Vibes: Synthesizing Vibrations with Interactive Visualizations

Anchit Mishra
University of Waterloo
Waterloo, Canada
amishra@uwaterloo.ca

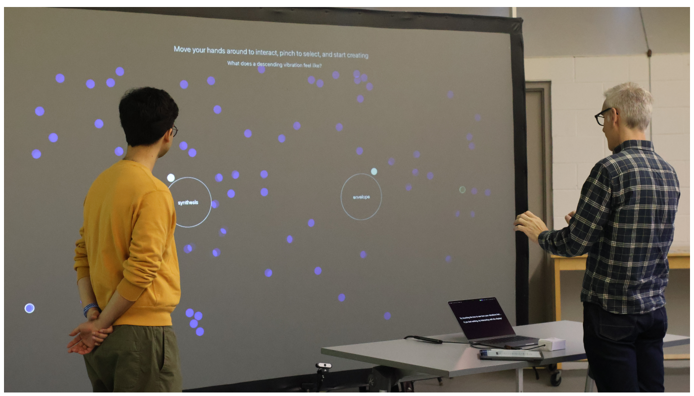


Figure 1: A user interacting with the Vibes installation.

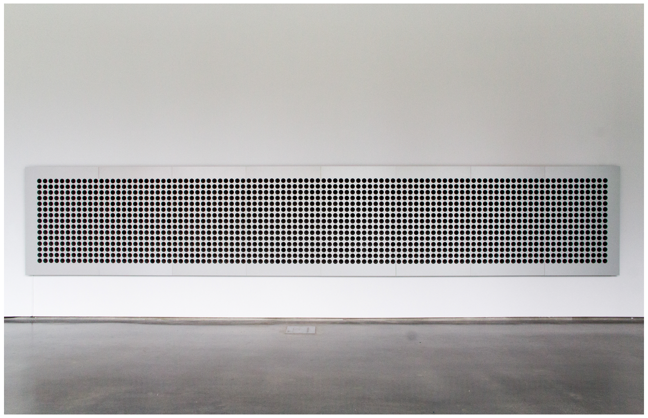
Every submission will be assigned their own unique DOI string to be included here.

Abstract
Despite its evolutionary importance and ubiquity in our everyday lives, haptic feedback is a modality of human-computer interaction that is poorly understood by non-expert audiences. The most accessible form of haptic feedback is based on vibrations, and its synthesis is largely similar to music synthesis techniques. To help audiences develop an intuition for how vibrations are synthesized, this design tool installation, named Vibes, presents a hand-tracking and pinch-based interface for synthesizing vibrations in real time. People can stretch, compress, and reshape waveforms and obtain live feedback through an actuated box, authoring vibration effects corresponding to different labels of sentiment/affect. Vibes illustrates how audio primitives, synthesis techniques such as amplitude and frequency modulation (AM and FM), and envelopes work through an unassuming, home speaker-like form factor, helping convey the natural connection between sound and touch.

Introduction
Conveying the idea behind haptic feedback to general audiences can be challenging due to various factors, including a lack of accessible design and prototyping tools, the increased subjectivity of touch as compared to vision and hearing, and the lack of consistent, grounding vocabulary to communicate haptic sensations without experiencing them

firsthand. To make things even more confusing, haptic feedback spans multiple modalities, including vibrations, force feedback, thermal feedback, skin-stretch, and even mid-air feedback using ultrasound waves. For designing vibrations, the typical approach is similar to music production, but vibration frequencies used for haptic design are more limited and hence not as expressive as the music someone would write in a music-production tool such as Garageband, for example. For all other modalities, a wide variety of design tools exist to help lower the technical barrier to entry, including voice-based actuation interfaces [12], physical demonstrations [13], and sketching [15, 17].

In this project, I developed an interactive design tool installation named Vibes for the most popular form of haptic feedback - vibrations. Inspired by existing design tools for haptics, coupled with elements from existing art installations, this tool is intended to be used with a larger display, a camera for hand-tracking, and a custom-fabricated box with a haptic actuator mounted on top of it. As shown in figure 1, the visual component of the tool draws most of the attention, but a small white box kept in front of a laptop (along with a prompt on the laptop) invites participants to explore how the interface works. The installation also serves to teach people how vibrations are designed by making use of mid-air gestures, helping convey the similarity between haptics and sound design.



