~~Global~~ Local Warming

Creating a Multisensory Representation of Climate Data

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1 Introduction

Why do we represent data through sight? Why do we create data *visualizations*? From Covid-19 data dashboards (The New York Times, 2022; Center for Systems Science and Engineering, 2022) to the powerpoints presented everyday (Franconeri, 2021), data visualizations are ubiquitous in our world. Due to our robust sense of sight and visual perception, data visualization is a common medium for the production and consumption of information. We leverage these visuals to condense and convey information, to reveal underlying patterns and relationships, and to understand complex issues. Of course, we can represent data beyond the visual domain, too. In his Atlantic article, Luke Stark defines data visceralizations as "representations of information [that] rely on multiple senses including touch, smell, and even taste, working together to simulate our feelings as well as our thoughts" (Stark, 2014). Data visceralizations extend data visualizations by engaging more than one sense. To visceralize data is to make someone *experience* it, not just see it.

In this paper, I will discuss the creation of Local Warming, a visceralization of climate data. Local Warming is one of several data stories featured at the Picturing Climate Justice exhibit at the Jefferson School African American Heritage Center. This exhibit represents the culmination of work and collaboration between community organizations like the Community Climate Collaborative (C3), Cultivate Charlottesville, Wildrock, and the UVA School of Architecture Project Pipeline Youth Design Mentorship Program, the UVA Equity Center, the UVA Democracy Initiative Center for the Redress of Inequity through Community-Engaged Scholarship, UVA Sustainability, and the Jefferson School African American Heritage Center. The exhibit launched on March 5th, 2022 and will run until May 28th, 2022. You can view Local Warming in person at the Jefferson School or online at https://local-warming.vercel.app/.

The goal of Local Warming was to provide a new way to look at and experience global and local climate data. In this paper, I will expand on my iterative and design processes to describe the creation of Local Warming. I will demonstrate how Local Warming extends beyond the typical constraints of data visualization to represent emotion. Lastly, I will use feminist, liberatory, and critical thought to frame and discuss the development and impact of the Local Warming story, positioning it as a more emotional and visceral way to experience data.

2 Related Work

I was first exposed to the concept of data sonification while listening to an *NPR* segment titled *U.S. Home Prices, Sung as Opera.* On the show, which first aired in April of 2011, Jacob Goldstein and David Kestenbaum — the hosts of the episode — bring on guest Timothy McDevitt, a baritone and master's student at Julliard, to *sing* the Case-Shiller home price index data (Goldstein & Kestenbaum, 2011). If you visualize the index over time with a line plot, you get a clear view of the 2008 housing crisis — you can quite literally see the housing bubble expand and then pop! Goldstein and Kestenbaum (2011) wanted to depict that same boom and bust to their radio listeners, yet they needed a way to represent the data beyond the visual, so they turned to sound.

In the segment, McDevitt performs three separate times for different sections of the data: one for Miami, Dallas, and the U.S. as a whole. In these performances, the values of the Case-Shiller index are mapped to vocal notes, with notes of a higher pitch corresponding to higher values of the index. Unfortunately, that mapping is not explicitly shared with the audience, a critique of mine that I will elaborate more on later.

The first two performances delineate the change in the index over time for Miami and Dallas. Miami experienced an extreme bubble, which we hear through the dramatic rise then fall of McDevitt's voice. Dallas appeared to be relatively unaffected by the housing crisis as McDevitt hovered around the same pitch for the majority of that performance. Lastly, for the U.S. performance, McDevitt sings a

description of the period — combining both spoken word and pitch to create meaning. His voice gets higher and higher as he makes his way through his description of the housing boom and the financial circumstances that led to the 2008 housing crisis. Then, he drops low quickly, while discussing the bust.

The performances of McDevitt are data sonifications. While simple, their inclusion in this *NPR* segment points to a core challenge that data sonification attempts to solve: accessibility. Goldstein and Kestenbaum (2011) turned to sonification as a way to make the Case-Sheller home price index data itself accessible to their radio listeners, who could not view a visual representation of the data due to the medium. Emotion is one of the most salient pieces of information shared through music (Dowling & Harwood, 1986 as cited in Davis & Mohammad, 2014). Of course, emotion is a loaded term. What counts as emotion? Is there a difference between picking up on the emotions of a song or artist and feeling those emotions yourself (Juslin & Laukka, 2004)? I can listen to a sad song and tell you afterwards that it is a sad song, but does that mean I felt sad while listening to it? These questions I'm posing get at the complexities of the difference between perception (recognizing that a song is sad) and induction (actually feeling sad after listening to a sad song) of emotion (Juslin & Laukka, 2004). I won't elaborate on the difference right now, but it's an important framing, as I further discuss the emotional impact of sonifications and work that specifically seeks to elicit an emotional response.

The second sonification that I encountered was Sophie Chou's (2018) sonification of gun deaths in America, which she created for a segment of *The World*, a public radio program, discussing global gun violence. Chou's work first aired in November, 2017 and was updated in 2018 after the Parkland shooting, a mass shooting at Stoneman Douglas High School where 17 people were killed. The piece begins with a rapid fluttering of soft, high-pitched piano notes. Each note represents one mass shooting, and the intensity (or loudness) of the note corresponds to the number of people killed in the shooting. There are few moments of silence, and the piece is occasionally marked by very intense, hard notes that represent the most fatal shootings in the dataset, like the Pulse massacre where 49 people were killed.

Like *NPR*, *The World* wanted to find a way to make the data related to their segment accessible to their audience. They wanted their listeners to engage with the data itself, rather than aggregations and summarizations of it from the radio hosts. Most data visualizations are designed intentionally for the immediate extraction of some main point, yet Chou created the sonification so that the listener has to sit with the data. It's almost as though you're forcing the listener to go row by row through a dataset and read each data value. This slow progression through the data is intentional — Chou (2018) doesn't want to abstract away the deaths of individuals through aggregation as they so often are through dominant visualization techniques. Moreover, she wants the listeners to hear the thousands of deaths that don't make the headlines. We know the names of those shootings that make the front page — we are all too familiar with the heavy strike of the piano key. Chou's design forces us to grapple with the constant, never ending flurry of light notes, shootings of four and five people, that occur every day, sometimes multiple times a day, all over the country. It's the explicit revealing of what is often not seen dichotomized with what is often known that makes this piece so emotionally powerful. I remember having chills after I first listened to it. To this day, I remember how that sonification made me feel.

