An evaluation of the interstitial beat across the modalities of touch and sound for the characterization of a meaningful haptic metronome

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To my grandmother, for early guidance towards a lifelong quest of knowledge and truth.

Abstract

The following work is an expansion of sensorimotor synchronization research. It provides an evaluation of the intervening space between the beat as it applies to the modalities of touch and sound. The crux of the experiment is a tap test comparison of continuous and discrete impulses over static (isochronous) and dynamic (non-isochronous) intervals. Time based response metrics of a wearable haptic are contrasted to a suite of audible tests. Though vast evidence promotes auditory an advantage in guiding rhythmic accuracy and low asynchrony, this work hypothesizes that there will be improvement shown when the interstitial beat is occupied with a continuous wave across the modality of touch at slower tempi where space between successive beats is significantly spread apart, as well as throughout the occurrence of unpredictable or dynamically changing events.

The analysis over 10 individuals, professional and amateur/non-musicians resulted in

add experiment results brief overview

The overarching goal is to inform validity and design of a haptic wearable which seeks to supplant the traditional metronome experience in providing a meaningful gestural system. The work holds value towards future entrainment studies in expressive performance but can be expanded to include extra-musical applications via stroke gait rehabilitation practice, Parkinson's patients, and military based navigational applications.

Acknowledgments

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Chapter 1

Introduction

The interstice is an intervening space. When applied to a rhythmic context, the interstitial beat can be represented by two distinct states; whether energy exists within this small moment in time or if it does not.

The underlying question, as applied to the daily practice of a trained musician or the innate entrainment (external rhythmic synchronization) of the average human being, is whether the space between the beat matters. Does filling the space provide an added awareness or preparation for upcoming onsets?

The objective of this work is to display whether a continuous wave, one which leads up to the maximum amplitude of the beat and trails off into a smooth decay, exhibits differentiation from it's instantaneous counterpart in communicating regular or irregular pulses. To quantify this differentiation, an expansive set of analog and discrete tap synchronization tests spanning the modalities of sound and touch are conducted across a group of musicians, amateurs, and non-musicians.

Ancillary to this work, a haptic wearable is prototyped and evaluated for design optimization with an overarching goal of translating the gestural motion of the conductor.

The project presents a unique opportunity to enable expansion of the existing sensorimotor synchronization findings to the haptic modality in continuous form, with the intent to resolve the inquiry as to whether filling in the space between the beat, the interstitial, has a positive impact in communicating dynamic changes more effectively.

1.1 Motivation

While it is clear that nearly every professional musician has honed technique over countless hours of practice to an audible metronome, it is not directly obvious whether they have ingrained a true sense of rhythm at the foundational level with the primary instrument of expression, the body itself.

Intrinsic awareness to subtle nuances of tempo remains a subject commonly unexposed to a student in training. Yet this ability, to perform in the spaces surrounding the beat, defines the difference between a rigid performance and one that flows with elasticity and musical expression.

Is there missing information from the daily practice of a trained musician to an audible metronome? In a traditional sense, the audible click of the metronome minimizes the interstitial space with an instantaneous (or discrete) impulse signal. The pendulum motion exhibited also seeks to convey meaningful rhythmic information with the space it occupies in the visual modality, much like the gestural motion of a conductor. Although an excellent tool in establishing a sense of musical time and precision, the danger in use of such a mechanical object lies within the mathematical exactitude according to American composer and music critic Daniel Gregory Mason. Therefore manifesting a lifelessness where instead a living and breathing musical entity should exist with its own "ebb and flow of rhythmical energy."[1]

1.2 Background

Humans have an innate ability to not only notice periodic movement, but to mimic and adapt to changes in their environment [2]. The extent of these capacities can be expanded through training which consists of recognizing, retaining, analyzing, and reproducing rhythms [3]. The results of which can hold extra-musical impact as rhythmic stability finds important applications in everyday life.

The practice of Dalcroze Eurythmics has sought to fill this knowledge gap as a curriculum developed by composer and educator Emile Jaques-Dalcroze in the early 1900's to integrate natural musical expression via movement [4]. Through a series of exercises the instructor ushers his students to coordinate movement to varying levels of rhythmic push and pull. For example, a student's hands might be conducting a subdivision heard in the melody while simultaneously walking in coordination to the fundamental pulse played in the harmony. A sense of constant forward motion pervades the actions of the student allowing an embodiment of continuity which seeks to permeate all elements of musicality development.

From nearly two decades of work as a licensed Dalcroze instructor at Carnegie Mellon University, Professor Stephen Neely has implemented these techniques. His current research in design seeks to further explore the interstitial. In doing so he imparts an inquiry as to what is gained in attempting to fill the space between the *crusis* (click moment of the beat) with a natural analog wave, one that provides a build up and decay common to natural happenings, much like the gestural motion of a conductor.

1.3 Sensorimotor synchronization

Research surrounding the psychology of rhythmic perception is grounded within the framework of *sensorimotor synchronization* (*SMS*); defined as the coordination of rhythmic movement to an external rhythm.

What follows is a brief overview of SMS. Critical terminology is defined 1.3.1, and followed by a primer of available tap test software 1.3.2. A framework of the current work is established through discoveries illuminated by prior SMS research 1.3.3. Finally, a brief discussion of both biomechanical and perception limitations 1.3.4 concludes this chapter.

1.3.1 Terminology

The main method of data collection for SMS tap based tests involve collection of the time delta between the tap and event onset, called the *asynchrony*. Within the context of this work it shall be defined as:

$$TapOnset - TrueOnset$$

The mean of this asynchrony is typically negative (NMA), indicative of the participants anticipation of the beat rather than reaction. Positive asynchronies imply a reactive approach thereby unfavorable within the context of this work. A positive asynchrony shorter than the fastest possible human reaction time window of 150 ms, or 400 bpm, (further discussed in 1.3.4 and A.1.1) are arguably an anticipation of the preceeding stimuli. This window of acceptable tap time informed the sanitization algorithm developed and outlined in

Ref Sanitization here

The standard deviation of the asynchrony, SD_{asy}, is an index of stability; lower values indicative of a better level of synchronization [5]. For the purposes of this research, SD_{asy} is predominantly shown superimposed onto bar charts as confidence interval lines.

Other important metrics include the variability and mean of the inter tap interval (ITI) and the inter onset interval (IOI), or the time between successive beats, measured in milliseconds. Mismatch between the ITI and IOI implies poor synchronization skill from the participant.

Phase Correction Response is defined as the shift of the immediately following tap from its expected time point, given by:

$$PCR = (TapOnset_{n+1} - TrueOnset_{n+1}) - (TapOnset_n - TrueOnset_n)$$

When a participant is instructed to tap on the beat, this is termed 1:1 synchronization. 4:1 synchronization, for example, is a beat subdivided into four with one tap on the beat. Subdivision tests typically yield lower mean (SD_{asy}) values [5]. This work will focus on 1:1 synchronization as discussed in 3.2.4.

1.3.2 Tap Test Software

The finger tap mechanism holds strongest precedence in SMS research due to its reliability, precision *(ms)*, and discrete nature. Studies predominantly rely on a MIDI based (drum pad) instrument to register tap events and provide some sort of auditory feedback. A few tap based software suites for experimentation and data acquisition are readily available: a Linux based system written by Finney in 2001 named *FTAP* [6], and a *Matlab* based toolbox by Elliot in 2009 called *MatTAP* [7]. FTAP relies on a MIDI source with a reported mean auditory latency of approximately 14.6ms (SD

= 2.8) [8]. Superfluous and unregistered taps were common.

Both *FTAP* and *MatTap* were viable options for this work but ultimately deemed either outmoded, lacking multi-threaded and high baudrate (115200) hardware support for haptic integration over serial, or incompatible with the system architecture in use *(OSX 10.11.6 2.6GHz Intel I7)*.

In a novel high-precision, low-latency approach by Prof. Schultz in 2015 at the University of Montreal [8], an Arduino force sensitive resistor (FSR) based tap mechanism was constructed. Latency between time of tap and auditory feedback was minimized with a mean of 0.6ms (SD = 0.3). The results also demonstrated the reliability of the FSR in recording fewer superfluous taps as well as fewer missed taps. It was inevitably decided to construct custom hardware and software to fit the test needs of the project as discussed in Section 3.2.1 which provided a round-trip latency of

Add latency metric here

as shown in 3.2.3.

1.3.3 Expectations

This section focusses on key insights from prior SMS research which inform expectations for the data analysis conducted in Chapter 4.

Variability

The variability (SD_{asy}) is generally lower in professional musicians than non-musicians (no prior musical exposure). In an isochronous test with an IOI of 500 ms (120 bpm), surprisingly no difference in SD_{asy} was found between amateurs and non-musicians **??**. From this study it is safe to assume the data analysis of this work will be grouped into professionals vs. (non-musicians and amateurs).

Percussionists and pianists had the lowest ITI of all musicians. This might imply that a high level of rhythmic expertise reduces variability of tapping, but due to the percussive nature of the instrument becomes hard to determine. Furthermore, as the duration of the IOI increases, SD_{asy} increased in a non linear fashion as confirmed in

Add data plot ref here

When professionals migrated away from the tap test and instead used their native instruments, the results were greatly improved. It was reported by Stoklasa, Liebermann, and Fischinger in a paper presented at the Music Perception and Cognition in 2012 that musicians playing their own brass or string instrument in synchrony with a metronome showed a negligible NMA of 2 ms, unlike their tapping results of -13 ms [5].

Negative Mean Asynchrony

The NMA is typically smaller for musicians and remains relatively constant throughout a changing IOI. A linear increase in NMA as the IOI increases can be expected from non-musicians [5]. It was found that nonisochronous tapping introduces distortions within the ITI as opposed to steady or isochronous patterns. This had a tendency to affect local asynchronies but the global NMA remained persistant [9].

As a counter to the proposed hypothesis, Bialunkska et al. argued that the reason for a negative mean asynchrony was due to faster sensory accumulation from the auditory and visual modalities than from tactile feedback received from taps [10]. The expectation was thus a dependence of the sensory accumulation rate to the stimulus intensity. This was later found to be uncorrelated [10].

A positive mean asynchrony is expected as the IOI approaches the biomechanical limit of execution as discovered by Krause, Pollok, and Schnitzler in 2010 [11].

Auditory Dominance in SMS

SMS research historically identifies what is known as an auditory advantage, or the dominance of the auditory motor connection within the task of beat synchronization. The auditory advantage is discussed in detail in Section 2.1. Recent studies have proven that given meaningful spatiotemporal information (as in the bouncing ball example discussed in 2.4) synchronization is almost as good as an auditory metronome.

1.3.4 Rate Limits

In order to impose valid constraints on the tests carried out in this work, it is important to understand the SMS rate limits.

According to experiments done by Keele, Pokorny, Corcos, and Ivry, in 1985, the calculation for the fastest absolute response time possible for a tap based test can be divided into either that of perception or motor speed, also known as the biomechanical limit [12]:

1. Biomechanical Limit:
    - Between the 5 - 7 Hz range, or a period of 150 - 200 ms [13].
2. When discussing a perceptual basis, SMS tests are valid within a particular temporal range:
    - For audio based tests with 4:1 synchronization:
        - The upper rate limit was shown to be as high as 8 - 10 Hz, or a period of 100 - 125 ms (approximately 600 bpm).
        - The lower rate limit was modality independent and found to be 0.56 Hz, or a period of 1800 ms (33 bpm) [13].
    - Visual stimuli was found to be less than 2.5 Hz, or a period of 400 ms (150 bpm).
    - The haptic design section A.1.1 discusses the rate limits of the touch modality.

In order to establish a middle ground and determine a fair and effective IOI window across musicians and non-musicians, this work has chosen to focus on tempi ranging from **45 - 180 bpm**, or a period of **333 - 1333 ms**. The selection presents an opportunity to test the higher bounds of relative ability and noise for the haptic metronome past the biomechanical limit range (> 150 bpm).