The Microtonal Wall artwork by Tristan Perich. 1,500 one-bit circular speakers play a combined sound with each speaker playing a different note.

Yoko Ono's Wish Tree series of artworks. A tree is selected by the artist, and people are encouraged to tie written wishes to its branches.

Figure 2: Artworks that inspired Vibes' design.

Context

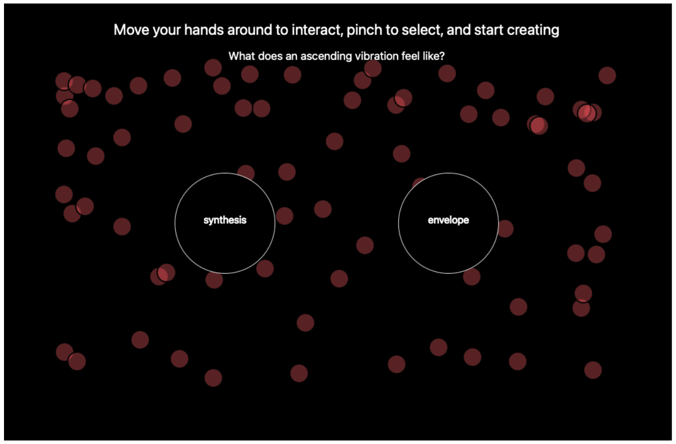
When working with vibrations, two areas of interactive computing and digital art are relevant in addition to haptics. These are audio and vision. Audio involves vibrations, and hence prior work related to sound is relevant. Further, vision was an important consideration when implementing Vibes, given the use of a large display. Even though Vibes is intended to be experienced by one person at a time, the visual elements behind it are visible to other people as well, which I wanted to use as a way of capturing their attention.

Since the end-goal of this project was to create a design tool that could also function as an interactive art installation, I drew ideas from both areas of work. From an art perspective, I was intrigued by the idea of having a minimalist representation of haptic feedback, very loosely inspired by the Bauhaus school's use of simple geometric shapes and emphasis on function [2]. A digital sound artwork by Tristan Perich titled *Microtonal Wall* inspired Vibes through its use of circular geometry along with the idea of different speakers playing distinct sounds. Another influence was Yoko Ono's *Wish Tree* series, specifically in the way it allows people to add to it over time [1]. Figure 2 shows these art pieces.

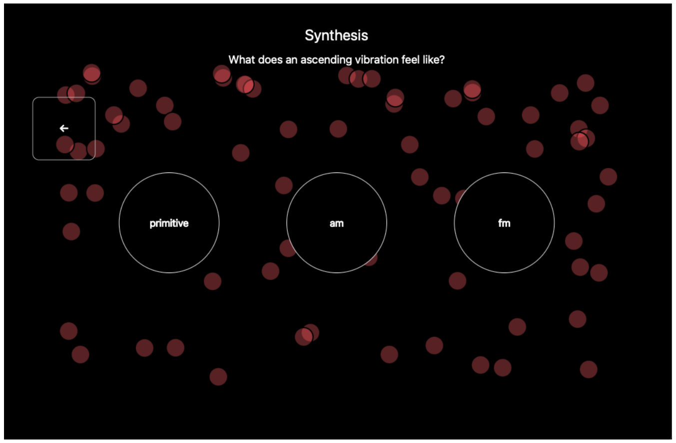
Zooming in on design tools for haptic feedback, existing systems have taken different approaches to the core interaction loop. Voodle, a system that allows users to actuate a 1 degree-of-freedom robot using their voice, uses the simple-but-powerful idea of tying a user's voice to the robot's motion [12]. Vibes does not take voice inputs, a decision which was made considering the public exhibition setting in which the installation was set up. Instead, it allows users to 'pinch', 'stretch' and 'compress' virtual representations of waves, tying the movement of their fingertips to the generated vibration. Another system, Macaron, presents a much more recognizable interface that resembles an audio editor, allowing users to create rhythmic vibrations [14, 9]. While maintaining consistency with the idea of representing waves that can be reshaped, Vibes includes an envelope-shaping interface that allows users to vary the intensity of a vibration over a 2 second loop, which takes inspiration from Macaron. Besides this, some more subtle ideas that Vibes draws upon are the use of ambiguity of information in art and technology [10], and the idea of creating haptic representations of affect [16, 8].

