibrotactile Absolute Threshold

All subjects could detect all of the stimuli of intensity levels from 0.2 to 0.5. As for the stimuli with a duty cycle below 0.2, only 4.2% of the presented stimuli were detected. Duty cycles below 0.2 could thus be considered to be below threshold. We can conclude that duty cycles below 0.2 should not be used when designing tactons with this particular set-up, i.e., with a configuration with a vibrating disk motor actuator with a locus on the back of the torso.

4.3.2 Vibrotactile Differential Threshold

The overall aim of the differential threshold experiment was to investigate which difference in duty cycle ($X_0$) that was required in order to ensure robust discrimination between vibrotactile stimuli. It has previously been found that a difference of at least 20-30% in amplitude is necessary for such robust discrimination (Choi and Kuchenbecker, 2013). An assumption before carrying out the differential test was that not only the difference between two vibrotactile stimulus but also the order of the presented stimuli would affect vibrotactile perception (i.e., that the results would depend on whether the lowest or the highest intensity level was presented first).

From the 810 observations collected from the perceptual experiment an average correctness was calculated for each difference in duty cycle, i.e., for each $X_1$. The correctness was defined as the percentage of the observations where a stimuli-pair was rated as “different” where there was actually a physical difference in duty cycle, i.e., a $X_1$ of 0.1 or more. The average correctness was computed for each of the 72 stimuli pairs that were different in terms of intensity. Results, collapsed over subjects, can be seen in Table 4.3. As seen in the table, for intensity differences equal to or larger than 0.3, correctness is above chance.

<table>
<thead>
<tr>
<th>$X_0$</th>
<th>$X_1$</th>
<th>%</th>
<th>$X_1$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.32</td>
<td>39.90</td>
<td>0.1</td>
<td>25.63</td>
</tr>
<tr>
<td>0.3</td>
<td>0.35</td>
<td>43.26</td>
<td>0.2</td>
<td>37.86</td>
</tr>
<tr>
<td>0.4</td>
<td>0.37</td>
<td>46.63</td>
<td>0.3</td>
<td>55.00</td>
</tr>
<tr>
<td>0.5</td>
<td>0.40</td>
<td>49.99</td>
<td>0.4</td>
<td>63.00</td>
</tr>
<tr>
<td>0.6</td>
<td>0.43</td>
<td>53.35</td>
<td>0.5</td>
<td>81.25</td>
</tr>
<tr>
<td>0.7</td>
<td>0.45</td>
<td>56.72</td>
<td>0.6</td>
<td>83.33</td>
</tr>
<tr>
<td>0.8</td>
<td>0.48</td>
<td>60.09</td>
<td>0.7</td>
<td>90.00</td>
</tr>
<tr>
<td>0.9</td>
<td>0.51</td>
<td>63.45</td>
<td>0.8</td>
<td>95.00</td>
</tr>
<tr>
<td>1.0</td>
<td>0.53</td>
<td>66.81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Required duty cycle differences ($X_r$) for robust discrimination. Table 4.3: Correctness for actual duty cycle difference ($X_1$).

By dividing the 72 stimulus pairs into two subgroups depending on whether a low stimulus level was presented first or second, two groups of 36 pairs each were ob-
4.3. PERCEPTUAL CHARACTERIZATION OF THE TACTILE DISPLAY

tained. In order to investigate if the order of the stimuli influenced the vibrotactile
differential threshold, a two-sample t-test for comparing means was performed on
the two samples (since \( n > 30 \)). For a 95 % confidence interval a p-value of 0.97 was
obtained, hence the null hypothesis of that the two distribution’s true difference in
means is equal to zero could not be rejected. Thus we could conclude that intensity
discrimination, in terms of average correctness, is not affected by the order in which
the stimuli are presented.

Consequently logistic regression analysis was performed on the data set. Logistic
regression (Peng et al., 2010) has the advantage of predicting the probability of an
event outcome from a set of predictors (in our case start value of the duty cycle and
difference in duty cycle between two stimuli). The proposed model for probability
of a perceived difference was defined as follows:

\[
\logit P = \beta_0 + \beta_1 X_0 + \beta_1 X_1 + [\beta_2 \ldots \beta_{10}][X_2 \ldots X_{10}] + \epsilon \tag{4.1}
\]

Where \( \beta_n \) corresponds to the regression coefficients, \( X_0 \) and \( X_1 \) are the explanatory
variables (start value of duty cycle, i.e. the first stimulus intensity, and absolute
difference in duty cycle, respectively), \( [X_2 \ldots X_{10}] \) a vector of dummy variables with
Corresponding coefficients \( [\beta_2 \ldots \beta_{10}] \) and \( \epsilon \) is an error term. Dummy variables
are incorporated in the regression model in order to account for effects caused by
individual differences in sensory perception among the subjects, i.e. that some
subjects perceived the stimuli as consistently being stronger or weaker. Subject 10
was set as reference for the dummy variables. Clustered robust standard errors were
used in order to correct standard errors for model specification.