Chapter 2

Previous Work

This chapter begins with SMS research in support of the hypothesis of this work in an attempt to debunk what is known as the auditory advantage 2.1. From there, three specific research projects are discussed, each directly informing design of the haptic built for this project: the haptic drum kit 2.2, vibrotactile metronome 2.3, and the continuous visual metronome 2.4. To conclude, 2.4.1 grants a brief insight towards commercially realized products relevant to the field.

2.1 Auditory Advantage

Most SMS research leans toward the notion of a distinct advantage from the discretely timed auditory stimulus, implying that the neural and evolutionary mechanisms underlying beat synchronization are modality-specific. The following examples are proponents of the counterargument, predominantly involving the relatively new field of touch.

2.1.1 Multisensory Cues

Maintaining synchrony with a periodic event requires that the central nervous system (CNS) compensate for timing variation arising from sensory, decision and motor processing noise. Keeping in time with a pacing source (metronome) requires continual corrections based on the timing error (asynchrony) between the metronome and performed actions. The CNS can alternate between cues depending on the demand of the task or combine info from different senses. In the context of rhythmic cues the brain will weigh signals according to the relative reliability in the timing of the events across modalities, ensuring optimal movement production to the underlying event extracted from the signals.

In an experiment carried out by Elliott in 2010, it was discovered that the variability of asynchrony for unimodal tactile cues was lower than for the visual metronome ($F1,9 = 6.929$, $P = 0.027$) and only slightly higher than that for unimodal auditory cues [14].

2.1.2 The Tactile Modality

A 2016 study by the Department of Psychology at Ryerson University considered whether the auditory advantage persisted across the tactile modality [15]. The experiment was a tap test of non musicians put through a series of simple and complex rhythmic sequences with a varied area of haptic stimulation. In conditions involving a large area of stimulation and simple rhythmic sequences, tactile synchronization closely matched auditory. They proved that if made salient enough, the accuracy of synchronization to a tactile metronome can equal synchronization to an auditory metronome, further challenging the idea of an auditory advantage over all other modalities for synchronization to discretely timed rhythmic stimuli. However, auditory won out for synchronization of complex rhythmic sequences.

2.2 Haptic Drumkit

In 2010, a group at the Open University designed a haptic which would enable a drummer to learn multi-limb coordination with the broader goal of polyrhythmic entrainment. They too adopted Dalcroze entrainment theories for guiding rhythmic perception.

Four haptics were worn on the wrists and ankles of five participants. Each haptic consisted of a single vibrotactile and as such operated in an instantaneous mode. The devices would communicate in synchronization to a singular beat, while an individual device could vibrate to the subdivision. Each stimulation represented an action which the drummer would take [3].

In a user survey following the tests, it was mentioned that the haptic guidance felt intimate. The users appreciated not having to work out the division of labor like one would with the audible modality. However, the drummming had a tendency to drown out the vibrotactile signal and the attack was seemingly blurred or lost to the noise as the haptics reached higher tempo.

It was found that a haptic had to be on for a minimum of 50 ms in order to be felt completely. Furthermore, a minimum gap of 50 ms would have to be in between each pulse in order for two pulses to feel distinct. Another frequent request was to reposition to just the arms or to have the option to disable the ankles as it was found to be very difficult to feel on the lower limbs.

This research gave insight into training with haptic stimuli alone, and is a strong proponent for utilization of the touch modality within the context of Dalcroze training. Throughout their research an important distinction was made between stimulus response and fostering entrainment. It was found that a more optimal solution in the future would promote more of a proactive rather than reactionary response. Further, replacement of the vibrotactile with a tactor (see Appendix A.1.2) in the next revision promoted a cleaner signal with wider dynamic range and finer temporal resolution.

2.3 Vibrotactile Metronome

The *Vibrotactile Metronome* is the current thesis project of Patrick Ignoto of the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) program at McGill University.

The work has some fascinating parallels to this project and has granted some very tangible insights towards testing and overall procedure. Patricks overall goal was to propose a device which uses tactile sense to provide similar functionality to a click track as its used for a contemporary classical music conductor with the added benefit of not blocking the ear or interfering with the conductors perception [16].

His guide for design requirements was the director and conductor of the contemporary music ensemble, Professor Guillaume Bourgogne. He gave Patrick the constraint that the pulses should feel continuous and not discrete, even mentioning a pendulum motion as the descriptive feeling. Furthermore, the pulses peak amplitude had to line up with the audio track. To synchronize with the audio click he triggered the haptic pulse midway between two audio clicks.

The haptic design consisted of two ERMs and one pager buzzer. A transmitter was connected to a PC running the visual programming language Max. Real-time audio analysis of the incoming signal was completed using the bonk object to find downbeats. This triggered the generation of the vibrotactile envelope signal and a control message was transmitted to the device.

A novel addition to SMS research was the proposition to redefine the Inter-Onset Interval as half previous IOI (rise time) + half nexts IOI (decay time) in what is claimed as more precision to accommodate varying pulse lengths.

At the end of the proposal, the real-time setup was migrated to post-processing in Matlab since the hardware was having trouble in keeping up with the buffering. Not much insight was given as to how the vibrotactile waveform was shaped; it is assumed that some level of motor control was involved.

2.4 A Continuous Visual Metronome

In a novel advancement challenging the auditory advantage and perhaps paving the way towards a more meaningful gesture, researchers in the Psychology department at Sun Yat-Sin University in Guangdong found continuous motion of a bouncing ball to be as stable as synchronization to an auditory metronome [17].

Though stability of beat synchronization to discrete visual modalities, such as a flash of light, has been shown to be less stable that its auditory counterpart, the design of a more meaningful visual had been previously unexplored. The team designed a visual bouncing ball simulation which manipulated acceleration animation to fit the IOI desired. Participants were instructed to tap to the bottom position of the bounce. Results for the bouncing ball visual were nearly equivalent to the auditory control tests. The research carried out by this group was direct motivation to expand this project into the tactile modality.

2.4.1 Commercial Introspection

The Peterson tuner BodyBeat Sync ($140) seeks to revolutionize the traditional metronome through its extensive coverage of all three modalities with a wearable pulsing vibration unit which claims to allow musicians to easily internalize the beat and develop a note value relationship both audibly and physically [18].

The Soundbrenner ($99) is a vibration based metronome using an instantaneous pulse and claims that in freeing the ears, it has brought the rhythm closer to the body, making it more comfortable and natural to feel the beat and swing of the music instead of chasing the click [19].

2.5 Summary

These specific haptic ventures have served as foundational works to inform design perspective. The work accomplished by the haptic drumset research group directly served to inform the threshold for acceptable timing of the vibrotactiles. 50 ms ramp up time with 50 ms separation yields a 400 ms (150 bpm) window which agrees well with prior SMS research of rate limits. The vibrotactile metronome gave insight toward test methodology and potential challenges involving latency or real-time strategy. The continuous visual metronome was a solid baseline for data analysis metrics and one of the key inspirational works for the hypothesis of this work.

Chapter 3

Method

The design and prototype iterations of the haptic metronome are discussed extensively throughout Appendix A.2 along with a parts list and schematic of the hardware builds.[1]

This chapter outlines each test case and describes the motivation behind the test plan. Furthermore, it briefly delves into the test suite design and calculates a round-trip latency of the system in order to find a close approximation of relative accuracy. The hope is to establish a level of confidence in the precise time dependent information.

The overall test principle was derived from traditional sensorimotor synchronization tasks in which a user is asked to tap to a corresponding stimulus. The asynchrony was tracked and plotted along with the *PCR* and any missed taps. Since the haptic domain is of primary focus, the auditory modality functions primarily as a benchmark or baseline foundation. The work presented in 2.4 covers the idea of the interstitial beat occupying the visual domain and as such will not be re-evaluated here.

Each test case is defined and presented in 3.1. The overall software development process is detailed in 3.2.1. The test suite is discussed in 3.2.2 and latency calculated in 3.2.3.

[1]All of the code is open source and readily available at `https://github.com/afaintillusion/he-sm`

Steady									
	Discrete		BPM	Runtime (sec)		Interstitial		BPM	Runtime (sec)
A1a	click	i.	45	20	A1b	legato chime (swing click)	i.	45	30
		ii.	90	20			ii.	90	16
		iii.	135	20			iii.	135	11
		iv.	180	20			iv.	180	8
A2a	staccato music (melody)	i.	45	32	A2b	legato music (melody)	i.	45	32
		ii.	90	16			ii.	90	16
		iii.	135	11			iii.	135	11
		iv.	180	8			iv.	180	8
H1a	poke / all on (instantaneous)	i.	45	15	H1b	oscillate down and back up	i.	45	15
		ii.	90	15			ii.	90	15
		iii.	135	15			iii.	135	15
		iv.	180	15			iv.	180	15
Dynamic									
	Discrete		BPM	Runtime (sec)		Interstitial		BPM	Runtime (sec)
A3a	click	i.	45 +/- 15	20	A3b	legato chime (swing click)	i.	45 +/- 15	20
		ii.	90 +/- 15	10			ii.	90 +/- 15	10
		iii.	135 +/- 15	10			iii.	135 +/- 15	10
		iv.	180 +/- 15	10			iv.	180 +/- 15	10
A4a	staccato music (melody)	i.	45 +/- 15	30	A4b	legato music (melody)	i.	45 +/- 15	30
		ii.	90 +/- 15	15			ii.	90 +/- 15	15
		iii.	135 +/- 15	10			iii.	135 +/- 15	10
		iv.	180 +/- 15	10			iv.	180 +/- 15	10
H2a	poke / all on (instantaneous)	i.	45 +/- 10	15	H2b	oscillate down and back up	i.	45 +/- 10	15
		ii.	90 +/- 5	15			ii.	90 +/- 5	15
		iii.	135 +/- 3	15			iii.	135 +/- 3	15
		iv.	180 +/- 1	15			iv.	180 +/- 1	15

Table 3.1: Test Plan

3.1 Test Plan

Testing was divided into two major sections, **Steady** and **Dynamic**, implying either an *isochronous* or a *non-isochronous* pulse respectively. While structurally identical, the dynamic tests however focussed on rubato within a range starting at the predefined BPM and rising or falling within a specified window (maximum span of +/- 15 bpm). The chosen tempi parallels slow walking to running gaits spanning a range of 45-180 beats per minute.

Each section has three subsections centered around either an audible metronome tone (**A1, A3**), musical note (**A2, A4**), and lastly the haptic modality (**H1, H2**). Subsections were further broken down into **a** and **b**, denoting either *discrete* or *interstitial* (*continuous*) mode of operation. A breakdown of the test plan is shown in Figure 3.1. The data analysis in Chapter 4 will frequently reference this table as a legend.

As discussed in Appendix A.2, the haptic was designed with two operating modes in mind, discrete and continuous. These modes were programmatically controlled to match the desired test cases, extensively explained in section 3.2.1.

Group	Instrument	User ID
Amateur	Bass	729
	DJ	390
	Piano	399
	Voice	379
Neither	None	486
		514
		932
	Piano	394
Professional	Flute	410
		591
		824
	Percussion	367
		506
		521
		552
	Piano	510

Table 3.2: Subject Grouping

3.1.1 Subjects

Out of 18 subjects tested, 16 were parsed to equivalently divide the groups into 8 professionals and 8 amateurs/non-musicians. Usernames were anonymized into User ID's using a cumulative char to int conversion method. A breakdown of the grouping per instrumentation is shown in Table 3.2.

3.1.2 Audio File Generation

All tracks were rendered using the digital audio workstation (DAW) *Logic Pro X* as *.wav* files at a 44.1kHz sample rate with 16 bit resolution.

Metronomic click and legato chime

A1a and **A3a** required a standard metronomic pulse. This was accomplished using the default Klopfgeist (metronome) plugin from Logic Pro X. No additional tuning was modified and the tonality was left at 0.83 of unity as shown in Figure 3.1.

A1b and **A3b** however required a swing or legato type of chime in order to convey filling the interstitial space. To capture this effect the Klopfgeist tonality was increased to unity and tuned -27 semitones lower which served to both soften diminish the discrete click, provided an elongated or continuous audible sensation.