Experience

When a person first approaches Vibes, they can see a single 'home' screen on the main display, shown in figures 1 and 3. Both the home screen as well as the laptop placed in front of the person hint at using their hands and pinching with their fingers to interact with the large display. The main screen also shows a prompt, asking the user to think of what a vibration associated with a particular emotion would feel like to them. If they pinch to select the first option, **Synthesis**, they are presented with more options for the specific synthesis technique they want to use - 'Primitive' (using a single oscillator), 'AM' (amplitude modulation), or 'FM' (frequency modulation). For each choice, a new screen opens up, depicting one or three waveforms depending on the synthesis method being used (see figure 4).



Home Screen

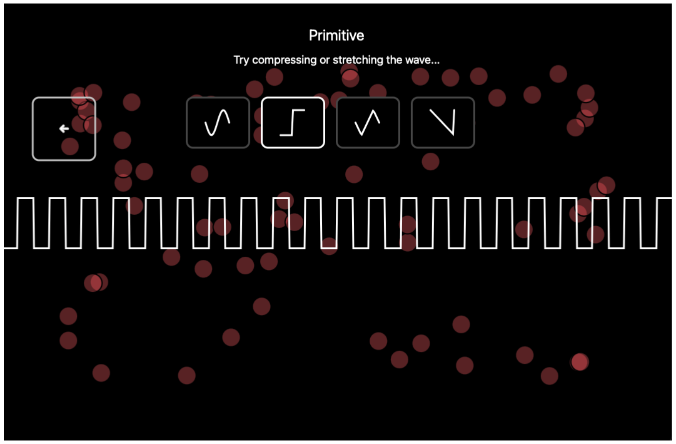


Synthesis techniques available to user

Figure 3: Menu screens

These waveforms can be pinched and dragged to change their frequency; for AM and FM synthesis, the bottom waveform represents a composition of the other two waves and thus cannot be directly controlled by users; this is indicated by drawing it with a muted gray color, similar to a disabled button on a webpage. In addition, the wave shapes can also be adjusted by selecting the corresponding shape option - this adds to the variety and expressivity of the vibrations that can be created with Vibes.

In the background, there are multiple coloured circles that oscillate with frequencies determined by the selected synthesis method, adding some movement to the installation while helping convey the effects of user actions visually. At the same time, a white box placed in front of the laptop plays the synthesized vibrations on a 2 second loop, updating parameters in real time to provide live playback. Users can touch this box to get a sense of the vibration they are designing. Figure 5 shows a close-up view of the box.



Primitive synthesis visualization

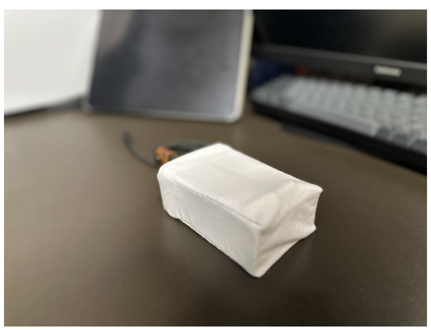
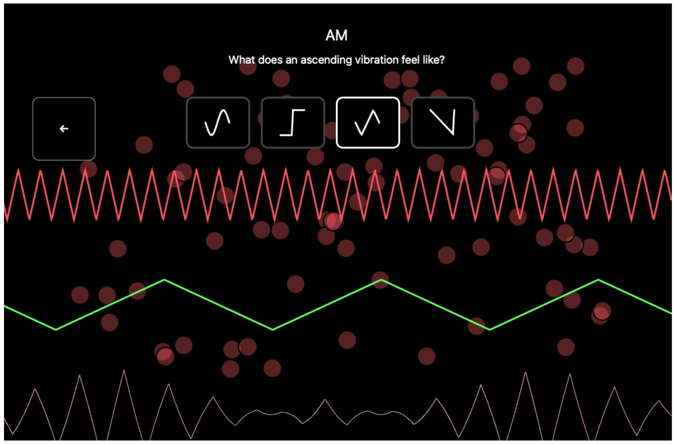
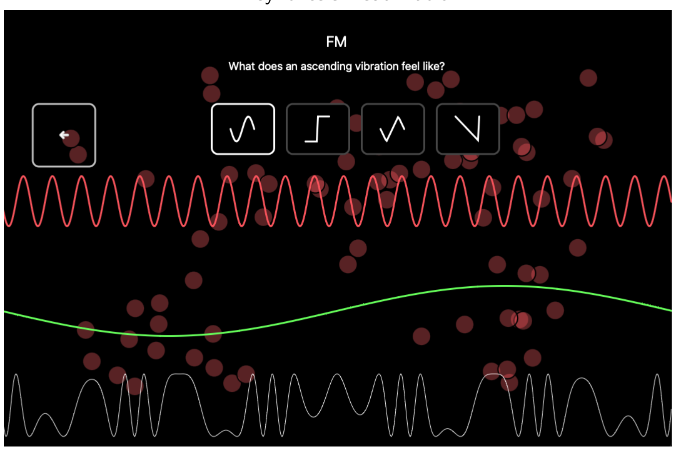