<table>
<thead>
<tr>
<th>( \beta ) estimates</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_0 )</td>
<td>-0.67 ***</td>
</tr>
<tr>
<td>( X_0 )</td>
<td>2.09 ***</td>
</tr>
<tr>
<td>( X_1 )</td>
<td>7.75</td>
</tr>
</tbody>
</table>

Observations | 810

Table 4.4: Regression coefficients with standard deviation (*** \( p < 0.001 \)).

The obtained \( \beta \) estimates, i.e. the resulting regression coefficients, can be found
in Table 4.4. According to the results, both absolute difference in duty cycle and
start value of the duty cycle was were significant predictors of the probability of a
response equal to “different” (\( p < 0.001 \)). The logit function was transformed back
to the probability scale according to the formula specified below. The resulting
probabilities for \( X_0 \) from 0.2 to 1.0 and \( X_1 \) ranging from 0.2 to 0.8 were subsequently
computed, and the results are visualized in Figure 4.3 and 4.4.

\[
P_{\text{different}} = \frac{1}{1 + e^{-x\beta}} \tag{4.2}
\]

Where \( x\beta \) is the resulting model:

\[
x\beta = -0.67 - 2.09X_0 + 7.75X_1 \tag{4.3}
\]
CHAPTER 4. RESULTS

Figure 4.3: Predicted probability versus difference in duty cycle $X_1$ plotted for different start values $X_0$.

Figure 4.4: Predicted probability versus absolute difference in duty cycle $X_1$ for different start values $X_0$ (red intensity signifying low probability values).
4.3. PERCEPTRAL CHARACTERIZATION OF THE TACTILE DISPLAY

In order to ensure robust discrimination between vibrotactile stimuli of different start-values \(X_0\) we opted for a predicted probability of \(P = 0.8\) and computed the required difference in duty cycle \((X_r)\) in order to achieve such a probability for a fixed duty cycle start value \((X_0)\). The obtained values can be found in Table 4.2 (see page 30). As seen in the table, the required duty cycles range from 0.32 to 0.53, corresponding to a difference in percentage of approximately 40 to 67 % (if the total range is set to \(1 - 0.2 = 0.8\)). The obtained percentage values can be compared to the confirmed results of 20 to 30 % in amplitude difference, as suggested in Choi and Kuchenbecker (2013). The fact that this study had strict constraints (the 80 % predicted probability) might be the reason for this increase from 20 to 30 to 40 to 67 % in our case.

After analysis of the values introduced in Table 4.2 we propose information encoding in terms of the intensity parameter consisting of any combination of the following couplings of discrete duty cycles. Presented in Table 4.5 (with Weber fractions), these couplings are likely to ensure robust intensity discrimination and thus effective information display. In contrast to the findings in Choi and Kuchenbecker (2013), the Weber fractions are not clustered around a ratio of 1.1 to 1.3 in difference.

<table>
<thead>
<tr>
<th>Stimulus 1</th>
<th>0.2</th>
<th>0.2</th>
<th>0.3</th>
<th>0.3</th>
<th>0.4</th>
<th>0.4</th>
<th>0.5</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus 2</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Weber Fraction</td>
<td>2.5</td>
<td>3.0</td>
<td>2.33</td>
<td>2.67</td>
<td>2.0</td>
<td>2.25</td>
<td>1.8</td>
<td>2.0</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Table 4.5: Suggested intensity couplings for effective information display.

4.3.3 Vibrotactile Temporal Threshold

Box plots showing the time needed for the subject to perceive two separate succeeding vibrotactile signals (not a single continuous signal) can be seen in Figure 4.5. The results are collapsed over subjects. 4 outliers can be detected in the plot. The cause of the two outliers found for duty cycles of 0.6 is not known. As for the the low-value outlier found for duty cycle 0.8, it is worth mentioning that the participant from which this data point originates from sometimes answered that the stimuli were perceived as being “different”, despite that fact that the actual time difference was 0 ms.