In my opinion, there is perhaps no one that does data sonification better than *Loud Numbers*, a data sonification podcast created by Duncan Geere and Miriam Quick. At the time of writing, their podcast has five episodes, each spotlighting a new sonification. In the beginning of every episode, Geere and Quick describe the data, explain their creative process, and discuss the various sonification elements. Later, I will elaborate on their sonification elements because I think that is an important part of what makes their work so impactful and accessible. I will discuss two episodes in particular: *The Natural Lottery* (2021a) and *The End of The Road* (2021b), the first and last episodes of Season 1.

The Natural Lottery delineates the progression of climate change by sonifying data from the Nenana Ice Classic, a tradition that began in 1906 in which Alaskans place bets on when the ice on the Nenana river will defrost (Geere & Quick, 2021a). As you might expect, the ice has melted earlier and earlier each year. *The Natural Lottery* sonifies three different datasets: (1) data from the Nenana Ice Classic, (2) atmospheric carbon dioxide (CO_2) measured from the Mauna Loa observatory in Hawaii, and (3) the aurora borealis and sun spot cycles. The sun spot cycles are included for artistic effect since they

have no impact on when the ice breaks up. In the Nenana Ice Classic, the citizens of Nenana place a tripod on the river with a camera attached. The ice is considered to have broken when the camera falls into the river. In *The Natural Lottery*, this date is sonified by a chord progression of varying pitch, with a higher pitch representing earlier broken ice. Atmospheric CO_2 is directly mapped to pitch and intensity. The natural, cyclical pattern in the data makes it sound like a siren as carbon dioxide levels rise decade after decade. Lastly, the sun spot cycles are represented with a shimmering sound that increases in intensity during periods of greater sun spots. Geere and Quick (2021a) also leverage voice recordings of years, occurring at 16 year intervals, to act as a x-axis of sorts and ground the user in the temporal location of the sonification.

Unlike the previous two examples of sonification discussed above, Geere and Quick put significant work into the musicality of the piece. The sonifications by *NPR* and *The World* are single parameter, direct mappings of data to sound, whereas the Natural Lottery joins several, disparate data sets and includes several non-data elements that contribute to the overall vibe of the song. Describing *The Natural Lottery* as a dance track, Quick explains that she adds filters to the chord progressions that sonify when the ice is breaking to create "hands in the air moments" (Geere & Quick, 2021a).

The End of the Road by Geere and Quick similarly tells a climate-related story, focusing on environmental degradation and the loss of biodiversity, both locally in Denmark and globally. Geere and Quick (2021b) sonify the biodiversity data published by Anders Pape Møller (2019). Between the years of 1997 and 2017, Møller (2019) recorded how many insects hit his windshield as he drove down two different roads in Denmark. In the podcast, Geere recounts how in the early days of automobiles it was common to get out of the car halfway through driving to clean your windshield because you had hit so many bugs that it made it nearly impossible to see (Geere & Quick, 2021b)! Of course, this is not an issue today — yet the lack of insects in the air points towards a more troubling problem with the stability and health of global ecosystems. Through his study, Møller (2019) finds insect reductions of 80% and 97% in the two locations he observed. Geere and Quick set out to make their audience hear and feel those astonishing and disconcerting statistics.

As in their other episodes, Geere and Quick (2021b) represent this data with sound, yet in *The End of the Road* they also play with silence as a data-driven variable. They sonify the smoothed, monthly averages of how many insects hit Møller's windshield with ephemeral, fluttering sounds of varying pitch according to the size of the insect. Lower pitches represent larger insects, while higher pitches represent smaller insects. As the years pass, you hear less and less of these insect sounds as the silence grows greater and longer. In their discussion leading up to the piece, Geere and Quick talk about the challenges of representing what is effectively a mass-murder of insects, which is presicely why silence becomes an important part of the sonification. Geere and Quick want the piece to feel oddly empty, nearly desolate towards the end — you are supposed to hear and experience the loss of insects firsthand. They could have chosen a different route and used a melody declining in pitch to signify the decline in insects, but again, they chose to sonify loss, not decline, which is an important distinction. We hear less of these insect sounds, instead of hearing a difference in the sound itself, which in my opinion, better represents the data and makes it easier for the listener to internalize and conceptualize the loss. Geere and Quick couple the sonification of Møller's insect data with a note that drops in pitch every decade to represent the estimated decline of insects globally. By situating the local within the global, they expand this story beyond what is happening just in Denmark to the rest of the world. Through that element, listeners from across the globe can hear this decline and react, with horror, to the devastation that is happening in their backyard too.

In most of their work, they leverage non-data elements to influence the overall emotion of the piece. In *The End of the Road*, the sound of a tolling funeral bell plays every decade which both acts as a time axis and helps create the overall feelings of loss, grief, and death of the piece. They also add ambient sounds like the sound of a car passing on a highway or a bird squawking and flying above to create their desired soundscape of driving through an ecosystem that becomes more desolate with time (Geere & Quick, 2021b).

So far we have only examined sonifications — what about work that engages both our senses of sight and hearing? *London Under the Microscope* by Valentina D'Efilippo with data sonification by

Duncan Geere is a perfect example of a multisensory representation of data (D'Efilippo et al., 2021), or what Luke Stark might call a data visceralization (Stark, 2014). *London Under the Microscope* is a project commissioned by the Museum of London which explores the impact of Covid-19 on London from March 1st, 2020 to February 28th, 2021 (D'Efilippo et al., 2021). This video combines animated data visualization with data sonification to go beyond the single sensory representation of data and make the audience really feel and experience the underlying pandemic data.