Figure 5: The physical box through which vibrations were played for users to feel. The box itself was a hollow 3D-printed shell, housing electronics and covered with white cotton fabric.



AM synthesis visualization



FM synthesis visualization

Figure 4: Synthesis visualization screens. The thicker waveforms can be manipulated by users by pinching and stretching or compressing them.

Once satisfied with their creation, a user can navigate back to the home screen and select the **Envelope** option. This opens up a visualization of the vibration's intensity or volume over the course of a 2 second long clip. See figure 6 for reference. Similar to the waveforms from the **Synthesis** screens, this visualization is a line that can be manipulated by pinching and moving it around. Changing the shape of the line alters the intensity of the vibration over time, allowing users to convey rising sensations, falling sensations, and everything in between. They can also choose between the different synthesis methods to switch the base vibration pattern being looped.

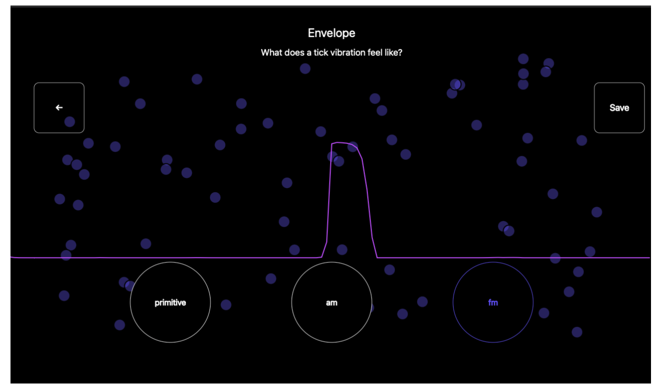


Figure 6: The envelope editing visualization, allowing users to control vibration intensity over time and thus define rhythm.

Once a desirable vibration has been created, users can select the 'Save' option to save their vibration, completing the experience. At this point, the system resets to the home screen and displays a new emotion to direct the next person's vibration design. The vibration created by previous users do leave their mark on the installation, though. Similar to the other coloured circles present in the background on screen, for each user-created vibration, a dynamic circle is permanently added to the display, shifting around based on its frequency (or in the case of AM/FM, frequencies) and

Figure 7: Klipsch's The One II speaker. It has a simple look with minimal parts protruding from the basic cuboid shape, and a fabric finish that makes it blend into a home environment.

changing in size based on its envelope. Over time, these vibrations are accumulated, potentially helping inspire ideas for future users while simultaneously adding to the visual appeal of the installation. See the accompanying video for a walkthrough of the experience.