Figure 3.1: A1a and A3a metronome

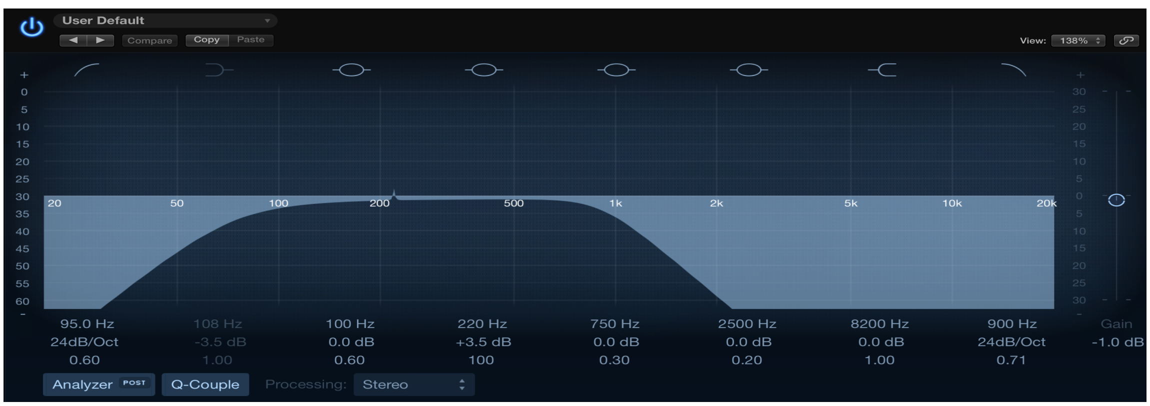
To give the impression of a sound that was ramping up in amplitude and decaying after the peak, a tremolo effect which mimics a sawtooth wave was added to the signal chain as seen in Figure 3.2. Last, a multi-band EQ was placed at the end of the signal chain with a bandpass filter from 95Hz-750Hz to remove unwanted frequency presence and a 3.5dB high-Q peak at 220Hz to emphasize the tonality.

Figure 3.2: Modified click parameters for interstitial tests.

(a) Modified metronome

(b) Superimposed tremolo

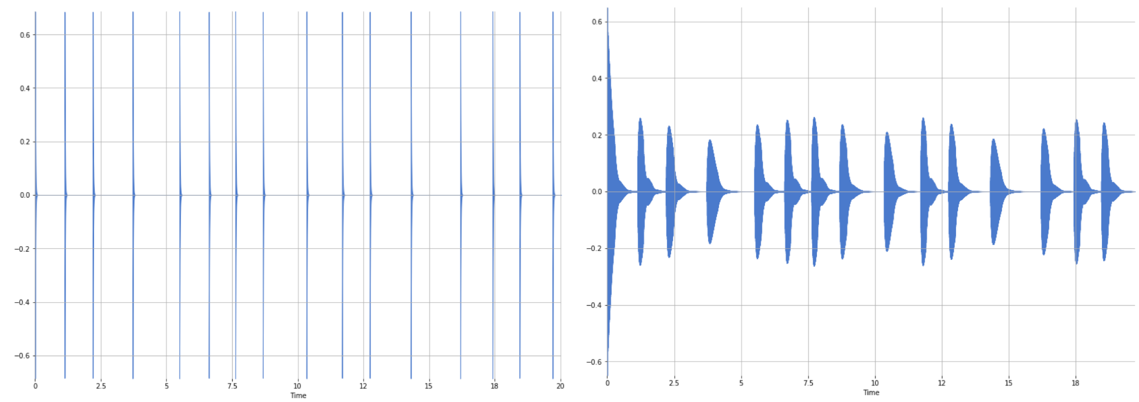
(c) Equalized tone



The resultant waveform encapsulated the occupation of the interstitial space. A comparison of this waveform in contrast to it's discrete counterpart is shown in 3.3. Note the envelope of signal (b) follows a natural build up and decay.

Figure 3.3: Metronomic waveform comparison

(a) A3a1: discrete audible click (b) A3b1: interstitial tone

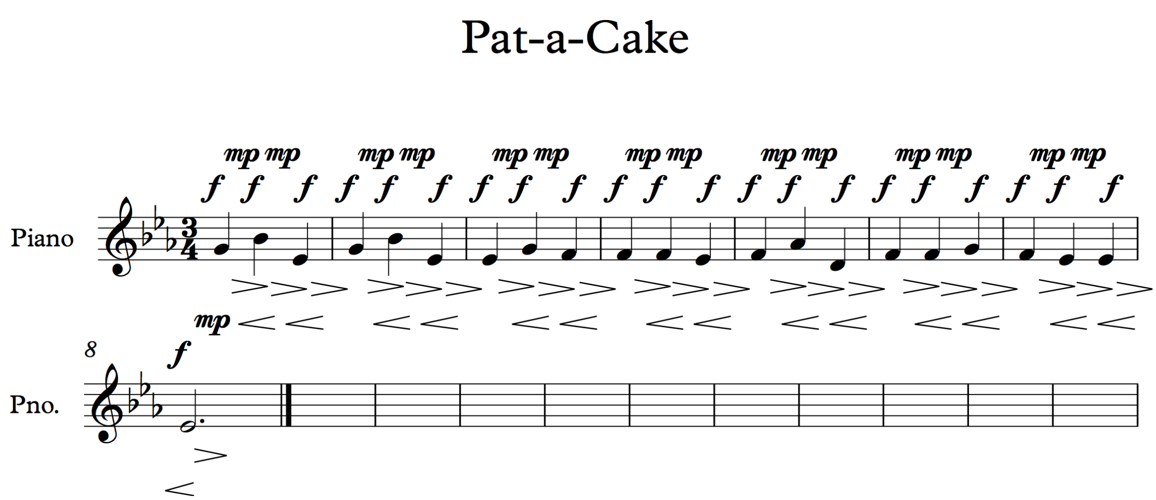


Stacatto and legato melody

As a specific musical listening task, test cases **A2a**, **A4a** and **A2b**, **A4b** involve synchronization to a simple melodic sequence of notes. The music chosen was the nursery rhyme *Pat-A-Cake*. The initial mockup was drafted in Sibelius and exported to Logic Pro X for bpm adjustment.

Each quarter note represents a beat and therefore a tap onset. In order to emphasize a discrete event for test cases **A2a** and **A4a**, notes were input as stacatto, shown below in Figure ??.

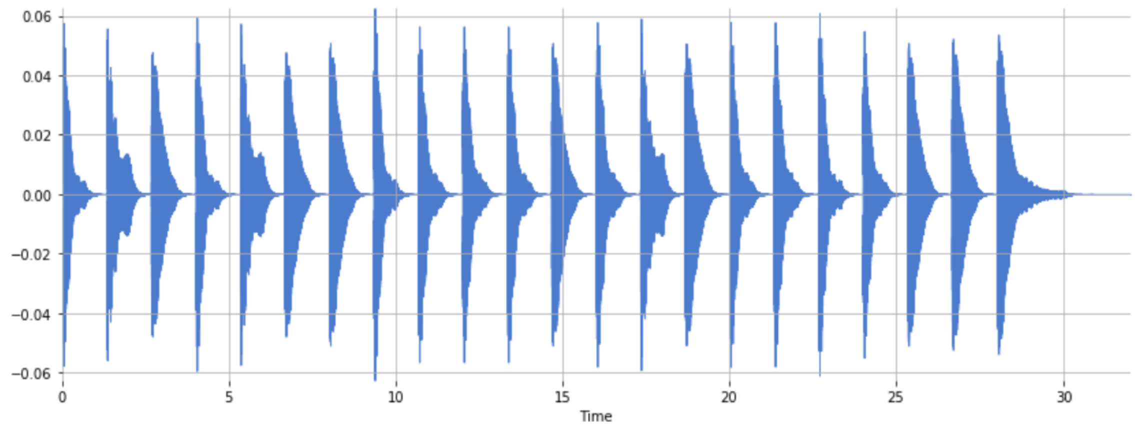
The interstitial counterparts (**A2b**, **A4b**) similarly underwent crescendo and decrescendo after every note onset with forte accents surrounded by mezzopiano to give the impression of amplitude build up and decay, shown below: ??



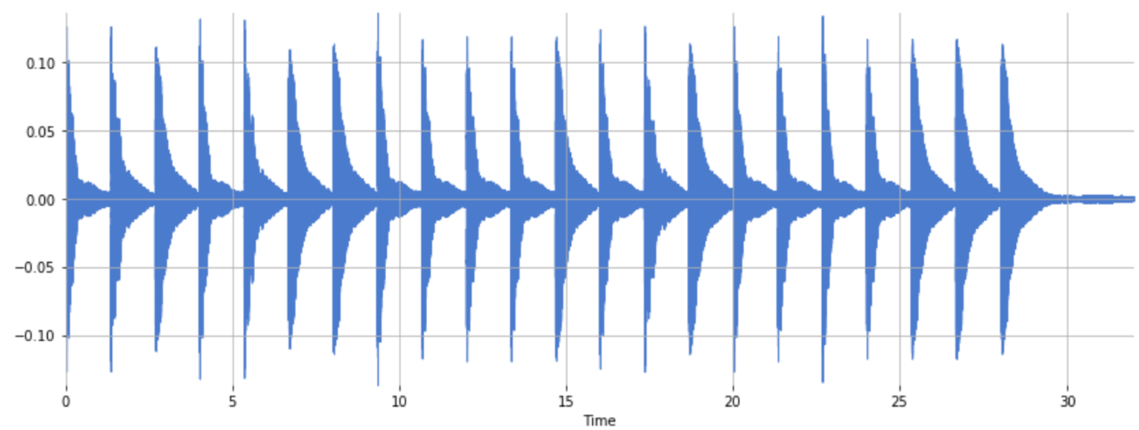
Note below in Figure 3.4 the gradual, nearly exponential decay displayed in the interstitial tone as a result of the legato input.

Figure 3.4: Musical waveform comparison

(a) A2a1: stacatto melody



(b) A2b1: legato melody

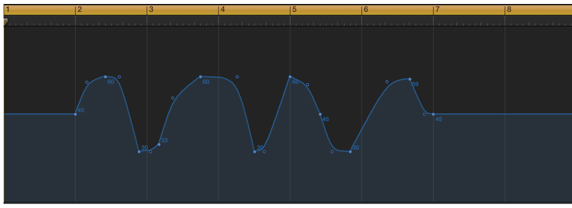


Dynamic tempi manipulation - audio

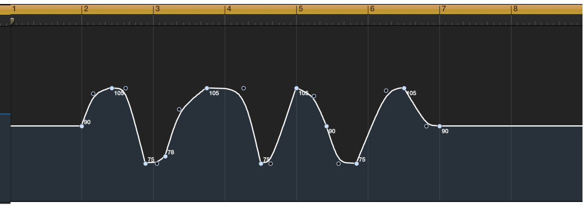
Dynamic manipulation of tempo was accomplished in *Logic Pro X* through automation of the tempo parameter over the time period of the desired waveform. Each test case started on one of the pre-defined BPM's (45, 90, 135, 180) but traversed either sinusoidally or triangularly through segmented time blocks as peaks and troughs ranging plus or minus 15 bpm; shown in 3.5.

Figure 3.5: Dynamic audio tempo automation patterns

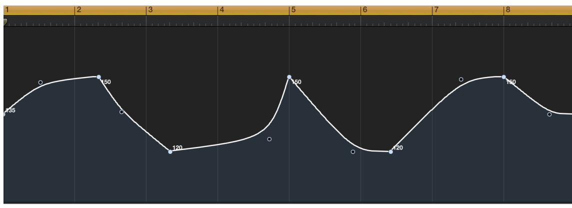
(a) 45 +/- 15



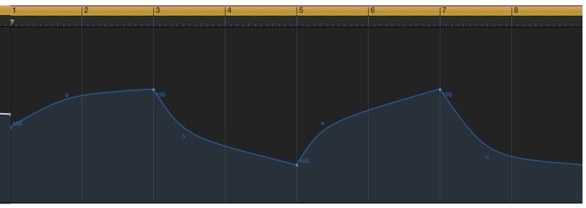
(b) 90 +/- 15



(c) 135 +/- 15



(d) 180 +/- 15



3.2 Test Suite

High precision data acquisition and the minimization of delay were the central foci of the test suite design. Due to the extensive amount of publicly available libraries, multithreading capability, pandas dataframe structure, and plot integration via matplotlib, *Python* was chosen as the development environment. Complementary to the software platform was the implementation of a tap onset detection mechanism via force sensitive resistor (FSR) and the *Arduino Uno*.