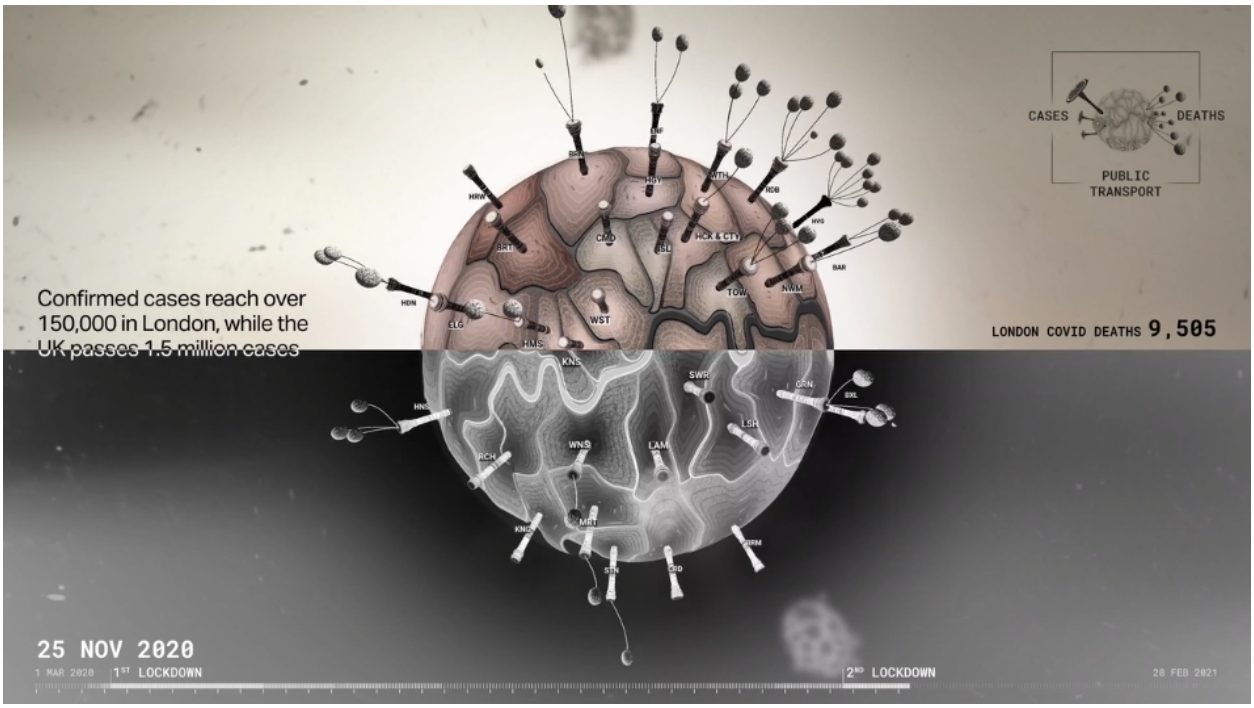

Figure 1. Screenshot of *London Under the Microscope (D'Efilippo et al., 2021)*

D'Efilippo conveys an enormous amount of data visually throughout the piece, and Geere's sonification plays with your emotions to make you really feel the horror and tragedy behind the numbers. The piece begins with the daunting sound of a heartbeat and a quote from a Covid-19 survivor, which appears rhymically, in sync with the heartbeat — all visually backgrounded by a blurred, microscopic view of virus-like entities. Then, the text changes to a description of the beginning of Covid-19 in London as a quick yet unsettling melody is layered on top of the heartbeat. The video encodes 365 days of data, where 1 second of the video corresponds to 1 day. When the data-driven visual component begins, a sphere sits in the center of the screen. It is divided into sections, which presumably correspond to different parts of London. At the bottom of the screen, the viewer can see a timeline of events which also tracks the current progress of the video, the date, and when lockdowns went into effect as seen in Figure 1. As the video progresses, a gray-scaled rectangle grows up the screen tracking London Covid deaths and spires grow from each part of London visualizing the total number of cases in that locality to date. With each second, the virus-like visual "beats" like a heart and balloon-like structures shoot out from each spire representing each individual that died from Covid-19 in that locality on that day. Moreover, D'Efilippo provides societal context in the empty spaces of the visual by including news headlines, what is trending on London social media, and key thresholds such as confirmed cases or deaths reaching a new daily high. It's hard to infer the meaning of certain sonification elements beyond invoking an emotional response since they are never explicitly explained in the video, but there are some sounds that are clear. When a new variant is detected, the virus-like visual shimmers and appears to slightly change form while a distinct auditory tone plays. The number of beats per bar of the base appears to increase when daily

average cases are rising. Lastly, a whining, static noise increases in volume during periods when deaths are also increasing.

I looked to *London Under the Microscope* for significant inspiration for the development of Local Warming because of how effectively it wielded sight and sound to create both an informative and emotional experience for the audience. The beauty and genius of *London Under the Microscope* is its seamless integration of emotion and reason, which blurs the binary and false distinction between the two (D'Ignazio & Klein, 2020). Like in Chou's sonification of gun deaths in America, D'Efilippo doesn't abstract the deaths away. Each individual death is represented, giving the audience the opportunity to grapple with the sheer loss of human life in London from the pandemic. We, as the audience, can collectively mourn the loss of each life as we watch the video — we are able to understand the magnitude of death and sorrow because D'Efilippo encourages us to look closely. Governments and businesses are telling us that things are returning to normal, yet we, as a society, haven't reconciled with the loss of life. That high level of granularity is particularly important given the context in which this video is watched. Part of that is because the tools we have for representing and communicating the death toll from the pandemic just aren't good enough (Raji, 2020). We don't fully comprehend what it means to hear that 18,708 people died from Covid-19 in London between March 1st, 2020 and February 28th, 2021, and honestly we still don't after watching *London Under the Microscope.* I'm not sure our brains are capable of understanding loss of life at that scale, but *London Under the Microscope* certainly gets us closer to reconciling with that number. Local Warming doesn't deal with loss of human life, but I struggled with the same issue that D'Efilippo attempts to solve: how do you move beyond and break down a number? In D'Efilippo's work that number is Covid-19 deaths. In mine, it's temperature and atmospheric carbon dioxide.

To reduce the risk of climate catastrophe, we have to keep the planet below 1.5 degrees Celsius (°C) of warming relative to pre-industrial temperatures. Right now, we're on track for about 4 °C of warming. These numbers sound so small and insignificant — it's hard to imagine that the world warming up by a couple degrees would really radically alter society and put many lives of many people, particularly those who live in the Global south, at risk. How do we realize the impact of these numbers? How do we understand the gravity behind them? These are questions I wanted to explore through the creation of Local Warming. The same goes for carbon dioxide. What does it mean that carbon dioxide levels have increased by over 100 parts per million (ppm) since 1958? What is a hundred in a million? Just like with Covid-19 deaths, we struggle to comprehend these climate indicators. This is all to say that Local Warming exists as an attempt, as a recreation of new tools, to get us to more deeply and sincerely understand these opaque numbers.