Concept

As mentioned previously, the inspiration for Vibes' visual appearance came from the Bauhaus school's use of simple geometries and minimalist design and the Microtonal Wall artwork. As a result, the main menu buttons and background shapes are all circles. The shapes of other navigational buttons were rectangular with rounded corners to distinguish them from the main menu options, while also helping usability as they were positioned closer to the edge of the camera-based hand tracking and were thus harder to consistently select with a circular shape. User-created vibrations are rendered as background circles with white outlines, mirroring the Microtonal Wall's use of individual speakers that all play different tones, while also drawing from the Wish Tree's approach of accumulating inputs from other people. And while the remaining background circles all play the same vibrations with some randomization in their movement, the motion created a satisfying noisy 'jiggle' effect that helped attract other visitors in the room.

The colours for the interface were chosen to be lower saturation with a black background in anticipation of the large display's form factor. A large public display with a bright white background could quickly fatigue people during the exhibition, whereas a darker background would not, despite suffering from slightly more washed out tones (this is why lower saturation colours were used). All text was rendered with the San Francisco typeface, maintaining a simple, clear look [11]. The contents of the text were also kept minimal in an attempt to achieve a balance between a design/creativity-support tool and an art piece. The laptop screen always prompted people to touch the white box to feel the vibrations they created, while the large display always showed the target emotion or affective label that the user was encouraged to design for. Besides that, the menu options did not include extension descriptions of their functionality, but instead just a single word.

In terms of designing the physical components of the system, I was inspired by the home-friendly design of Klipsch's The One II speaker [5]. The concept of having a simple box resembling a speaker really appealed to me, and in my opinion helped ground haptic feedback in a form factor that isn't quite as exotic as most haptic devices we see in the real world, including video game controllers and fancy trackpads. The box housed the ESP32 microcontroller that I used to drive a haptic actuator; however, most of it was hollow, which also helped make the vibrations more noticeable than if the actuator was touched in isolation. The entire contraption was covered with white cotton fabric, which was selected for its clean, minimal look and soft texture.

At a higher level, I decided against having the system navigate to the home screen after each time a person walked away from the installation. Thus, a person might walk up to a different sub-menu or even a visualization screen. The idea behind this was to allow multiple people to contribute to a single synthesized vibration, while also keeping the perceived 'cost' of interacting with the display low enough so that interacting with a single visualization would seem approachable while still conveying something about how designing vibrations is similar to designing sound. This also meant that people who pressed the 'Save' button did so with intention, reducing the number of accidental saves or the creation of random vibration effects.

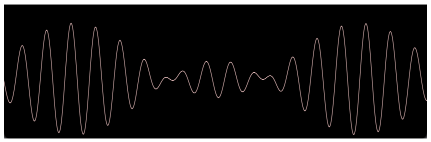


Figure 8: An AM waveform visualization. Notice how the amplitude varies over time; this is controlled by the modulating oscillator.

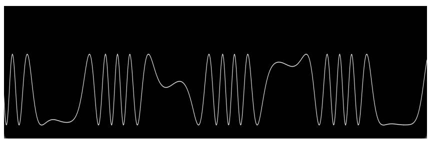


Figure 9: An FM waveform visualization. Notice how the frequency varies over time; this is controlled by the modulating oscillator.

Implementation

Vibes was developed using p5.js, a popular client-side javascript platform for creative applications, artworks and prototypes [6]. For rendering vibrations, the Web Audio API was used [7], while hand-tracking was supported by the ml5.js library [3]. Figure 10 shows the overall code architecture in the form of a block diagram.

Code Structure

As is the case for all p5.js applications, any prerequisite computations were carried out by the `preload()` and `setup()` functions. This includes setting up the hand-tracking model, assigning initial values to application state variables and generating an emotion/affect label to help direct vibration synthesis.

The system's different menus and visualization screens were stored as state variables, and different combinations of state variables resulted in different visuals being rendered in the `draw()` function. Interacting with on-screen elements involves a pinch gesture, which is implemented based on the distance between the index finger and thumb for a given tracked hand. To reduce chances of accidentally triggering the interface due to people's hands in the background, only up to two hands are tracked.