The relatively short box plots for duty cycles of 0.6 and 0.8 indicate that there was a relatively high level of agreement among the subjects. Subjects held more different opinions concerning the duty cycles 0.2 and 0.4. In general, interquartile ranges are higher for the lower duty cycle values. The longer whiskers for duty cycles 0.2 and 0.4 suggest that the subject’s view varied among the quartile groups. Short whiskers, or even no whisker, as can be seen for duty cycle 0.6, indicate that the subject’s views were similar. A detailed summary of the results can be seen in Table 4.6. As seen in the table, the mean time (ms) was highest for a duty cycle of 0.2 and and lowest for a duty cycle of 0.8.
Figure 4.5: Box plots showing required time difference for two stimuli to be perceived as different.

Table 4.6: Descriptive statistics for required mean time differences for two succeeding stimuli (ms).

<table>
<thead>
<tr>
<th>DUTY CYCLE</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>48.77</td>
<td>31.47</td>
<td>26.17</td>
<td>20.11</td>
</tr>
<tr>
<td>MEDIAN</td>
<td>48.17</td>
<td>28.50</td>
<td>22.01</td>
<td>20.51</td>
</tr>
<tr>
<td>MIN</td>
<td>30.67</td>
<td>18.34</td>
<td>15.34</td>
<td>10.34</td>
</tr>
<tr>
<td>MAX</td>
<td>67.34</td>
<td>56.34</td>
<td>46.34</td>
<td>31.34</td>
</tr>
<tr>
<td>STD. DEV.</td>
<td>11.29</td>
<td>11.84</td>
<td>10.84</td>
<td>5.56</td>
</tr>
</tbody>
</table>

4.4 Tacton Design

4.4.1 Tactile Building Blocks

Initial ADSR envelopes were tested on the fingertips of the author, and multiple intensities and temporal patterns were investigated. After defining an initial set of possible tactons, the number was narrowed down to 8 tactons that were considered to be perceived as having different vibrotactile envelopes by the author. Since sensory perception on the back of the torso is lower than on the fingertips, the majority of the tacton’s envelopes had to be adjusted in terms of temporal length, in order to be distinguishable from each other when presented on the back. After multiple pilot tests and adjustments, a set of eight tactons were finally suggested, as seen in Table 4.7. A summary of the envelopes of the tactons defined in Table 4.7 can be found in Figure 4.6.
4.4. TACTON DESIGN

Figure 4.6: Tacton envelopes.
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<table>
<thead>
<tr>
<th>No</th>
<th>Tacton</th>
<th>Attack</th>
<th>Sustain</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Click</td>
<td>0</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Buzz</td>
<td>70</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>Bump</td>
<td>15</td>
<td>110</td>
<td>325</td>
</tr>
<tr>
<td>4</td>
<td>Reversed bump</td>
<td>325</td>
<td>110</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Ramp up</td>
<td>900</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Ramp down</td>
<td>0</td>
<td>0</td>
<td>900</td>
</tr>
<tr>
<td>7</td>
<td>Double click</td>
<td>click + 90 ms pause + click</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Double buzz</td>
<td>buzz + buzz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7: A(D)SR for tactons (ms).

#### 4.4.2 Development of a Prototype - Defining a Vibrotactile Library

After having defined a set of basic building blocks that could be combined into more complex stimuli, a prototype of a vibrotactile library was developed. The purpose of developing a prototype was to provide the user with a simple patch where (s)he could try out different tactile stimuli on the fly. However, the vibrotactile library could also be used within a musical piece.

The library was developed as an external Max patch that could be used together with the tactile module for CLEF. Conceptually, tactons in the vibrotactile library are defined as events, similar to musical events in CLEF. This design allows for tactons to be triggered within other musical events, and to be cued in the CLEF score. A sketch describing the structure can be seen in Figure 4.7.

With the different message types (defined in Section 4.1.1) in mind, a table of suggested mappings between different message types and vibrotactile stimuli was initially created. Results can be found in Table 4.8. We can conclude that the four different message categories differ in terms of urgency. The concept of urgency in the context of vibrotactile information display has previously been investigated by Saket et al. (2013) and Hoggan and Brewster (2007).