3 Methods

In this section, I will discuss the data used in the creation of the Local Warming story, provide insight into my iterative process, and elaborate on the design of the final sonifications and visualizations.

3.1 Data

In the final Local Warming story, I use local and global temperature data from the NOAA National Center for Environmental Information and atmospheric carbon dioxide from the Mauna Loa Observatory in Hawaii in both my visualizations and sonifications. I also discuss data used in earlier versions of the sonification that were not used in the final version like annual CO_2 emissions data from Our World in Data.

Temperature

Both local and global temperature data were used in the creation of the Local Warming story. Global temperature data was sourced from the NOAA National Center for Environmental Information (NOAA National Centers for Environmental information, 2022). The global temperature data ranged from 1880 to 2019. Local temperature data for each locality in the Charlottesville region (Albemarle, Charlottesville City, Fluvanna, Greene, Lousia, and Nelson) was originally sourced from the Climate Divisional Dataset from the National Center For Environmental Information (Vose et al., 2014), but that cleaned data used in this project is a product of the work done by Tolu Odukoya, Lee LeBoeuf, and the UVA Equity Center. The local temperature data ranged from 1885 to 2021.

The global temperature data is in the form of temperature anomalies–that is, each annual value represents the difference between the average annual temperature and the average 20th century temperature, not raw temperatures. When you hear scientists and policymakers talk about different warming scenarios (like 1.5 °C, 3.0 °C, or 4.5 °C) warming, they are referencing temperature anomalies. Again, this temperature anomaly is the difference between the average annual temperature and some baseline period. For the global temperature data used in this project and taken from the National Center for Environmental Information, that baseline period is the 20th century. Different organizations use different baseline periods but the intent is to capture the difference in global temperature between pre- and post-industrial periods.

In the initial form of the local temperature data, each row represented a month, year pair with columns for month, year, average daily maximum temperature, and average daily minimum temperature. To compute annual temperature anomalies, I first calculated the annual average daily maximum temperature and subtracted the value for each year by the average of the 20th century. Once I had the annual temperature anomalies for each locality in the Charlottesville region, I could use that data to generate the heatstripes chart data present in the Local Warming story and input that data into the sonification-generating code.

CO_2 Emissions

The first several iterations of the Local Warming sonification relied on annual CO_2 emissions data from Our World in Data (Ritchie et al., 2020). This data ranged from 1750 to 2020. The final versions of the sonification did not use this data, however, because it was not as sonically interesting. Instead of CO_2 emissions data, I decided to use atmospheric CO_2 from the Mauna Loa Observatory in Hawaii.

Atmospheric CO_2

The Mauna Loa Observatory boasts the longest direct measurements–beginning in March, 1958 and continuing to the present–of atmospheric carbon dioxide levels (Tans & Keeling). The atmospheric CO_2 measurements are more sonically interesting because of the seasonal cycles in which forests in the northern hemisphere sequester then release large amounts of carbon dioxide (Geere and Quick, 2021a). Due to the natural ebb and flow of the data, mapping it to pitch creates the siren-like effect seen in *The Natural Lottery* (Geere and Quick, 2021a). I was so inspired by the sheer urgency expressed by that sonication technique that I wanted to recreate it in Local Warming.

3.2 Iterations and Design

In the hopes of fostering greater understanding of how the global climate crisis will manifest in Charlottesville and encouraging greater mobilization towards action, I wanted not just to create a data sonification but to combine the visual and the auditory into one experience for my viewers — enabling the audience to feel instead of view the data. Local Warming began as an interactive, web-based sonification of the traditional, global heat stripes chart, which was originally created by climate scientist Ed Hawkins (Hawkins, n.d.).