3.2.1 Software Development

fill out section

Discuss code breakdown

GUI

Haptic onset detection

Tap onset detection

Multithreading

Audio onset detection

Plotting

3.2.2 Tap Onset Hardware

fill out section

3.2.3 Latency Evaluation

Overall strategy to minimize delay maximize accuracy/precision

fill out section

Sources of potential error:

*FTDI/USB -¿ Pro Trinket (16MHz) –¿ Laptop

*USB -¿ Arduino -¿ Laptop

*Serial write to haptic to motor spin up

*FSR analog read/mentioned debounce

*python thread time

Evaluation with scope:

3.2.4 Setup

To initialize setup, the subject is seated and given a pair of closed-back headphones. The FSR is situated to their preference, either dominant or non-dominant hand, and secured into place. Unlike a keyboard or button the FSR gives little to no feedback or rebound. This ensures a confident tap on each onset while providing no tactile response. The approach seeks to avoid intrinsic lag due to its independence of mechanical components. The delay limit is defined by the threshold applied in the software to avoid debounce, as discussed in Section 3.2.1

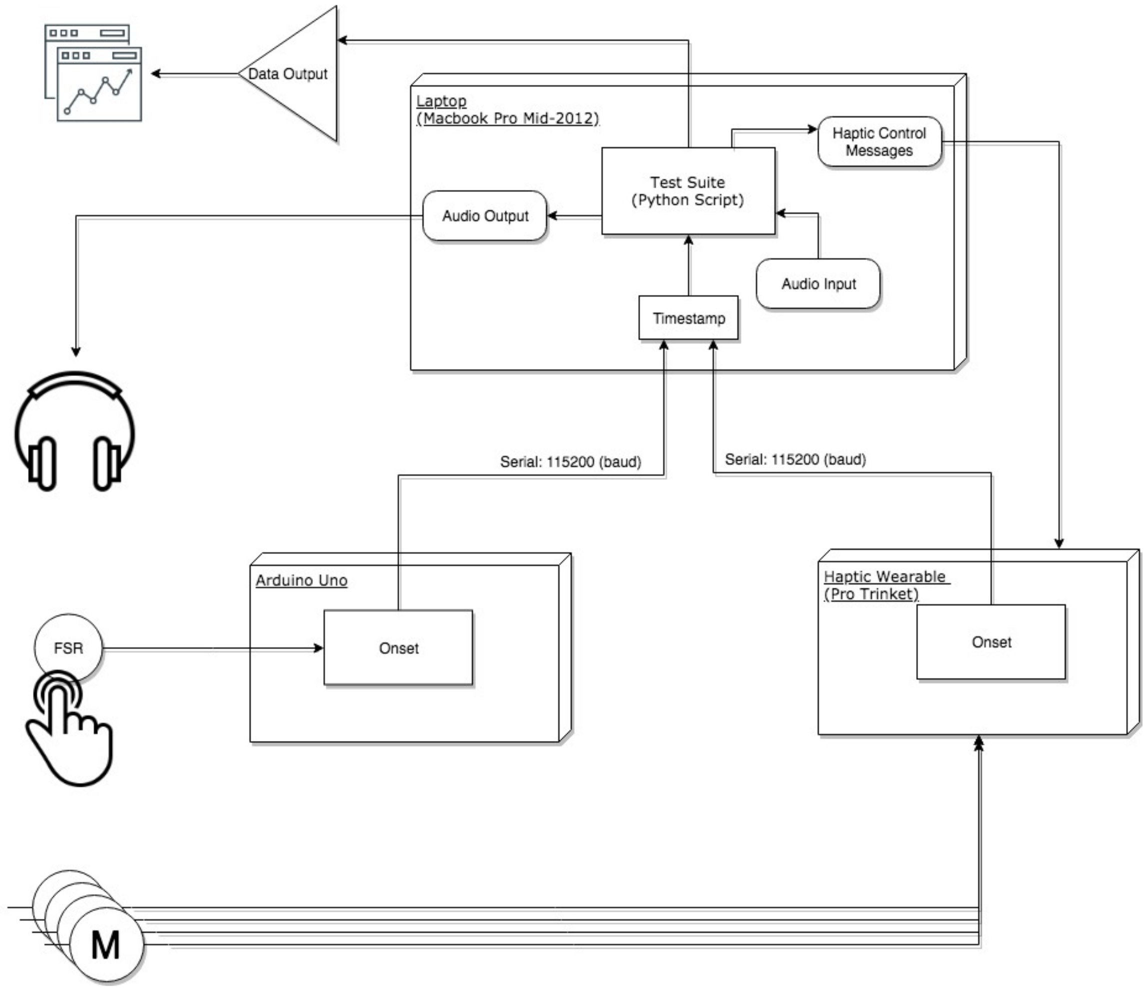


Figure 3.6: Test Suite Flow Chart

The Python file *testSuite.py* is run and the UI will prompt the subject to input their name, read the instructions, agree to the conditions of the test suite, and commence with the test. The first 8 are practice tests to get used to the haptic sensation as well as the variety of audible test cases. The order of test case execution is scrambled with a static seed pseudo-random generator such that every user encounters the same test order. Every iteration of the test plots the Tap Onset, True Onset, and Sanitized Onset for the purposes of feedback and affirmation of correct tapping as seen in Figure 3.7. Upon completion of the 48 test cases, the users are asked to fill out a survey for feedback.

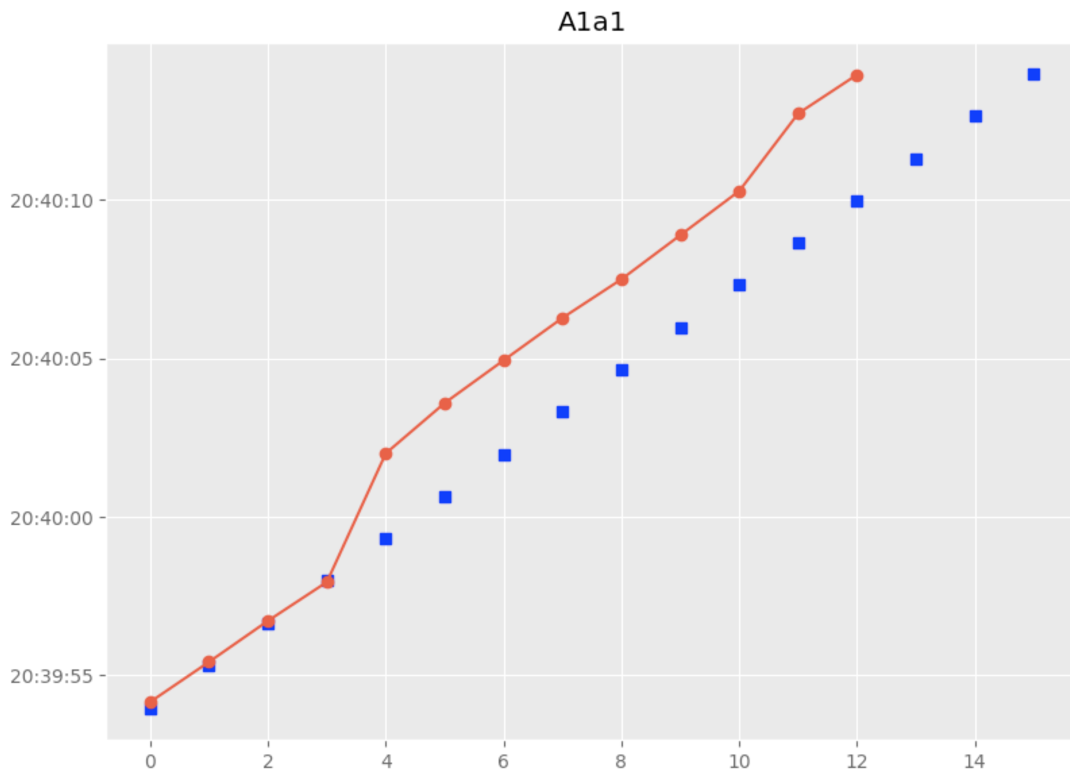


Figure 3.7: Test Case Feedback Example

Example Output

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Chapter 4

Data Analysis

4.1 Results

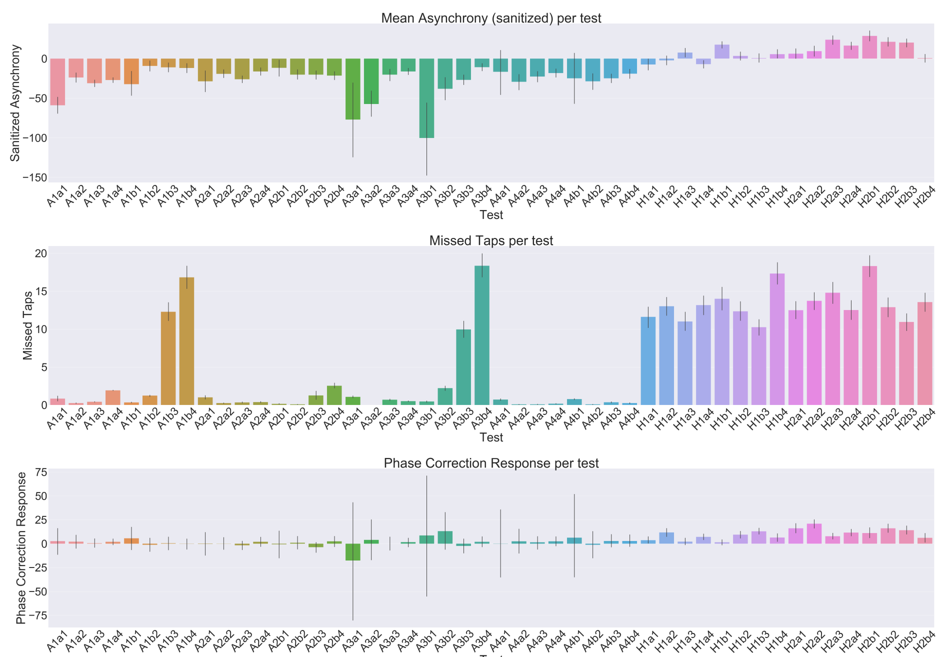


Figure 4.1: Overview of all tests across all participants

Chapter 5

Conclusions

5.1 Future Work

Though much effort went into providing an important framework for the haptic to operate smoothly from a hardware standpoint, the most important progress with the final prototype was the solidification of the software framework. With the integration of delay independent state-machines performing synchronous tasks, haptic mode selection, and precise bpm control, the vibrotactile haptic could enter the next phases of development.

The addition of BLE capability to issue commands over a paired interface such as an app on a smartphone, custom PCB to minimize form factor, and independent node abstraction of each vibrotactile could be realized. This would allow wearers capability to place a programmable array anywhere on their body enabling wide surface area dispersion.

Lastly, experimentation with other types of vibrotactiles; either the Tactor, TacHammer, or LNA's would be more optimized for touch applications with cleaner signals, dynamic range, and optimized for skin resonance (250Hz).

5.1.1 Wireless Prototype

Over the course of summer of 2018, a wireless prototype was developed which eliminated the FTDI over USB interface and was completely reliant on battery power.

A 9 V was connected to a voltage regulator supplying up to 5 V for the motors and 3.3V for the new MCU, sourcing up to 500 mA/hour with enough isolation to have a significantly stronger motor vibration. The MCU was based on the Particle ecosystem, a cloud based IoT framework, and granted BLE and wireless capability. The code was altered to adapt the publish/subscribe methodology where simple numeric BPM values could be passed as API calls to the device given proper OAuth2 authentication.