It could be suggested that different levels of urgency in the tactile notifications may help the user to prioritise the incoming tactile information. One suggestion could therefore be to communicate the level of urgency of a tacton in the intensity parameter, or in temporal patterns. Strong intensities could thereby be used to communicate messages with high priority. Low intensity signals could signify messages with low priority. Moreover, repeated fast temporal patterns or rhythms could represent urgent and important messages.

The different tactons presented in Table 4.8 were sorted whereafter a number of different tacton categories (see Table 4.9) were defined and incorporated in the tactile library. This grouping of tactons into different categories is motivated by the fact that such “chunks”, or groups of items, might enabling the user to learn of a larger set of tactons with less effort (Miller, 1956).
4.4. TACTON DESIGN

Figure 4.7: A musical event that triggers a tacton from the tactile library.

Figure 4.8: Tacton envelope defined as an event in CLEF.

Figure 4.9: Compound tacton example.
CHAPTER 4. RESULTS

Table 4.8: Suggested mappings between messages types and vibrotactile stimuli.

<table>
<thead>
<tr>
<th>Message</th>
<th>Suggested tacton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback</td>
<td>compound tacton</td>
</tr>
<tr>
<td>confirmation (start, stop, on, off, triggering)</td>
<td>double tactons</td>
</tr>
<tr>
<td>continuous feedback (during action)</td>
<td>triple tactons</td>
</tr>
<tr>
<td></td>
<td>repeated clicks</td>
</tr>
<tr>
<td></td>
<td>rough tactons</td>
</tr>
<tr>
<td></td>
<td>sustain with various amplitude</td>
</tr>
<tr>
<td>Notification</td>
<td>compound tacton, short time-gaps</td>
</tr>
<tr>
<td>alerts or errors</td>
<td>compound tacton, high intensity</td>
</tr>
<tr>
<td>low priority notifications</td>
<td>compound tacton, longer time-gaps</td>
</tr>
<tr>
<td>Synchronization</td>
<td>compound tacton, low intensity</td>
</tr>
<tr>
<td>countdowns</td>
<td>repeated single tacton</td>
</tr>
<tr>
<td>tempo or meter changes</td>
<td>deccelerando or accelerando</td>
</tr>
<tr>
<td>notification from other musician</td>
<td>vibrotactile metronome</td>
</tr>
<tr>
<td>Immersion</td>
<td>ramp ups or downs</td>
</tr>
<tr>
<td></td>
<td>pulsations</td>
</tr>
<tr>
<td></td>
<td>compound tacton</td>
</tr>
<tr>
<td></td>
<td>continuous “rough” tactons (as opposed to smooth envelopes)</td>
</tr>
<tr>
<td></td>
<td>continuous tactons, amplitude mapped to events in score</td>
</tr>
</tbody>
</table>

Table 4.9: Categories of tactons in the vibrotactile library prototype.

<table>
<thead>
<tr>
<th>Category</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Single short tactons (basic building blocks)</td>
<td>Strong, medium or soft intensity</td>
</tr>
<tr>
<td>2. Double tactons</td>
<td>Strong, medium or soft intensity</td>
</tr>
<tr>
<td>3. Combined, i.e. compound tactons (presets)</td>
<td>Low or high priority</td>
</tr>
<tr>
<td>4. Direct mappings</td>
<td>Discrete or continuous mapping</td>
</tr>
<tr>
<td>5. Metronome presets</td>
<td></td>
</tr>
<tr>
<td>6. Customized tacton</td>
<td>Customized envelope or compound tacton</td>
</tr>
</tbody>
</table>

The first category (1) of tactons involve single short vibrotactile stimuli that could be used as building blocks that could be combined into longer and more complex tactons. The double tactons (2) are double combinations of some of the tactons presented in the single category. The combined tacton (3) category combines all tactons defined above, thus producing a number of compound presets. These presets are designed and divided depending on priority, aiming to communicate a low (e.g. immersive messages or low priority notification messages) or high (e.g. high priority notification messages such as errors or alerts) level of urgency. A category entitled “Direct mappings” (4) was defined in order to enable direct discrete mappings between bangs from discrete musical events, and continuous mapping between CLEF parameters or envelopes and a vibrotactile envelope. This category relates to
4.4. TACTON DESIGN

the concept of tactile translation as defined in the taxonomy suggested by Giordano and Wanderley (2013); an auditory stimulus can be translated into the tactile channel by means frequency rescaling and cross-modal mapping between the features of sound and the target tactile stimulus. Furthermore, a category of metronome presets (5) was defined, introducing a simple mapping between a CLEF metronome module and a basic building block tacton from (1). Finally, a customized tacton category (6) providing the user with the possibility to sketch a customized envelope or to design an own compound stimulus was provided.