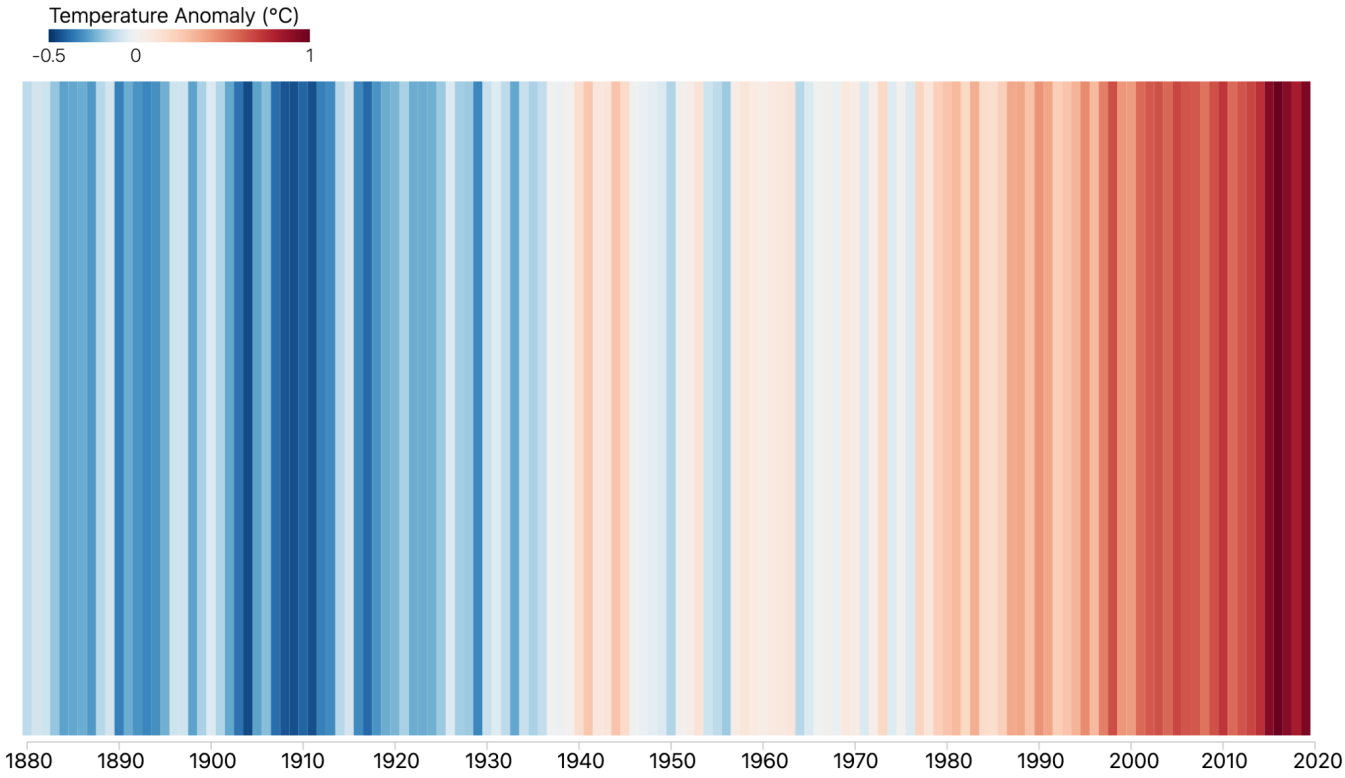

Figure 2. Screenshot of Global Heat Stripes Chart in Local Warming

Built with Svelte and Tone.js, this version mapped global temperature anomalies directly to pitch, so higher sounding notes represented numerically higher temperatures. It was interactive in two senses: it could be "played" and the visual responded to movements of the user's mouse. The visual was animatable, and upon pressing the play button, each stripe would appear in chronological order and the respective note would be played aloud simultaneously. A user could hover over a particular stripe and hear the pitch associated with a certain temperature.

While a good start, this sonification version was little more than "bells and whistles", meaning that it was interesting only insofar as it was novel. It didn't convey emotion–and to do that I needed to create something that sounded more like a song.

There were some issues with this first version, of course. Tone.js created undesired auditory artifacts. An unwanted crackling, static noise often accompanied the playing note. Moreover, there was a general lack of well-written documentation available online for Tone.js, and the documentation assumed a great deal of prior knowledge about music composition. So, I switched to using Sonic Pi, the platform the creators of Loud Numbers use to develop sonifications. The main difference between Tone.js and Sonic Pi is that Tone.js is a Javascript library and thus the code for generating the sonification could exist on the frontend, whereas Sonic Pi is a free "code-based music creation program" based on Ruby whose goal is to foster learning how to code and compose music. I could create the sonifications on my machine and export them as .wav files, but the process of hosting them on a web-app and syncing them with some visual animation would be more complicated. Sonic Pi has an extensive, beginner friendly online documentation, a robust online community, and a wide-ranging set of examples. Additionally, the platform contains many pre-made synths and samples, which helps offload some of the work of sound generation from the user to the platform itself.

After familiarizing myself with Sonic Pi, I then began producing more song-like, data-driven sonifications of global temperature data and carbon dioxide emissions. This version mapped carbon dioxide emissions to the intensity of a continuous static-y note and only sonified years with above average temperature anomalies, which were represented by a wobbly synth sound. Through this version, you could start to hear the relationship between temperature and carbon dioxide–as CO_2 levels continued to rise the number of warmer year notes also increased to the point that every year was an above average year in terms of temperature and the warmer year sound was playing constantly. The major drawback of this design was that it didn't sonify the intensity of the warmth or any years that were colder than the 20th century average. A listener could only learn about when the warmer years occurred and that warmer years became more common with time and increased carbon dioxide emissions. Lastly, it is harder to distinguish between changes in loudness than changes in pitch (Hegg, 2018), so intensity may not have been the best choice for representing increasing carbon dioxide emissions.

In the final sonification, a year lasts four beats. Temperature is represented by a melody composed of seven notes played sequentially from a chord in a minor key. The minor key was chosen intentionally because minor keys are associated with sadness. In one of my earlier iterations of the sonification, some chords in the melody were in the major key. I received feedback from several people that that version sounded too much like a dance track. The melody cycles through the C, F, B flat, and F minor key chords, so for one year, seven notes are taken from the C chord and for the following year, seven notes are taken from the F chord, and so on. Specifically, the melody has the structure: third note in chord, second note in chord, third, first, second, first, and finally second. The structure of the melody and bass was adapted from (mehackit, n.d.) and the pitch of the melody jumps up an octave at the 0.25, 0.5, and 0.75 thresholds in the min-max normalized temperature data. While the local temperature data ranges from 1885 to 2021, only the years 1950 to 2021 are included in the sonification to reduce its length and increase the overall carbon dioxide data, which starts in 1959 in the sonification.

Emphasizing the seasonal nature of the data, I sonified atmospheric carbon dioxide using a two beat pitch shift from the lowest annual recording to the highest of that year, followed by a two beat pitch shift from the highest recording of that year to the lowest of the following year. The notes also get louder as they approach the maximum recording of atmospheric carbon dioxide in the range. The idea to sonify the data this way and use CO_2 data in conjunction with the local temperature data came from listening to Geere and Quick's *The Natural Lottery*. In that podcast episode, they similarly mapped atmospheric carbon dioxide levels to pitch and intensity to create a siren-like sound that gets higher and more urgent as atmospheric CO_2 levels rise. I wanted to recreate that siren in Local Warming because I thought it did a fantastic job of expressing the unsettling, incessant increase in atmospheric carbon dioxide since the late 1950s. As atmospheric carbon dioxide levels get higher and higher with each passing year, so does the pitch and loudness of the corresponding note, resembling an encroaching ambulance.

The final Local Warming exhibit combines these sonifications with interactive visuals in a "scrollytelling" story. *The Pudding*, perhaps one of the best at this form of narrative media, describes scrollytelling as the process through which a graphic is changed as a user scrolls through the page (Goldenberg, 2017). Scrolling is monitored so that the user is presented with specific narrative and visualizations chronologically as they progress through the story. I implemented this scrollytelling technique to mirror the way that Geere and Quick describe their sonifications in *Loud Numbers*. Before presenting the sonification, they walk through each of the sonification elements, localizing each sound for the listener and explaining what each means. Of course, Local Warming isn't a podcast, but I wanted to imitate the same localization of data and sound that contributes to the final product.