5.1.2 Beat Tracking

Max Patch based on `THIS RESEARCH`

does this

for the purposing of testing this

5.1.3 Extra-musical Applications

Parkingson's research

Stroke gait rehabilitation research [20]

Through their research they discovered the extension of the application towards those with restricted mobility and morphed the project into the haptic bracelet 4 years later.

Stroke survivors usually suffer from for the purpose of gait rehabilitation. The results were promising.

Paper discusses the prior research of audio stimulation and how it yields immediate improvement through entrainment but that they are not lasting

Focussed on triggering the tibialis anterior which contrasts the principles of entrainment, which would utilize rhythmic beats in any sensory modality, regardless of placement. Also haptic masking from leg-to-floor-impact

One patient who was a veteran mentioned that it put a marching sense back into his mind and helped remind him of that sensation of even walking.

Appendix A

Haptic Design

This chapter briefly touches on the field of haptics A.1 and delves into considerations impacting design A.1.1. This leads to a discussion of the requirements A.2, initial prototypes A.3, and overall challenges which were overcome that led to the development of the final prototype, the vibrotactile array A.4.

A.1 Brief introduction to haptics

Haptics are the field of research which concern the sense of touch as it applies to *kinesthetic* and *tactile* sensation. The tactile sense enables humans to perceive object properties through skin contact while the *kinesthetic* or *proprioceptive* sense lets one perceive the positions, movements, and forces on one's own body.

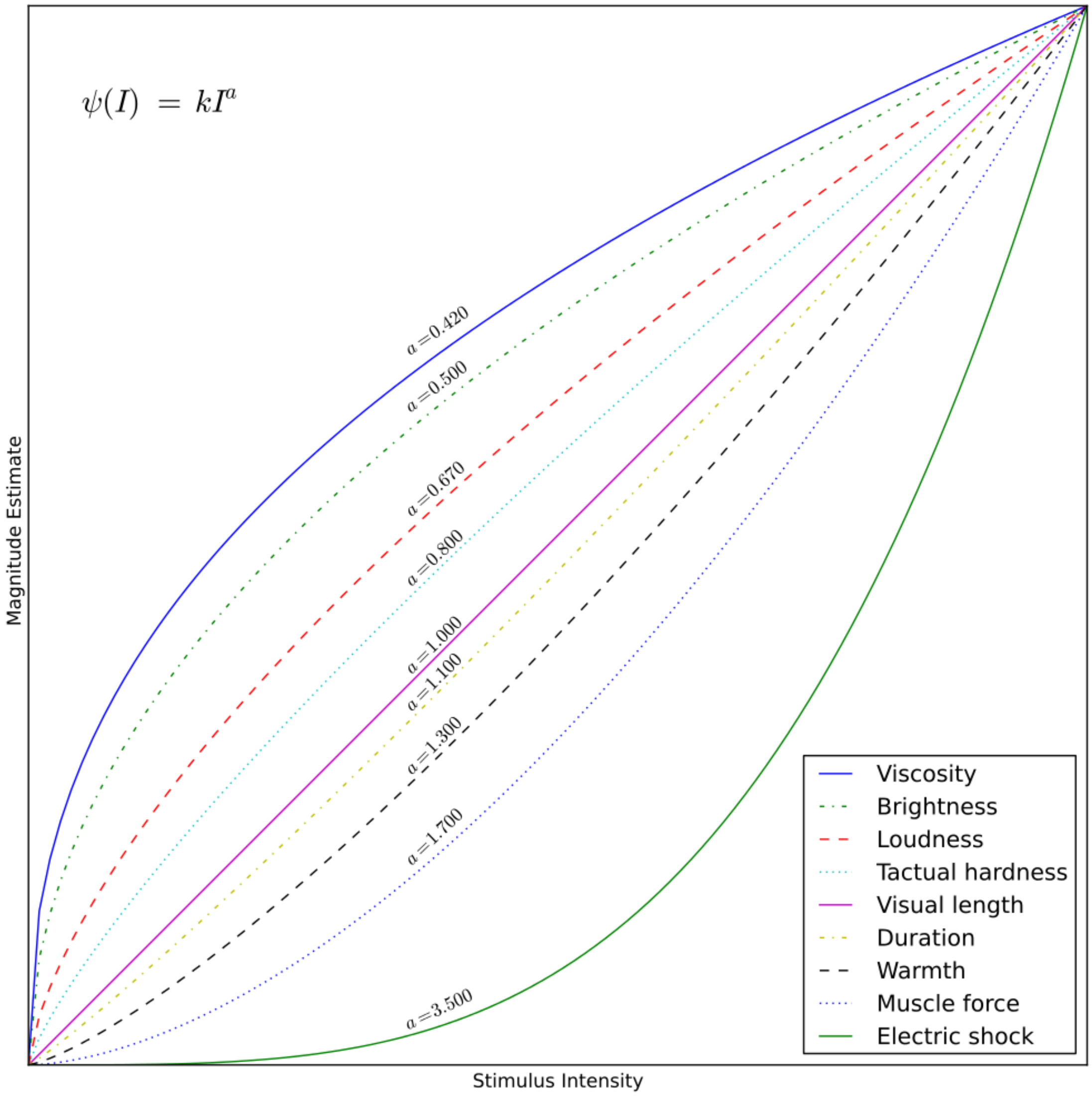
The skin is lined with an array of sensory receptors which respond to mechanical pressure and distortions such as skin deformation. The *lamellated* or *pacinian corpuscles* (PC) are responsible for sensitivity to vibration and pressure. These rapidly adapting receptors are responsible for vibrotactile perception in glabrous skin.

Sensitivity to a tactile stimulus grows with the area in contact with the skin and also improves with the stimulus duration until it reaches a point of saturation. When pressure is continuous an effect called *haptic masking* (also known as the *summation effect*) is possible. The overstimulation of the *pacinian corpuscles* causes the brain to ignore these messages with a mechanical filtering system which renders the stimuli to noise in order to focus on other important happenings. If this was not the case, a person could for example feel the pressure exerted by wearing clothing [21]. This phenomena is important to consider when dealing with haptic placement. As mentioned in 2.1.2, when the vibrotactiles were placed over a larger area haptic masking was avoided and the results closely matched the auditory modality.

A.1.1 Haptic Considerations

The following questions arise based on extensive research done by Choi and Kuchenbecker [21] and are crucial concepts underpinning the creation a meaningful haptic:

1. *Can the user feel it?* Perceptibility of vibrotactile stimuli is strongly dependent on the frequency of vibration. The minimum threshold is observed to be between 150-300Hz and can cover an area smaller than 0.1 micrometer. The absolute thresholds are dependent on factors such as body site, contact area, stimulus duration, stimulus waveform, contact force, skin temperature, presence of other masking stimuli, and age.
2. *Can the user distinguish between the different vibrotactile cues being displayed?* This is quantified by the discrimination or *difference threshold* also called the *Just Noticeable Difference* (JND). It is defined as the smallest amount a stimulus intensity much change to produce a noticeable change in sensory experience. The JND is measured as a *Weber fraction*: $\Delta I/I = k$ or the ratio of difference threshold to the reference level. Research into experimental psychology has deemed a 20-30% difference in amplitude or frequency is necessary for robust discrimination between vibrotactile stimuli in practical applications.
3. *How strong does a certain vibrotactile cue feel to the user? Steven's power law* describes the relationship between the magnitude of a physical stimulus and its perceived intensity or strength. See Figure ??



When a stimulus intensity I is above its absolute threshold, humans perceive its magnitude as $\Psi(I)$(perceptual strength). The exponent (dependent on stimulation freq) determines the growth rate of the perceived magnitude and ranges from 0.35 to 0.86 for vibrotactiles. Perceived intensity is a function of frequency and amplitude of vibration (also affecting perceived pitch).

4. *How good are users at judging timing of vibrotactile cues?* Tactile perception is generally considered to have high temporal acuity. Vibrotactile temporal

resolution research cites a human's ability to distinguish successive pulses with a time gap as small as 5 ms (12000 BPM). This resolution is better than vision (25ms) but slightly worse than physiological experiments into the peripheral auditory system which cites a theoretical best case scenario of approximately 2 ms [22] [23]. Keep in mind that these are temporal resolutions measured with brain scans and do not necessary translate into the limits of sensorimotor response, which, according to prior research, indicates a more realistic resolution of approximately 50ms.

5. *Can Vibrotactile cues elicit any other perceptual effects?* Below 3 Hz is considered slow kinesthetic motion. Between 10-70Hz is the sensation of rough motion or fluttering and between 100-300Hz is the sensation of smooth vibration. Subjective quality of a vibrotactile stimulus can be controlled by modifying the envelope of the stimulus amplitude.

A.1.2 Vibrotactiles

The exploration of touch actuation led to the evaluation of available vibrotactiles. The following is a breakdown of available vibrotactiles conducted to inform design perspective.

1. Linear electromagetic actuators
   - solenoid:
     - can leverage resonance, large output for small input
     - force dependent on position within magnetic field
     - influenced by device orientation relative to gravity
     - heats up during use
   - voice coil:
     - linear dynamics yields consistent output, relatively easy to model
     - *C2 tactor*:
       - 7.6mm contactor preloaded against the skin
       - suspension resonates at 250Hz for maximum perceptibility

- *Haptuator*:
  - moving magnet design
  - not meant to touch the skin
  - optimized to render frequencies above 50Hz

2. Rotary Electromagnetic Actuators (ERM - eccentric rotating mass)
   - simple, reliable, rotate continuously with a constant voltage/current applied
   - off-center mass affixed to output shaft so that its rotation exerts large radial forces on the body of the motor
   - couples freq and amplitude of the resulting vibration to the motors rotational speed
   - small voltage yields weaker vibrations
   - intrinsic spin-up time could cause delay at the start of the cue
   - internal static friction can prevent motor from rotating when the applied voltage is very small
3. Nonelectromagnetic Actuators - Piezoelectric effect
   - respond to inputs very quickly and can output arbitrary waveforms
   - typically require input on the order of 100V
   - high stiffness of skin creates a need for relatively heavy vibrotactile actuator
   - most don't have power to move the skin without pushing off a cumbersome mechanical ground
4. EAP (electroactive polymer) actuators
   - uses elastomers rather than ceramics
   - can achieve larger deformations for lower drive voltages
5. SMA (shape memory allow) actuators
   - remembers original shape
   - mechanical properties altered in response to temp changes
   - slow response time, large hystoresis, high energy consumption
6. Pneumatic systems

- compact, light
- require high-pressure air source
- struggle to output high-frequency signals

7. Forced impact
    - TacHammer - new technology, specs unknown, hard to acquire

Vibrotactile Constraints

1. Create consistent mechanical coupling between actuator vibrations and users skin
2. Slight changes to such a system drastically affect a users ability to feel and comprehend the rendered signals.
3. For fixed actuator size/activation level, magnitude of created vibrations is inversely proportional to the mass of the object.
4. High bandwidth accelerometer can be used to measure vibration output performance [16].
5. When the application involves a large object, a wearable device, and/or multiple stimulation sites, the optimal vibrotactile rendering paradigm is to vibrate one or more small zones.
    - In a tactile display application the localization accuracy of 250-Hz vibrotactile stimuli around the waist was 74% with 12 equidistant tactile actuators (tactors), 92% with eight tactors, and 97% with six tactors [21].

A.2 Design requirements

The initial requirement set forth by Professor Neely in the Haptic Enviro-Sensing Metronome (HESM) design draft is centered around an analogue wave that could squeeze and release. As the analogue wave approaches its crest it provides insight forecasting the approaching *crusis*, allowing the user to prepare for and rebound from the "click-moment" with rich entrainment.

This observation is in direct parallel to external vibrotactile metronome research as discussed in 2.3. The constraint was such that the pulses should feel continuous and not discrete in order to capture the essence of pendulum motion.

As the intention is to encourage entrainment of the human body to external forces, the frequencies required are quite low, based on the tempi of slow walking to running gaits (40 bpm/.67 Hz to 180 bpm/3 Hz).

A.3 Initial Prototypes

In order to capture the sensation defined in the design requirements, a series of prototypes were rapidly developed.

A.3.1 Solenoid bracelet

Initial introspection towards capturing the squeeze and release sensation led to the rapid prototyping of a simple solenoid bracelet.