Figure 4.10: Library of vibrotactile presets, i.e. a library of tactons for CLEF.

The final interface of the vibrotactile library prototype can be seen in Figure 4.10. Three intensity levels were offered at duty cycles of 1.0, 0.65 and 0.3 respectively. These are levels that, according to results from the vibrotactile differential threshold experiment, should provide perceptually robust discrimination if tactons are presented in succeeding order. As we can see in the figure, all tactons do not occur for all three intensity levels, since some of the tactons are hard to distinguish from other tactons if presented at low intensities.
4.5 Evaluation

4.5.1 Identification of Tactons

In order to be able to create compound tactile stimuli that are perceptually robust for discrimination, it is first important to investigate identification rates of the basic building blocks of tactons. As seen in Table 4.10, the time used to explore the set of tactons was approximately 1.80 min (std. dev. 0.97 min). Learning time varied considerably across subjects, ranging from 0.87 to 3.25 min. The mean time measured for the practice phase was 1.27 min (std. dev. 0.55), with values ranging from 0.67 to 2.15 min. The mean time for the test phase, including all pauses of 30 s, was approximately 6.13 min (std. dev. 0.83), with times ranging from 5.22 to 7.45 min. The average time between presented stimulus and selection of labeled button was typically 2.7 s.

<table>
<thead>
<tr>
<th></th>
<th>Learning</th>
<th>Practice</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>1.80</td>
<td>1.27</td>
<td>6.13</td>
</tr>
<tr>
<td>MEDIAN</td>
<td>1.82</td>
<td>1.15</td>
<td>5.90</td>
</tr>
<tr>
<td>MIN</td>
<td>0.87</td>
<td>0.67</td>
<td>5.22</td>
</tr>
<tr>
<td>MAX</td>
<td>3.25</td>
<td>2.15</td>
<td>7.45</td>
</tr>
<tr>
<td>STD. DEV.</td>
<td>0.97</td>
<td>0.55</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 4.10: Identification experiment: time (min) used in different phases.

![Bar chart showing percent correct scores for tactons](image)

Figure 4.11: Percent correct scores for tactons.
4.5. EVALUATION

Tactons were generally identified at a 74 % accuracy level. Individual performance varied between 65.6 and 89.0 % in accuracy. From the 320 observations collected from the experiment, an average correctness was calculated for each tacton. The mean percent correct scores for each tacton when collapsed across all subjects can be seen in Figure 4.11, with mean rates ranging from 35 % (reversed bump) to 100 % (click). The results suggest that the tactons that were hardest to identify were the bumps, followed by the ramps.

It might be assumed that tactons that are harder to identify, i.e. tactons with a lower average percent correctness, required longer answering time. In order to investigate whether there was a correlation between the answering time and the average percent correctness, logistic regression analysis was performed on the dataset. The proposed model for probability of a correct answer was defined as follows:

\[
\text{logit} P = x\beta = \beta_0 + \beta_1 X_0 + \beta_2 X_1 + [\beta_2 ... \beta_{10}] [X_2 ... X_{10}] + \epsilon
\] (4.4)

Where \( \beta_n \) corresponds to the regression coefficients, \( X_0 \) is the explanatory variable (answering time in s), \( [X_1 ... X_4] \) a vector of dummy variables with corresponding coefficients (subject 5 was set as reference) \( [\beta_1 ... \beta_4] \) and \( \epsilon \) is a an error term. Clustered robust standard errors were used in order to correct standard errors for model specification. According to the results, the answering time was a significant predictor of the probability of a response correct response \( (p < 0.001) \). This motivates further investigation of average answering times for each tacton.

![Figure 4.12: Answering time for each tacton.](image)
The mean answering time for each tacton, ordered by decreasing time, can be seen in Figure 4.12. The order of the tactons are somewhat similar the order of percent correctness as presented in Figure 4.11. We find a number of outliers in the plot. By analyzing the data, it was found that the two largest outliers came from the same participant and the same tacton, the ramp up (number 5), with values of \( t = 32 \) and 19 s, respectively. Annotations from the experiment showed that these outliers might be due to the fact that the subject paused the experiment to ask a question. The analysis was therefore run with and without these two outliers. Results showed difference in means for this tacton, as indicated in Table 4.11, where the value including the outlier is indicated in brackets.