As a user scrolls through Local Warming, they are first presented with a line plot visualizing the atmospheric carbon dioxide data used in the sonification. The line plot is combined with narrative on the left which contextualizes this data within global climate change. Lastly, they have the ability to play and hear the isolated sound that represents carbon dioxide before using the final tool and listening to the complete sonification.

Next, the user is shown the global temperature data visualized through the aforementioned heat stripes chart. Similarly, narrative accompanies this visualization to describe and contextualize the data.

Again, the viewer can play just the melody representing the annual temperature anomaly before using the final tool. After the global temperature heat stripes graphic, a local temperature heat stripes visualization was shown which combined multiple heat stripes — the aggregation of multiple individual heat stripes into one was also originally created by climate scientist Ed Hawkins — for each locality in Charlottesville into one graphic as seen below in Figure 3.

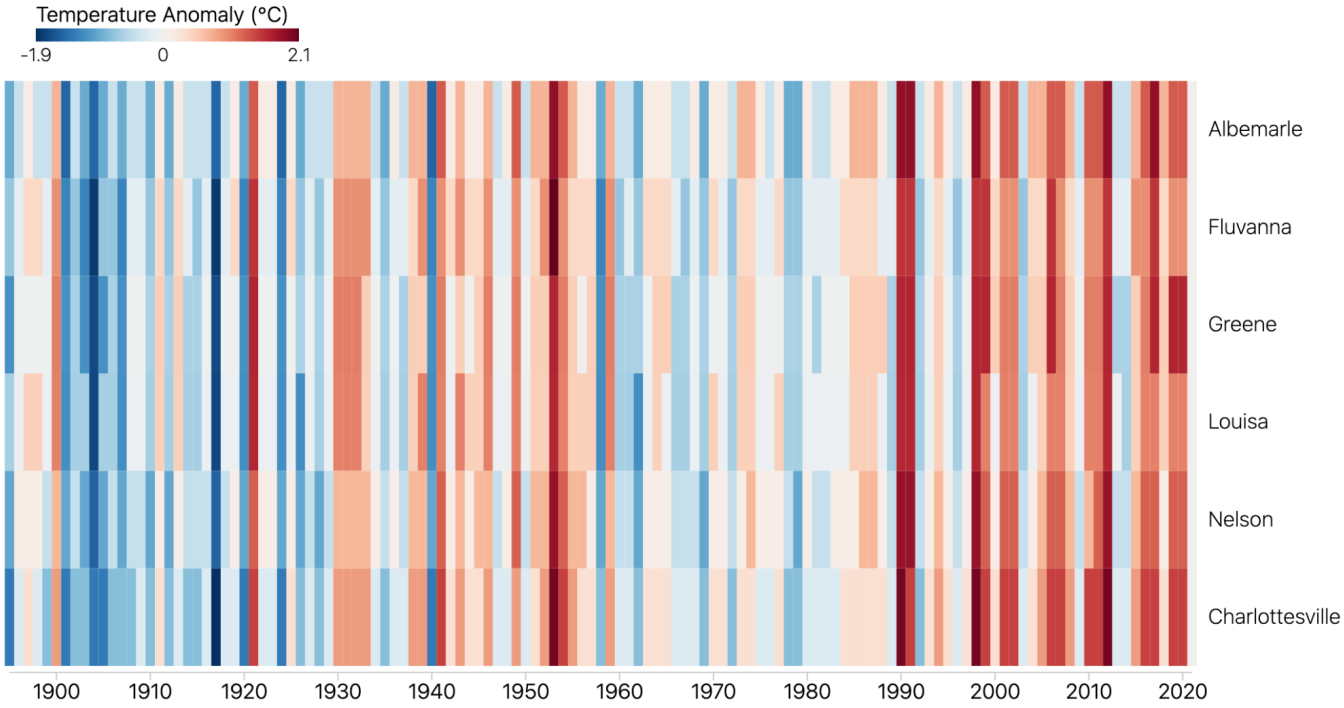

Figure 3. Screenshot of Local Heat Stripes in Local Warming

Lastly, the final multisensory tool, as seen in Figure 4 below, combines the heat stripes visual, carbon dioxide line plot, and data sonification into one interactive data "visceralization" (Stark, 2014). The user can select a locality in Charlottesville to see and hear data specific to that region. Note, the carbon dioxide data is the same for each visual and sonification, but the temperature is localized. The user can play the Local Warming story at which point the visuals and sonification animate and play simultaneously.