Parts List

1. Adafruit Pro Trinket 5V 16MHz
2. N-channel MOSFET
3. 1N4004 diode
4. mini push-pull solenoid

Assembly

The design was inspired and assembled per *Adafruit* specification [24]. The base of an N-channel MOSFET was connected through a 1K resistor to a digital I/O pin on the trinket per Figure A.1. The collector was connected through the solenoid and diode in parallel to Vcc running at 5V.

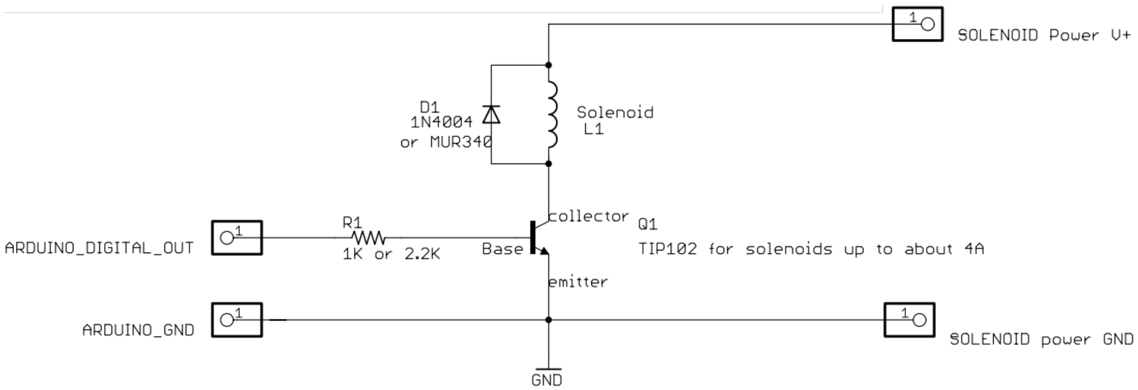


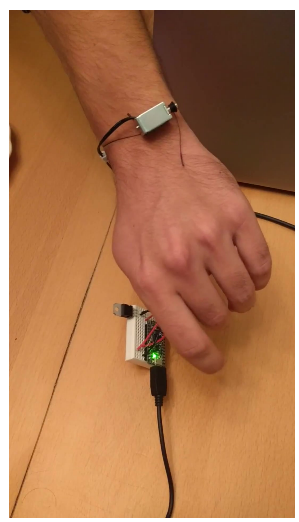
Figure A.1: Solenoid Schematic

Method

As a voltage is applied the slug in the middle of the solenoid is pulled into the center of the coil. The actuation pulls a taught wristband attached to the chasis of the solenoid and as the voltage drops the solenoid retracts releasing tension in the wristband, shown in Figure A.2.

This was controlled in the *Arduino IDE* through a simple PMW signal with increasing duty cycle which output through the digital I/O. The delay was hard coded proportional to the desired BPM.

Figure A.2: Solenoid Wristband Prototype



Outcome

Due to the linear relationship between current draw and pull force, the solenoid required high current and significant voltage thus isolation from the microcontroller was ideal. The necessary rigidity of the band was a cause of discomfort and the lack of positioning options was a detriment to musicians who relied on availability of their hand. Additionally, heat dissipation was at times unsafe and unbearable since the chasis was in direct contact with the skin. Though it captured the tension and release sensation well, there seemed to be a lack of clarity with regards to communication of whether each push pull iteration was a beat length or if a single contraction was the downbeat (i.e. eighth note pulse rather than quarter note). Coupled with the bulky nature of the solenoid chasis, high power requirements and excessive heat dissipation, the solenoid prototype was quickly abandoned.

A.3.2 Single vibrotactile

The subsequent prototype iteration was the first involving a vibrotactile motor. Since the goal was to run everything off of a single board, the voltage constraint was limited to the 5V maximum per *Adafruit Pro Trinket* spec. An ERM motor was chosen for its working voltage range of 2-5V and minimal coin cell form factor (10mm diameter). Like the solenoid, higher applied voltage yielded more current draw but stronger vibration. At 5V, a single motor draws 100mA. The specification was 1100 at 5V which roughly translates to 183Hz. Though not quite at the ideal 250Hz range optimal for skin sensitivity, this was deemed close enough.

To realize the spectrum of capability for vibrotactile sensation (beyond pulse width modulation of the signal) a haptic motor controller with a pre-installed library of effects was acquired.

The goal of this design was to test the ERM sensation on a portable wearable. The MCU was altered from the Pro Trinket to the Flora which ran at 3.3V and had less digital I/O pins, but supported external connectivity and took up less surface area.

Parts List

1. Vibrating mini motor disc
2. Adafruit DRV2605L Haptic Motor Controller
3. Flora Wearable Bluefruit LE Module
4. Flora Wearable electronic platform
5. LiPo Battery - 3.7v 1100mAh

Assembly

First, the ERM leads were soldered to the DRV2605 haptic motor controller and connected via I2C protocol to the complimentary pins on the Flora (SCL,SDA). To experiment with triggering the vibrotactile wirelesssly, the bluetooth low energy (BLE) module was added and the send and receive (Tx/Rx) pins were connected as referenced in Figure A.3. The battery was connected via the built-in terminal clip and last the entire prototype was fitted into the space of a sports wristband with the vibrotactile on the inside touching the skin.

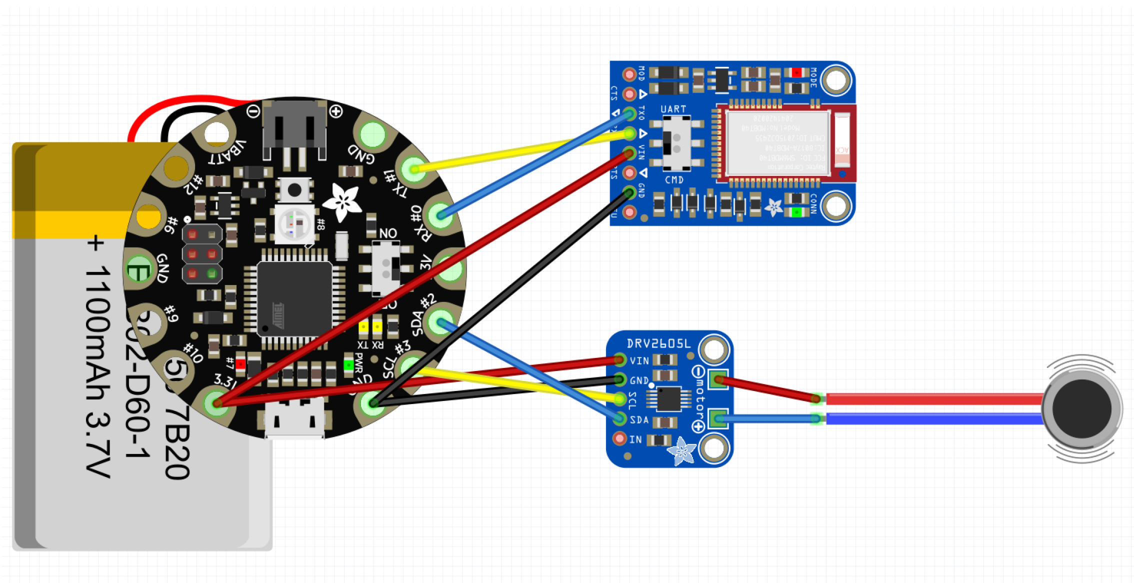


Figure A.3: Prototype 2 - Single vibrotactile, wireless connectivity

Method

Once the hardware was setup, the haptic library was iterated through for selection of the most influential effect. The optimal sensation chosen was a queue of two chained effects according to the DRV2605 datasheet[**?**]:

- 83 - Transition Ramp Up Long Smooth 2 - 0 to 100%
- 71 - Transition Ramp Down Long Smooth 2 - 100% to 0

Within the Arduino IDE the Bluefruit library and dependencies were imported and the bluetooth low energy connection configured via UART. On the client side, the connectivity was validated via the publicly available Bluefruit application on an external Android device. The app would send integer values representing the desired BPM to the connected haptic wearable. The code was written such that upon setup and BT pairing, the main loop was polling for packets. Once received in the buffer, the new bpm value was parsed into a period value in milliseconds via equation A.1

$$period = \frac{60,000}{bpm} \tag{A.1}$$

Since the highest operational bpm specified was 180, the shortest period would be an interval of 333.33 ms. This value divided in half gave the maximum allowed ramp up time for the motor, approximately 150ms. The new period value was fed into a state machine which set the on and off state of the motor based on a timer from half the calculated period as well as the 150ms off state.

Outcome

The singular ERM prototype granted key insight into the capability of a vibrotactile to create the desired awareness and fill the interstitial space; though it was found to be lacking the ability to fully command the wearer's attention. This was primarily due to the fact that it was driven by a 3.3V board which inhibited the vibrational strength. The next iteration needed to operate at higher voltage to get a stronger vibration. It was also deemed necessary to increase the number of vibrotactiles to work in an array format in complete synchronicity to explicitly communicate the necessary ramp down and up sensation.

Though the haptic motor controller was a critical evaluation tool for selecting the vibration effect, it was crucial for the final prototype to be able to turn on the motors at full voltage as quick as possible in order to minimize ramp up time. Chaining the motors would also optimize ramp up time in allowing a motor the time to fully spin back down while the adjacent was spinning up.

Furthermore, the *delay()* function added in the BLE section of code was causing the haptic to drift slightly in tempo beyond five minutes of runtime due to the programmatic halting and resumption of dependent timers. The next prototype would have to move away from the delay function which halted program execution.

A.4 Vibrotactile Haptic Array

The final prototype was an array of four vibrotactiles. Several hardware advancements were implemented in order to solve design challenges. The overall process is detailed below.

A.4.1 Hardware

The main board was reverted back to that used in the solenoid prototype, the 5V 16MHz *Adafruit Pro Trinket*, in order to provide maximum possible voltage to the motors. This board did not have built in serial communication so an FTDI to USB cable was necessary in order to communicate with the device. Bluetooth connectivity was abandoned to concentrate focus on minimized latency.

Parts List

Part Type	Properties	Quantity
Electrolytic Capacitor	capacitance 68F; package 0405 [SMD, electrolytic]; voltage 16V	1
Electrolytic Capacitor	capacitance 10F; package 200 mil [THT, electrolytic]; voltage 25V	4
Ceramic Capacitor	capacitance 100nF; package 100 mil [THT, multilayer]; voltage 6.3V	1
Diode	package diode-1n4001; variant pth	4
Vibration Motor	vibration motor 11000 RPM 5VDC	4
Adafruit Pro Trinket 5V 16MHz	variant variant 1; part # Adafruit #2000	1
2N7000 FET N-Channel	package TO92; type n-channel; part # 2N7000	4
220 Resistor	tolerance 5%; package 0805 [SMD]; resistance 220	5
10k Resistor	tolerance 5%; package 0603 [SMD]; resistance 10k	1
FTDI to USB	Adafruit FTDI Serial TTL232 USB Cable [ADA70]	1
Shrink wrap	Heat Shrink Pack	1

Table A.1: Vibrotactile Haptic Array Parts List

Assembly

Since each digital I/O of the Trinket could only source 20mA, four N-channel 2N7000 transistors were chosen to act as switches and current isolators for controlling power to the motors. These are labelled (N) in Figure **??**

Each motor was connected from the power source (5V Vcc), to the drain of the transistor. When the transistor received a signal past its bias voltage of 0.8V it was switched on. This allowed the drain-source channel to be opened and an onrush of current to flow from Vcc to the motors and through to ground.