<table>
<thead>
<tr>
<th>TACTON NO</th>
<th>MEAN</th>
<th>STD. DEV.</th>
<th>MEDIAN</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.23</td>
<td>0.80</td>
<td>1.0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>2.15</td>
<td>1.55</td>
<td>2.0</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>3.95</td>
<td>3.19</td>
<td>3.0</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>3.88</td>
<td>2.09</td>
<td>4.0</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>3.05 (4.17)</td>
<td>2.0 (5.49)</td>
<td>2.0 (2.5)</td>
<td>1</td>
<td>10 (32)</td>
</tr>
<tr>
<td>6</td>
<td>3.12</td>
<td>2.51</td>
<td>2.0</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>1.77</td>
<td>1.12</td>
<td>1.0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>1.57</td>
<td>1.06</td>
<td>1.0</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4.11: Answering times in seconds (without removed outliers in brackets).

<table>
<thead>
<tr>
<th>RESPONSE</th>
<th>TACTON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.12: Confusion matrix of the participant’s responses.

A confusion matrix summarising the participant’s responses can be seen in Table 4.12. This matrix indicate which tactons that were most frequently confused. The actual tacton is presented on the x-axis and the user’s responses on the y-axis. An assumption in this context might be that the patterns of errors are symmetric, i.e. that if tacton 1 often is confused with tacton 2, it is also likely that tacton 2 often is misidentified with tacton 1. The errors that are shown in Table 4.12 suggest that the tactons that were hardest to identify were tacton number 3 and 4, i.e. the bump and the reversed bump. As we can see in the matrix, tacton 3 (bump) was most often confused with tacton 2 (buzz) and tacton 4 (reversed bump), both in 8 out
4.5. EVALUATION

of 40 observations, respectively. Furthermore, tacton 4 (reversed bump) was most often confused with tacton 3 (bump) and tacton 5 (ramp up), in 16 and 5 out of 40 observations. The errors presented in the matrix are somewhat symmetric, but not entirely. The symmetric relationship is most prominent for tacton 3 and 4. The same strong symmetric error relationship can however not be found for tacton 2 or 5.
Chapter 5

Analysis

In this chapter the obtained results are analyzed and general guidelines for the design of actuator signals for the tactile display for CLEF are provided.

5.1 Discussion

5.1.1 Suggestions for Tacton Design

Intensities

Providing that the only control parameter for these type of actuators is the duty cycle of the PWM, we may conclude the most intuitive parameter for information encoding for our application is intensity. It has previously been found that it is possible to encode information by using different intensity levels of tactile stimuli Craig (1972). Based on the findings presented in the current study, we can conclude that subjects can discriminate between certain intensity levels for our specific actuator set-up. These results are promising, suggesting that information in tactons might be communicated through the intensity parameter despite the fact that the actuators used in our tactile display are the same type of basic vibrating motors as you would find in an average cell phone.

From the absolute threshold experiment we can conclude that duty cycles below 0.2 should not be used to encode information in our vibrotactile notification tool. Furthermore, the results from the differential threshold experiment indicate that the order of stimulus intensity will not affect intensity discrimination and will not to be needed to be taken into consideration upon the tactile notification design. Moreover, the logistic regression model provides useful guidelines for selection of duty cycles. As shown in Figure 4.3 and Table 4.2, the difference in duty cycle between two stimuli will depend on where we are in the intensity scale (0.2 – 1.0). A lower duty cycle will require a smaller difference between the two stimuli than a higher duty cycle, in order to ensure a high probability of them being perceived as “different”. It was found that Weber fraction values for suggested intensity couplings were surprisingly high, ranging from 1.8 to 3.0, in contrast to the findings in Choi...
and Kuchenbecker (2013). This is probably due to the fact that we have set rather high constraint, i.e. the 80 % predicted probability, before defining the couplings of discrete duty cycle values.