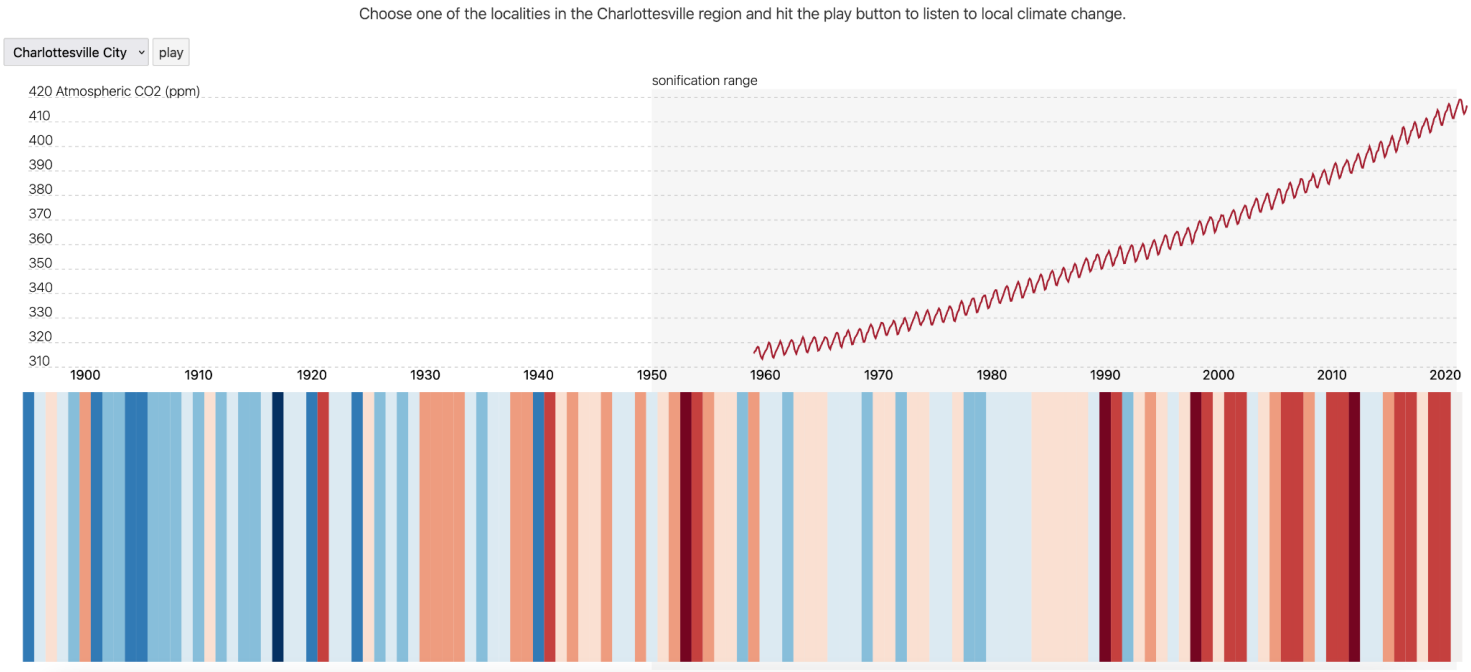

Figure 4. Screenshot of Final Visualization/Sonification Tool in Local Warming

4 Discussion

Each time we scan the room for a familiar face, drive a car, or watch TV, we subconsciously process an overwhelming amount of visual information. Data visualization capitalizes on our powerful sense of sight to display vast amounts of information in a way that we are biologically-wired to interpret. If our sense of sight is so powerful, what is the motivation to use sound to represent data? Why even bother to create data sonifications? By tapping into our often overlooked sense of sound, data sonifications have the potential to expand upon and complement visual representations of data by conveying more emotion, making data more accessible, and increasing public data literacy.

4.1 Conveying Emotion

A common critique of data visualization is that through summary and aggregation, we lose context and compassion for the people behind the numbers. While data sonification doesn't necessarily solve this issue, it provides another lens through which we can examine data. In this section, I will discuss how data representations can embrace and embody emotion, defend the importance of illuminating emotion, and think about the creation of multisensory representations of data.

In his online article, *DataViz—The Unempathetic Art*, designer Mushon Zer-Aviv investigates a heated online debate about Matthew Lucas' visualizations of the nuclear bombing of Hiroshima. Published by *Popular Science*, *Hiroshima Visualized* garnered significant criticism on Twitter because of, as Zer-Aviv (2015) states, the aestheticization "of this horror and the reduction of human crimes and tragedies to statistics and abstract graphics." These visuals centered the bomb and its production over the people whose lives were lost, and it was not accompanied by any commentary about the dropping of the nuclear weapon. Stripped of context to favor aesthetics, it was a set of extremely *uncritical* data visualizations (Hall, 2008).

Furthermore, Raji (2020) notes how data science and data visualization are often problematized for how they can "flatten and dehumanize the people they represent." Similar to how the data visualization community on Twitter critiqued the Hiroshima visuals, Raji critiques Covid-19 data dashboards and death counts by arguing that, at a certain point, large numbers become too abstract. With respect to the pandemic, they no longer serve to help us understand the current state of the crisis, but rather to minimize the toll of the pandemic compared to earlier stages of dealing with Covid-19 and to other crises involving massive loss of life (Raji, 2020). Just because certain designers get it wrong doesn't mean that there is no place for empathy in data visualization, however. There are examples of data visualization that strive to and succeed at humanizing.

Mushon Zer-Aviv positions *Periscopic*'s Gun Death visualization as a counter to the overly-abstract, dehumanizing Hiroshima visuals. *Periscopic*'s Gun Death visualization (Periscopic, 2018) is lauded by many as a good example of data visualization that reveals the horror and tragedy of gun violence in the United States (D'Ignazio & Klein, 2020; Cairo, 2013; Zer-Aviv, 2015). Periscopic moves beyond the summarization of gun death statistics to honor, individualize, and acknowledge the lives lost to gun violence. Mushon Zer-Aviv (2015) goes on to question the role of empathy in data visualization and asks if a line exists between reason and emotion, did Periscopic cross it? Catherine D'Ignazio and Lauren Klein, authors of *Data Feminism*, also discuss Mushon Zer-Aviv's labeling of data viz as "unempathetic" and analyze Periscopic's Gun Death to think about what is possible when you foreground emotion and eliminate the false binary between objectivity and emotion. With respect to the line between reason and emotion, D'Ignazio and Klein argue that not only can it not be crossed, but that the line between reason and emotion doesn't even exist and is rooted in a deeper, imagined separation of emotion and reason.

This scale, with emotion at one end and reason at the other, was how I first conceptualized sonification with respect to visualization, at least until I read D'Ignazio and Klein. It was even how I categorized different forms of sonifications. I viewed sonification as the expression of emotion and visualization as the expression of reason. Within sonification, I understood simpler, less abstract versions of the form like pitch mapping to be more rational or more readily understood by listeners, while I perceived the more musical representations of data like the *Loud Numbers* podcast as more emotional and thus inherently less rational. If these distinctions are false, what does that mean for Local Warming? Instead of conceptualizing the visualization as the manifestation of reason and the sonification as the manifestation of emotion, I think it is better to think about how both pieces individually convey reason and emotion and come together to create a fully embodied experience. By separating we give into the flawed idea that reason exists above (as in superior to) emotion (D'Ignazio and Klein, 2020).

Sonification is thought to convey emotion more readily due to its relationship with music. Emotion is one of the main pieces of information we extract from music when we listen to it (Dowling & Harwoord, 1986 as cited in Davis & Mohammad, 2014). Sound can evoke our full-range of emotions, yet there are many factors that influence the affective response to sound **(**Tajadura-Jiménez & Västfjäll, 2008). Inspired by the way I deeply experienced emotion while listening to other works of sonification like Chou's sonification of gun deaths in America and the *Loud Numbers* podcast, I wanted to create an emotional data sonification for the Picturing Climate Justice exhibit. I leveraged the studied emotional mappings of musical characteristics (Juslin & Laukka, 2004; Tajadura-Jiménez & Västfjäll, 2008) to attempt to create an overall sentiment of apprehension and anger about the state of the planet and the lack of progress towards addressing climate change. The melody representing temperature uses a minor mode, fast tempo, ascending pitch, sharp timbre, and wide pitch range to convey fear and anger (Juslin & Laukka, 2004). Likewise, the sound representing atmospheric carbon dioxide uses an ascending pitch, width pitch range, and dissonance to also convey fear and anger (Juslin & Laukka, 2004).