A feature that I particularly enjoyed implementing was the behaviour of the envelope interface, where an array of sample times stores the shape of the envelope and is then used to control the gain of the relevant oscillator outputs. Earlier versions that I experimented with attempted to enable the same behaviour for primitive waveforms as well (i.e., controlling the oscillation itself instead of its gain), but the resulting outputs were not as consistent or pleasant-feeling as this approach. The code for achieving a custom envelope is shown below:

```
function applyEnvelope() {
    if (envelopeTimeout) {
        clearTimeout(envelopeTimeout);
        envelopeTimeout = null;
    }
    let currentTime = audioContext.currentTime;
    envelopeNode.gain
        .cancelScheduledValues(currentTime);
    envelopeNode.gain
        .setValueAtTime(0, currentTime);
    let baseTime = currentTime;
    let timeIncrement =
        appState.envelopeDuration
            /
        appState.numPoints;
    for (let i = 0; i < appState.numPoints; i++) {
        let time = baseTime +
            i * timeIncrement;
        envelopeNode.gain
            .linearRampToValueAtTime(
            appState.envelopeShape[i],
            time
        );
    }
    ...
}
```

The remainder of Vibes' haptic feedback-related code includes functions to set up Web Audio Oscillator objects and connect different nodes to achieve primitive, AM and FM synthesis. For AM synthesis, the modulating oscillator controls the amplitude of the carrier oscillator to produce an output waveform; for FM, it is the frequency that is controlled by the modulating oscillator instead.

The circles that appear in the system's background at all

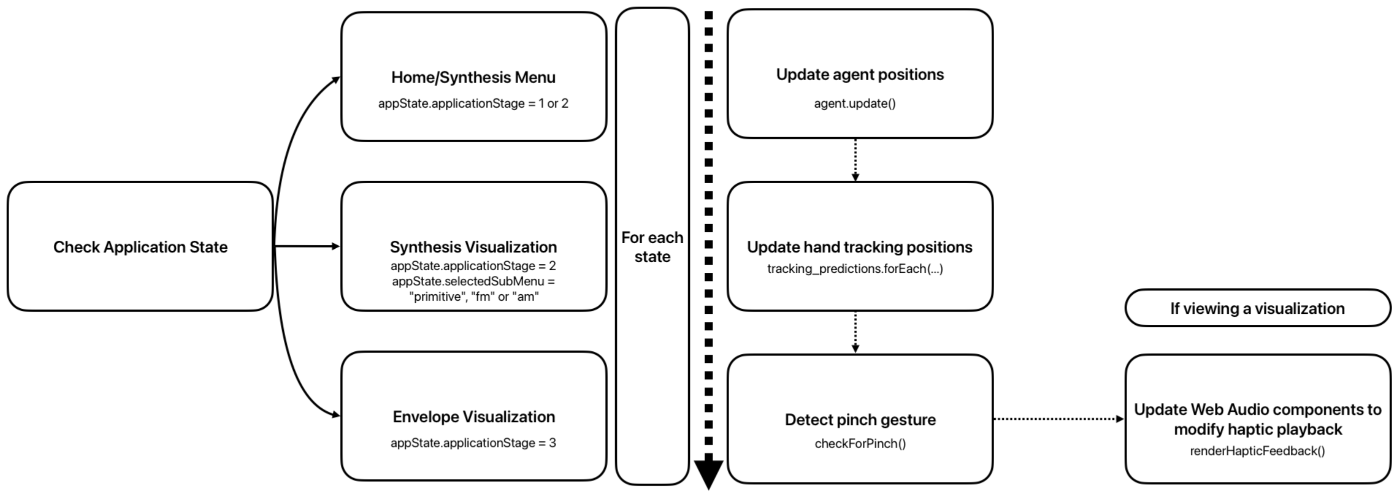


Figure 10: A block diagram illustrating the high-level code organization for Vibes, with a focus on how application states enable menu navigation. Based on the state, a particular screen is rendered in the `draw()` function. For all screens, however, agent positions are updated, hand tracking updates are applied and in the case of a visualization screen, haptic feedback is also updated to reflect user changes, in this order.

times were modeled using the `Agent` class, which defines a circle's radius, its position and functions for updating its parameters to generate movement. Lastly, when a vibration is saved, the `VibrationRecord` class is used to save its characteristics - this data is used to initialize a new Agent that moves in sync with the saved vibration pattern. The full code for Vibes is accessible through GitHub.