As suggested in van Erp (2002), not more than four different intensity levels between the detection versus comfort-pain threshold should be used when designing vibrotactile stimuli. Selecting couples from Table 4.5, we may propose 3 different intensity levels for information coding in our tactile display (e.g. 0.2, 0.5 and 0.9). Such a choice of intensity levels would, according to the predicted model, be perceived as different from each other for the probability value of \( P = 0.8 \). The selection of three intensity levels for information encoding are furthermore in line with previous findings presented in Brown and Kaaresoja (2006), where it was found that intensity can be successfully used as a parameter in tactons when three levels of intensity are presented using a standard mobile phone vibration motor.

**Temporal Properties**

Considering temporal aspects related to the physical characteristics of the vibrating disk motors, we can conclude that ramp-up times are almost negligible and need not to be taken into consideration upon tacton design. However, the ramp-down times are significantly longer, ranging up to 200 ms. This asymmetry in the envelope should be considered when designing, for instance, tactons with fixed decay time or pulse-train-like tactons. No successive pulses with inter-onset times less than 200 ms can be transmitted with this particular actuator set-up. If temporal factors such as ramp-down time is an important factor, one solution would be to use a different motor driver circuit. The motor driver circuit could use, for instance, a full h-bridge driver with switch capabilities. Such a driver allows an almost instantaneous stop of the motor by rapidly inverting the plus and minus terminals. However, changing the hardware in such a manner might require a drastic redesign of tactons.

Results from the temporal gap detection threshold experiment indicated that relatively short temporal gaps could be detected. We may therefore suggest time and temporal aspects as possible parameters for information encoding in the tactile display. It is worth noting that apart from the click tacton, no pause was introduced between the double tactons (this despite our previous findings suggesting that a pause of 11 to 49 ms is needed in order to ensure gap detection). In contrast to the pause of 0 ms needed for the double buzz to obtain high identification rates, the double click needed a considerably longer time than the estimate of 49 ms (the pause between the clicks was finally set to 90 ms). To conclude, it might be suggested that time gaps between vibrotactile stimuli may need to be adjusted individually, depending on spatial locus on the skin and intensity envelope of the specific tacton.

Furthermore, obtained results indicated that temporal length of the vibrotactile stimulus is an important factor for tacton identification and discrimination. Observations from the design phase of the tactons definition suggested that it is easier to discriminate between tactons if they differ a lot in terms of total length. The need to re-scale tacton envelopes in terms of temporal length when going from the

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5.1. DISCUSSION

fingertips to the back of the torso also suggested that spatial locus has an important influence on vibrotactile perception. To summarise, it may be proposed that all tactons should be re-scaled and adjusted according to the user, i.e. that each performer or composer should calibrate the library of tactile cues according to their own sensory magnitude.

Frequencies

The results from the measurements of peak frequencies of the disk motors show frequencies ranging from 140 to approximately 380 Hz. This information is useful for the selection of loci for the vibrating desk motors, since different parts of the human body have different sensitivity to certain frequency ranges. It is worth noting that the sensitivity peaks, i.e. the best frequency to lower threshold of perception, can be found around 250 Hz for the human tactile perception. According to the results presented in Figure 3.2, a frequency of 250 Hz can be found between the duty cycles 0.3 and 0.4. This goes in line with the low values of duty cycle difference $X_r$ required for robust discrimination of vibrotactile intensity, as presented in Table 4.2.

Mapping Messages to Vibrotactile Cues

Designing a set of vibrotactile cues that are intuitively mapped to information is not a trivial task. The choice of actuator in the current study puts some constraints on the design possibilities for tactons. We can not easily create a complex hierarchical tacton design using a simple vibrating disk motor. Since all the parameters such as frequency, intensity, envelope, spectral content and spatial positioning are not available for our specific actuator, our design of actuator signals will be focusing on what Giordano and Wanderley (2013) defines as tactile notification, rather than tactile synthesis. When creating a tactile language for our set-up using such a tactile notification paradigm, we need to make sure that the vibrotactile cues are supra-threshold and that the abstract mappings between cues and message meanings are comprehensible.

Based on the findings from this study, we may propose encoding of information in terms of temporal patterns and intensity. An example information coding could for example be to use three intensity levels and to map urgency of a message to vibrotactile intensity level. Low intensities levels (around 0.2) could for example be used for less urgent messages, e.g. could a low-intensity vibrotactile metronome provide information in a similar manner as a standard metronome provides information through auditory click tracks. Higher intensities could be used for notifications or alerts of great importance or higher urgency, such as messages preparing the performer for an important future event in a score. Moreover, fast rhythmical patterns with short pauses between stimuli could be used to encode urgent messages.