A 1N4001 diode was placed in parallel with the motor from the 5V Vcc node to the drain of the N-channel 2N7000 to protect the transistor by shorting out the onrush of back current emitted from the motor during immediate shutoff. Principally, the motor will act as an inductor; a sudden change in current creates an equivalent voltage to keep that current flowing short term. This could fry the transistor if the diode was not in place to short out this negative voltage spike as shown in A.4

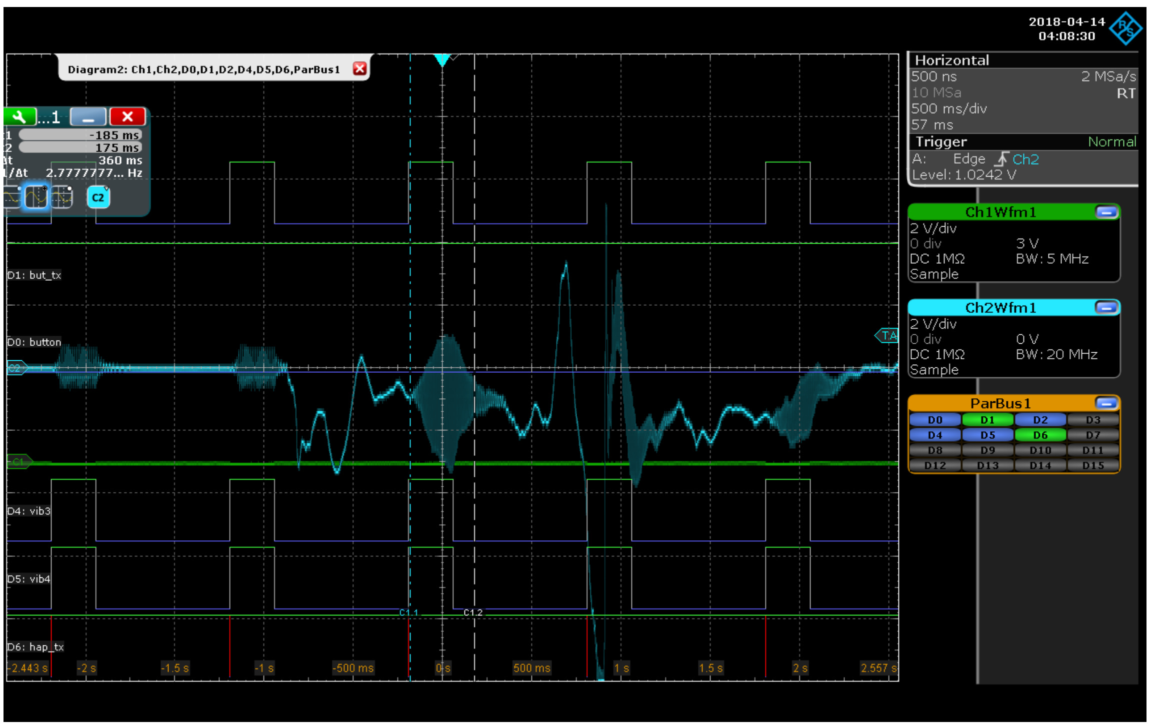


Figure A.4: Motor ringing after abrupt shutoff

The digital pins 5,6,9,10 (denoted with yellow and grey wires in Figure A.5) output a pulse-width modulated signal to be used as triggers, or control switches, for the transistors. In order to limit the current that the digital output must source and to protect the transistor gate, a 220 Ohm resistor was connected across the digital I/O pin and the gate of the 2N7000 for each pin.

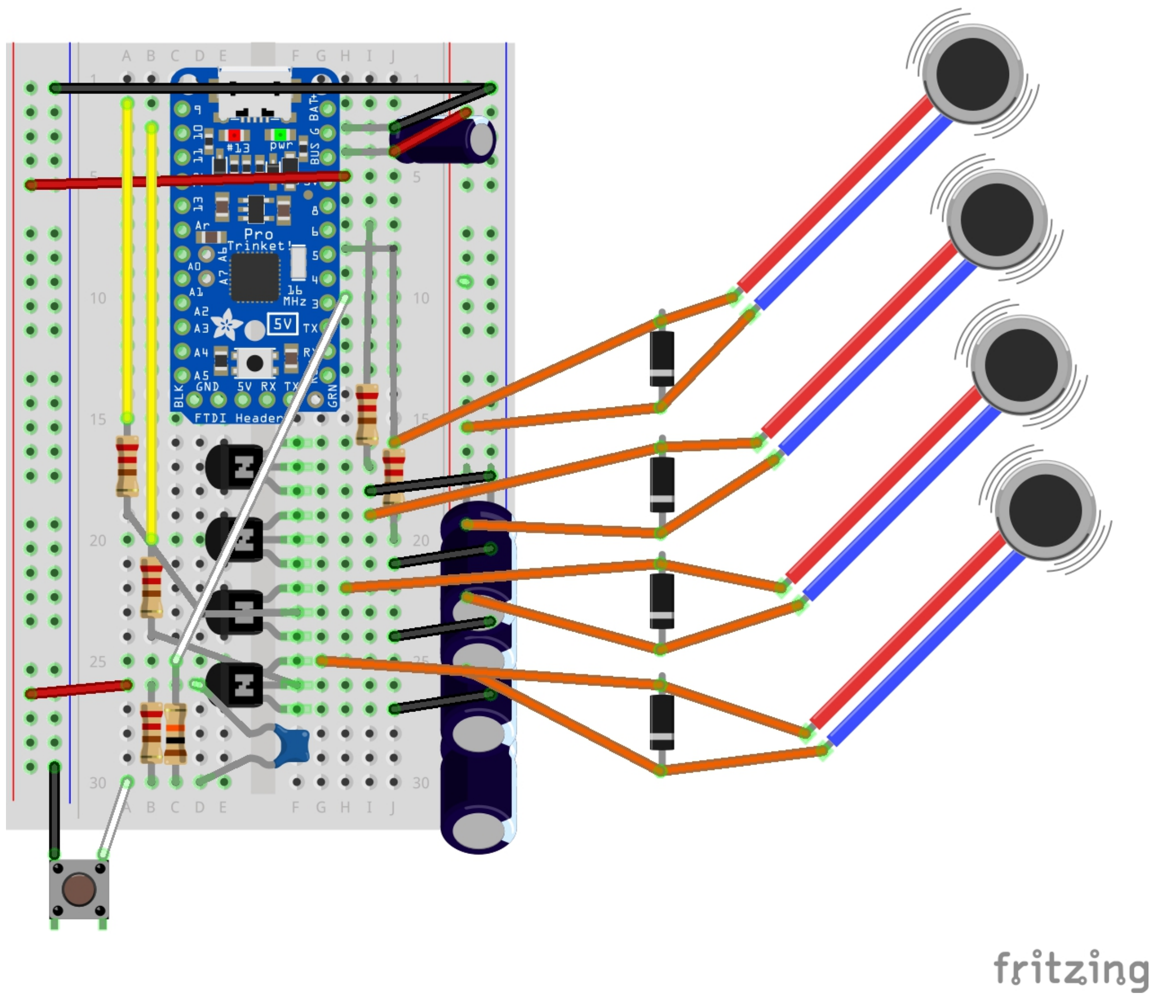


Figure A.5: Final prototype wiring mockup

The voltage across the rails (Vcc and ground) was viewed on a Rohde & Schwarz RTO 2004 oscilloscope. The analyzed waveform showed some unfavorable dips primarily when all motors were running due to the high current draw from the ERMs in addition to some ringing (overshoot), seen in Fig A.6.

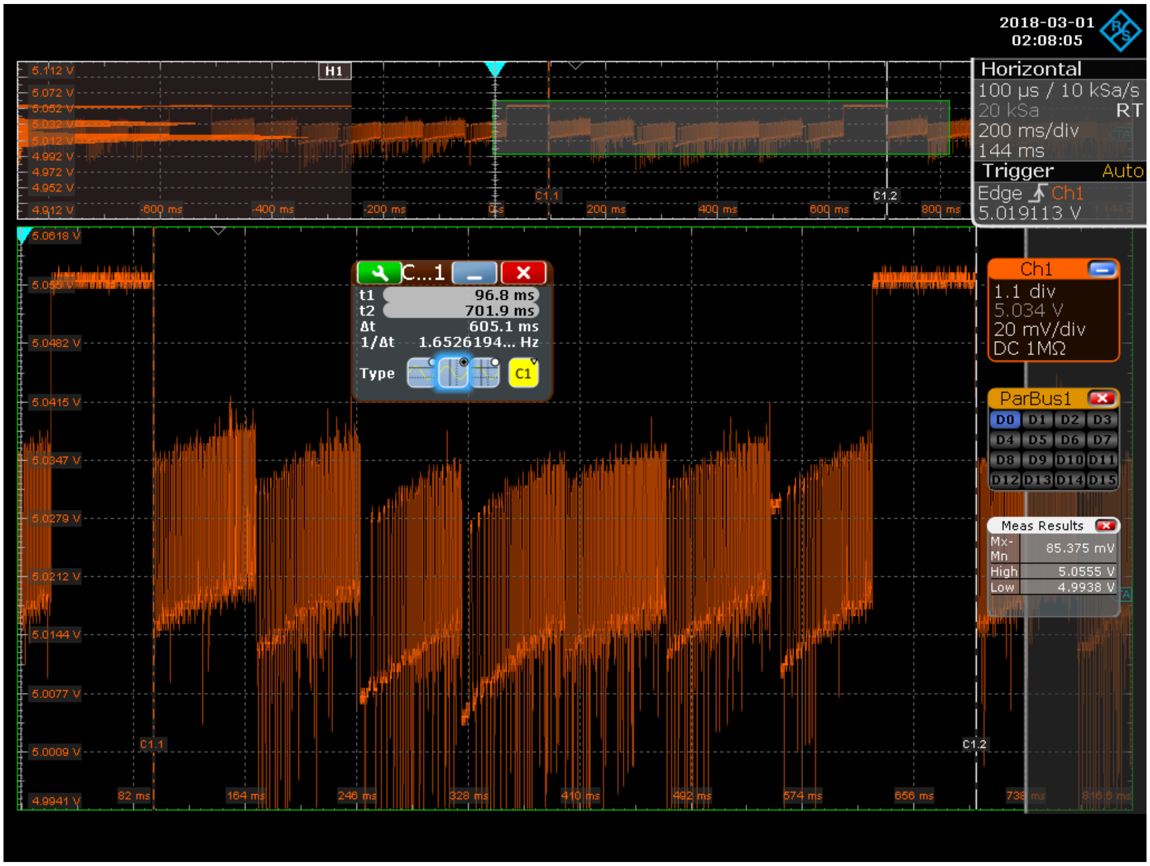


Figure A.6: V drop across Vcc and HF ringing: Pre-cap

A.4.2 Improvements

Capacitors were added to act as buffers from the power source to the motors, in doing so they helped provide immediate current to the motors when the PWM input signal engaged the transistor and the motor would go from an off state to an immediate on state drawing high amounts of current. Large electrolytic capacitors are known for their ability to supply high currents for a few milliseconds, more so than a battery or in the haptic wearables case, USB power. These were added across Vcc and ground nearest to the Trinket as well as across each of the node rails nearest to the motors. The change in output shape can be analyzed in Fig A.7.