Fabrication
The haptic interface itself was constructed using a Titan Haptics TacHammer Drake actuator [4], an ESP32 microcontroller for Bluetooth audio, and a 3D-printed box wrapped in white fabric, housing the ESP32 and with the actuator mounted on top. The device was functionally identical to a Bluetooth speaker, meaning that all haptic feedback could be played wirelessly. A USB-C power cable was still required to power the actuator, however. An on-body apparatus was not used, due to concerns regarding moving around with wired electronics as well as the risk of overstimulation and subsequent desensitization of touch receptors.

Discussion

Comparing the stated objectives for Vibes with its actual implementation, we have the following implications:

Can it be used as a design tool? Yes! As was observed in user testing as well as the actual exhibition, while not everyone followed through with the entire process of creating, editing and saving a vibration, 9 people were able to save haptic sensations. The remaining visitors engaged with the system as more of a novelty, playing around with sliders, observing their influence on the vibrations and then walking away. Hence, while Vibes is functional as a design tool, it doesn't require users to follow through with the entire process either.

Does it help people learn about haptics? To an extent, yes, since some visitors at the exhibition were able to understand how the main ideas were similar to a typical audio editing experience. However, some visitors were unable to make the connection without an additional verbal explanation.

Did people find the interactions 'fun'? Yes! The installation turned out to be quite popular amongst visitors, largely due to the use of a large display as well as the peculiar physical setup accompanying it. Some visitors enjoyed how the box felt to touch, whereas others found the pinch-based interactions creative. An interesting way to use the system was also observed during the exhibit, with one visitor using both their hands simultaneously to pinch and modify the shape of the wave envelope.

In addition to these findings, the implementation of Vibes revealed some shortcomings, which would ideally be addressed in future iterations. These were as follows:

Hand tracking - The hand-tracking capabilities of ml5.js, while easy to use, were not very accurate or temporally coherent, especially with lighting conditions or angles that produced ambiguous images and specifically near the edges of the camera's field-of-view. Hand tracking also limited the application's framerate to 30FPS, which reduced the smoothness of the experience.

Menu design - While the menu interface makes sense for a design tool, it ended up feeling somewhat out of place for an art exhibit and more reminiscent of a design tool. This wasn't necessarily a bad thing, but given more time I would have liked to figure out a more suitable interaction flow for an art piece.

Haptic device affordances - To assist new users, the laptop screen read 'Try touching the box to see how your vibrations feel / If you feel nothing, try interacting with the display', and the home screen on the large display read 'Move your hands around to interact, pinch to select, and start creating / What does a(n) *[emotion label]* vibration feel like?'. One visitor accidentally pinched the actuator mounted on the box, temporarily breaking the installation. Another common issue was that as the vibration pattern looped, the actuator heated up enough to be noticed by participants. While the actuator's playback was set up so as to not cause harmful levels of heat, I could have used a fabric with better insulation or a lower-powered actuator as well. The tradeoff in this situation would have been weaker haptic feedback, which could negatively affect the experience.

Future Work

Given the time to expand upon this project, I envision Vibes becoming a series of installations, each conveying a different haptic modality using a different core interaction. For instance, while stretching and compressing a spring makes sense for generating vibrations, making people move their entire bodies might be more interesting to explore kinesthetic actuation, or force feedback.

Another direction that interests me is that of data physicalization, given the central position the sense of touch occupies in Vibes. Instead of using hand tracking with pinches, what if vibrations were synthesized using another craft form, like sculpting clay or by throwing colours on a canvas? For example, the rim height and radius of a pot could control the base and modulation frequencies of a synthesizer, allowing users to take home a representation of the vibrations they generate.

Lastly, when looking at the system from an HCI perspective, we can look at its potential for crowdsourcing haptic sensations from general audiences. Such a project would involve multiple evaluations, including iterative interface design and basic cognitive load evaluations, an in-the-wild deployment evaluation to observe (1) the amount of traffic the system attracts, (2) the quality of data collected by the system and (3) the ability of the system to avoid or recover from failures. Taking such an approach, the goal would be to deploy easy-to-use kiosks for collecting data related to haptic feedback, helping developers move towards the use of powerful machine learning methods commonly seen applied to other modalities such as vision.

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