When it comes to categorizing tactile stimuli into different categories depending on message type and urgency of the message, it is possible that more sophisticated
methods, such as multidimensional scaling, could be used in order to enable creation of a larger set of stimuli which are perceptually far away from each other.

**Defining a Basic Library of Perceptually Distinguishable Stimuli**

When opting for a design where a set of simple tactons can be combined into more complex patterns in order to communicate more complex information, it is important to keep in mind that the number of tactile building block units may affect identification and discrimination rates. Human processes such as chunking and learnability during cognitive workload should be taken into account in this context. Although not in the scope of this study, it is worth mentioning that the optimum information transfer rates for communication through the haptic modality should also be considered when designing tactons (see for example Tan et al. (2010) for details).

Findings from this study indicate relatively high values for the identification rates of tactons, with a mean of 74 % correctness. This is a promising result, considering mean practise time was 1.8 minutes in this experiment. It may be suggested that arbitrary mappings between tactons and names can be learnt and that users do not require very long time to identify a stimulus, if not more than 8 different tactons are presented. Although findings from the study indicated that most tactons were easy to identify, the bump and reversed bump tactons were often confused with each other. It may be suggested that these two tactile envelopes should be excluded from the vibrotactile library.

5.2 Conclusion

In this study we presented measurements and perceptual, user-based tests to characterize a tactile display to be used in combination with CLEF, a live-electronics composition environment. Findings from the study provide guidelines for the design of actuator signals for our vibrotactile display. A categorization of different message types relevant in the context of live-electronics performance was initially defined. The definition of these messages allowed us to conceptualize the need of the musical performer and to translate messages into vibrotactile cues. After initial brainstorming, physical and perceptual characterization of the tactile display was done, whereafter a set of basic tactile building blocks, i.e. tactons, was designed and evaluated in terms of identification rates. Ultimately, guidelines for the design of tactons and their potential “intuitive” mappings to musical parameter into CLEF were provided, and an easily embedded software prototype providing a set of pre-defined tactons was developed. The conclusions that could be drawn from the study can be summarised as follows:

- Results suggests that participants can discriminate between intensity levels and that intensity can be used as a parameter in tacton design. Order of stimulus intensity does not affect intensity discrimination and duty cycles be-
low 0.2 should not be used with this particular set-up. The required difference in terms of intensity between two vibrotactile stimuli is a function of the absolute value with reference to the duty cycle scale: a lower duty cycle will require a smaller difference between the two stimuli than a higher duty cycle, in order to ensure the same probability of intensity discrimination.

- Concerning temporal aspects, relatively short time gaps between vibrotactile stimuli could be detected. Temporal aspects could thus be used to encode information in tacton design. Results indicate an almost negligible ramp-up time but a maximum of 200 ms ramp-down time for our specific set-up; this needs to be taken into account upon tacton design. Moreover, time gaps between vibrotactile stimuli and stimulus length may need to be adjusted for different users, tacton envelopes and actuator locus.

- Findings suggest that tactons can be learnt if provided sufficient time for practice. Mean identification rate for a set of 8 tactons in this study was found to be as high as 74 % for a mean practice time 1.8 minutes.

- Tactons should always be re-scaled and adjusted (in terms of intensity and time) according to the sensory magnitude of the user and the specific performance context.

Although the work on our tacton library design is CLEF specific, the results obtained from this study can be used as a perceptual base to build tactons in other musical contexts as well.

5.3 Future Work

One of the limitations of this study is the lack of evaluation of vibrotactile stimuli in the context of music performance. In future investigations, stimulus discrimination and identification in the context of musical performance or composition should be investigated. It is possible that the ability to perceptually discriminate between vibrotactile stimuli is affected when the subject is exposed to a considerable cognitive workload, i.e. when performing at the same as wearing tactile display. Future studies should therefore focus more on if and how tactile feedback could become part of a musical rehearsal and performance routine.

Moreover, it might be relevant to further investigate the appropriateness of tactile events in relation to the represented internal variables in CLEF. It is not a trivial task to map CLEF variables to vibrotactile cues while at the same time conveying musical information in an unobtrusive and transparent manner. By expanding the current set-up to more actuators than two, multiple-actuator tactons could also be created, thereby enlarging the vibrotactile library. Finally, it would be interesting to experiment with different positioning strategies in order to convey information to the musician through spatial locus.
Bibliography


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