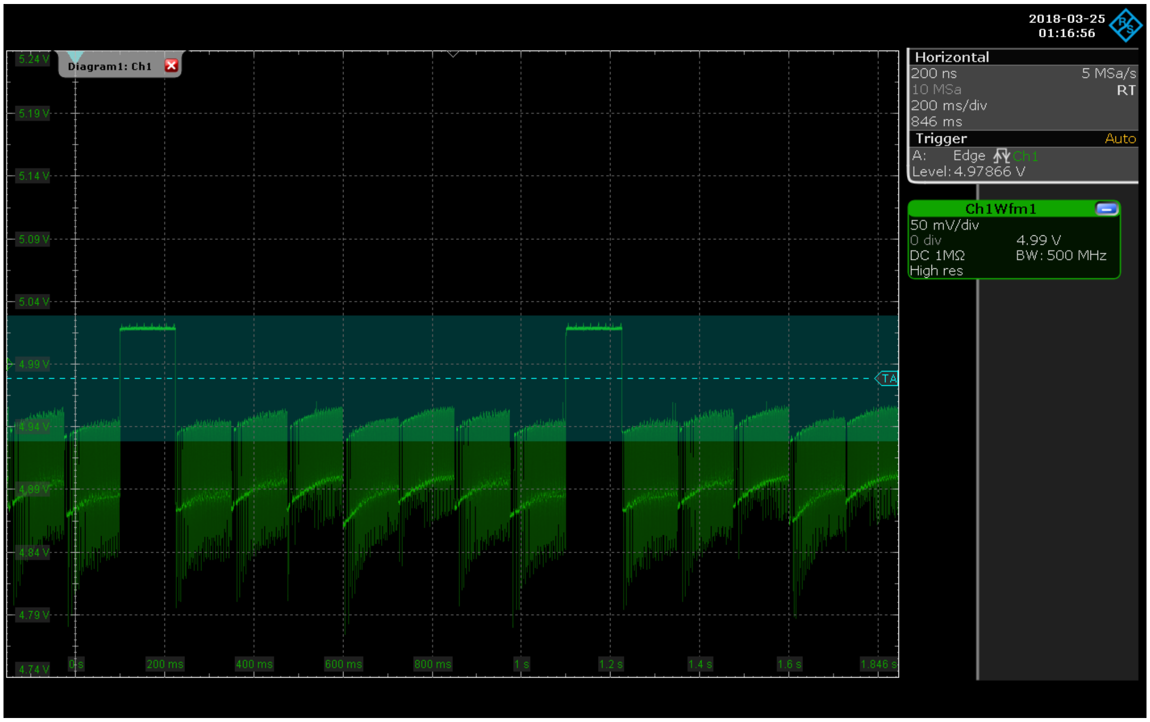


Figure A.7: V drop across Vcc: Post-cap

As an additional manual tap tempo option for the user to experiment with, a push-button was added and connected to the only interrupt capable pin on the Trinket, PIN 3. An RC combination was chosen to act as a low-pass filter to protect against debounce scenarios.

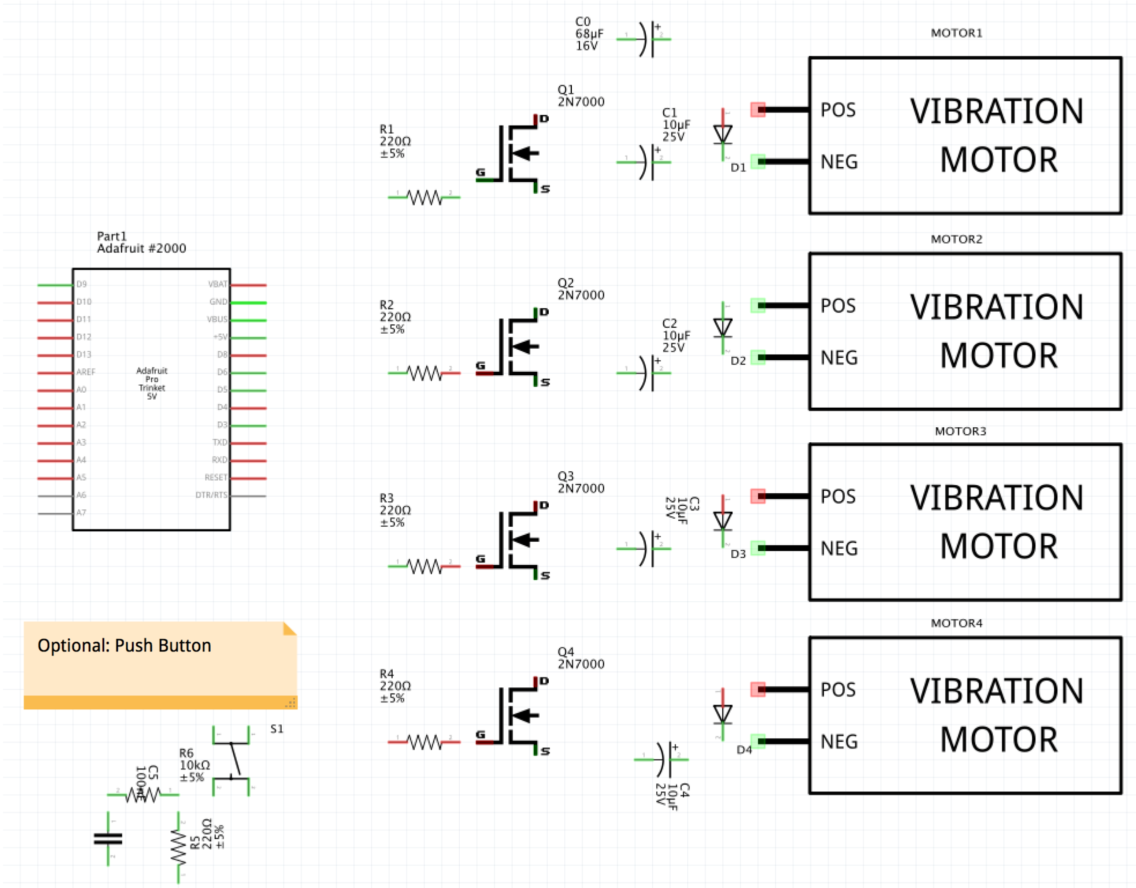


Figure A.8: Final prototype abstracted schematic

Motor Characterization

In order to determine an accurate baseline for motor ramp up, a singular motor was firmly attached to a piezoelectric transducer. The remaining motors were connected to the digital bus of the scope for timing analysis.

Figure A.9: Motor ramp up time

As seen in Fig A.9, the motors reach full amplitude over approximately 67ms before the signal goes low and starts to decay. The AC shape of the waveform is due to the nature of the ERM. The rotating mass translates left and right movement into a voltage oscillating in amplitude. Multiple ramp up times were averaged using this method such that the time before perceptibility was determined to be about a quarter of the ramp up time (approximately 50ms), in agreement with 2.2. This is clearly shown in Fig A.10 below.

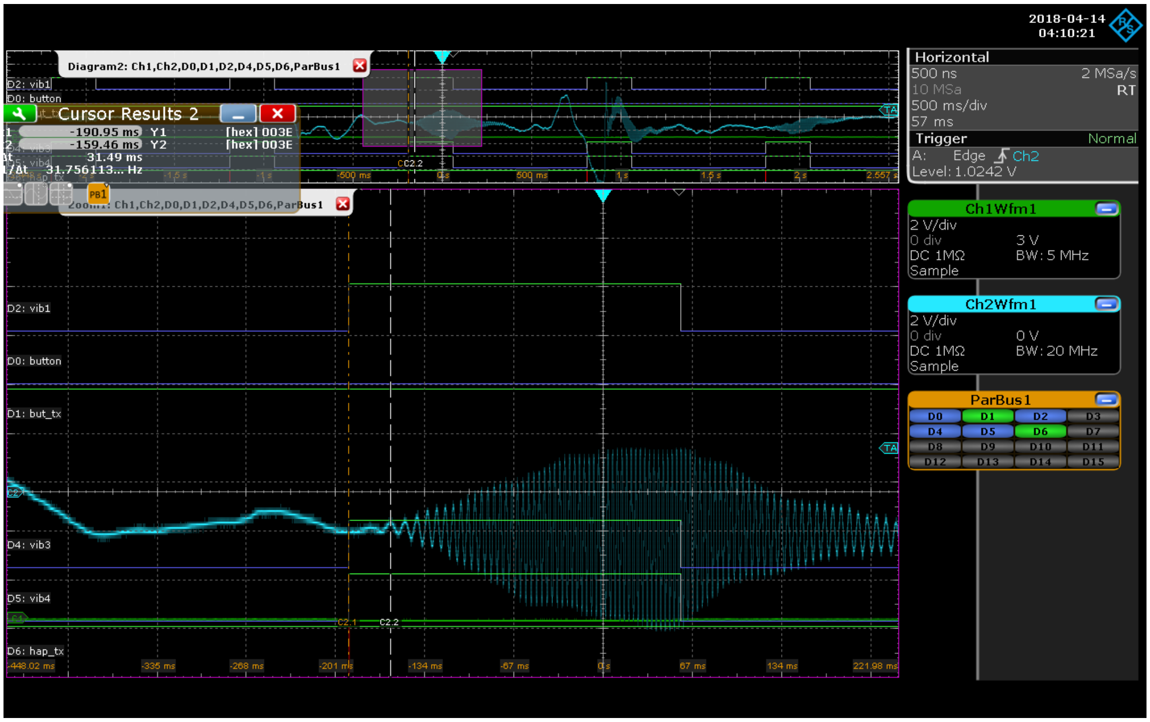


Figure A.10: 50ms motor ramp up time to perceptibility

A.4.3 Software

The code was written in the Arduino IDE which utilizes C++.

Outside of the tap tempo hardware push button, the main control flow was through serial communication over FTDI. The device communicated at 115200 baud and a small method was written to read the serial buffer and parse the incoming bytes into integers. The first input was a setter to store the current operation mode with 1 being the Discrete (Instantaneous) Mode and 2 Continuous. Afterwards, any other number (thresholded from 20 to 220) would be stored as the bpm.

The period was calculated using formula A.1

The main control flow was two state machines which were delay independent. Depending on mode selection it would send digitalWrite commands to each motor within the set time period. Though the AnalogWrite functionality built into the Arduino IDE could PWM the signal and potentially control the motor just below its turn on state, the transistors would not allow this due to their rapid speed and turn on voltage and the motors would be always vibrating. This was a design decision informed by the previous single vibrotactile prototype implementation.

The first state started a millisecond precision timer. In discrete mode the second state wrote all digitalIO pins HIGH for a quarter of the period as shown in Fig A.11. A half on/off implementation was considered but determined to be not as efficient in communicating rapid pulses since the ramp down time overlapped with the next on period. During this state a flag was printed over serial to be read in later indicating when the test software could timestamp the onset.

```
void go(){
  if(discrete==true){
    switch (newState){
      case READY:
        if(start){
          average = avg;
          startTime=millis();
//          Serial.println(startTime);
          newState++;
        }
        break;
      case ON:
        digitalWrite(vibPins[0],HIGH);
        digitalWrite(vibPins[1],HIGH);
        digitalWrite(vibPins[2],HIGH);
        digitalWrite(vibPins[3],HIGH);
        // digitalWrite(ledPin,HIGH);
        if((millis()-startTime) >= ((average * 1)/4)){
          newState++;
          Serial.println("onset");
        }
        break;
      case OFF:
        digitalWrite(vibPins[0],LOW);
        digitalWrite(vibPins[1],LOW);
        digitalWrite(vibPins[2],LOW);
        digitalWrite(vibPins[3],LOW);
        // digitalWrite(ledPin,LOW);
        if(millis()-startTime >= average){
          newState=0;
        }
        break;
      default:
        break;
    }
  }
```

Figure A.11: Discrete/Instantaneous state machine

The state machine in continuous mode functioned similarly but was divided into 4 ramp-up states and 4 ramp-down states as shown in Fig A.12. Each state held its vibrotactile high for 1/9 of the overall period or IOI but lingered on the fourth vibrotactile slightly longer *(2/9th's * IOI)* to convey the pinnacle of the beat. This state also sent the onset trigger.

```
if(discrete==false){
    switch (state) {
    case START:
      if(start){
        average = avg;
        startTime=millis();
//          Serial.println(startTime);
        state++;
      }
      break;
    case RAMPUP_STEP_1:
      digitalWrite(vibPins[0],HIGH);
      // digitalWrite(ledPin,HIGH);
      if((millis()-startTime) >= ((average * 1)/9)){
        state++;
      }
      break;
    case RAMPUP_STEP_2:
      digitalWrite(vibPins[0],LOW);
      digitalWrite(vibPins[1],HIGH);
      if((millis()-startTime) >= ((average * 2)/9)){
        state++;
      }
      break;
    case RAMPUP_STEP_3:
      digitalWrite(vibPins[1],LOW);
      digitalWrite(vibPins[2],HIGH);
      if((millis()-startTime) >= ((average * 3)/9)){
        state++;
        Serial.println("onset");
      }
      break;
    case RAMPUP_STEP_4:
      digitalWrite(vibPins[2],LOW);
      digitalWrite(vibPins[3],HIGH);
      if((millis()-startTime) >= ((average * 5)/9)){
        state++;
      }
```

Figure A.12: Continous state machine

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