After the launch of the Picturing Climate Justice exhibit, I received qualitative feedback on the Local Warming story from Dr. Michele Claibourn, Assistant Professor of Public Policy, Director of Equitable Analysis at the UVA Equity Center, and my thesis advisor, and Dr. Barbara Brown Wilson, Associate Professor of Urban and Environmental Planning.

Dr. Brown Wilson attended the opening ceremony with her 10-year-old daughter, who said she felt scared while listening to the sonification, but also that her daughter acknowledged that she should feel scared. *I'm scared, but this is supposed to be scary, right?* Her recognition of the dichotomy between what she is supposed to feel and what she actually feels is particularly interesting because it gets at the core difference between the perception and induction of emotion (Juslin & Laukka, 2004) discussed earlier. Her daughter understands that the piece is supposed to convey a certain emotion (fear) and that she does indeed feel fear. That, I think, is a measure of some success of the Local Warming exhibit!

Dr. Brown Wilson also later attended the exhibit in person with her class, PLAN 6020: Methods of Community Research and Engagement. With her permission and assistance, I shared a Google form with her students to elicit some feedback from them about their reactions to and thoughts of the Local Warming story. The survey asked the students to select how they viewed the exhibit (in-person, online — in the last couple weeks, or online — right before completing this feedback) and to answer the following free-form questions:

1. *What thoughts, if any, did viewing the piece elicit? Did you get the sense the piece was trying to convey a certain message?*

2. *What emotions, if any, did viewing the piece elicit? Did you get the sense the piece was trying to convey a certain emotion?*

3. *Anything else you'd like to comment on? This could be feedback, critique, anything!*

The feedback was generally positive, and the respondents commented on the sentiment that Local Warming expressed. In response to the second question, one student mentioned that "it created a sense of hopelessness," while another student recalled that it made them feel uneasy, and that they "think the piece was trying to elicit intensity and urgency of action." The second student is acknowledging and commenting on both their perception and induction of emotion from the piece. They contextualized what they actually felt with what they thought the piece was trying to convey. While only four students in the class responded to the survey, three of them remarked that in some capacity the piece expressed the *urgency* of climate change. This sense of urgency was intentionally embedded in the sonification through the siren-like sound of carbon dioxide and the disturbingly high-pitched melody of temperature witnessed when the sonification reaches the 20th century. One student, while talking about the sense of urgency created, says that the increasing unpleasantness of the sonification contributes to this feeling of apprehension. There is a distinct emotional shift between the start and end of the sonification which aids in transmitting emotion since viewers can reference the current state of Local Warming as it plays to the state it was in previously at the beginning. Lastly, a student reflected on the combination of sight and sound in the visual and how that impacted their experience with the exhibit: "I got a sense of impending crisis; the music in conjunction with watching the changing data values really evoked thoughts of the urgency of the issue being discussed." The student's labeling of the sonification as "music" validates the intended musicality of the piece. Also, this student recalled how sight and sound worked together to convey urgency. After all, Local Warming is more than a data sonification — it is a multisensory experience that enables the viewer to experience the data. Local Warming is a visceralization (Stark, 2014).

D'Ignazio and Klein promote the idea of multisensory representations of data or data visceralizations, stating that "humans are not two eyeballs attached by stalks to a brain computer. We are embodied, multisensory beings with cultures and memories and appetites" (D'Ignazio & Klein, 2020). By representing data through more than one sense, we can gain an increased understanding of it and convey the feeling behind it. Local Warming is an attempt to visceralize global and local climate data through the combination of sight and sound.

D'Ignazio and Klein position *A Sort of Joy* — a theatrical performance that represents data on the gender identities of artists featured in the Museum of Modern Art — as a data visceralization and

temporal experience that "makes the audience wait and listen and experience" (D'Ignazio & Klein, 2020). *A Sort of Joy*, Chou's sonification of gun deaths in America*,* and Geere and Quick's *London Under the Microscope* all encourage the audience to sit and engage with the underlying data for an almost uncomfortable amount of time. The sonification for each locality explored in Local Warming takes just over two minutes to complete, which isn't even that long compared to the nearly eight minute length of *London Under the Microscope*. Yet, when I was sharing Local Warming with friends, professors, and peers, I found myself constantly preemptively apologizing for the length, considering two minutes far too long to engage with data since the dominant forms of data visualization promote succinct and fast interpretations. In the climate space, we're so used to the visualizations depicting the steady incline of carbon dioxide and temperature that they no longer generate an affective response. The drawn out, temporal nature of the way the audience interacts with Local Warming works to counteract the primary ways we think about data representation and contributes to the embodiment of emotion. As the viewer watches and listens to Local Warming, they intimately experience the gradual rise in temperature and carbon dioxide. If they're a resident within one of the Charlottesville localities, they see and hear each part per million increase in atmospheric carbon dioxide and understand how that relates to the warming in their local community. In an attempt to move away from the critiqued aggregation and summarization present in data visualization, I made six distinct sonifications for each locality in Charlottesville, so that the viewer can understand global climate trends and locate themselves and their communities within those global trends. The interactivity and ability to switch between localities contributes to this individualization that allows the local community to see themselves in the data.

The perception of data visualization as inherently objective and the tendency of data visualization practitioners to create dehumanizing charts originated from the idea of visual minimalism and the theories of Edward Tufte (D'Ignazio and Klein, 2020). Tufte (2018) defines chartjunk as all non-data-ink, redundant data-ink, or graphical decoration which does provide new information. Tufte (2018) also coins the term data-ink ratio, a measure for how much "ink" in a graphic is dedicated to representing the data. Tufte takes a maximalist approach to the data-ink ratio, claiming that the best data visualizations are inherently the ones with the highest ratio of data to ink. D'Ignazio and Klein (2020) critique this idea of visual minimalism because of its primary appeal to reason, reinforcement of a false distinction between reason and emotion, and hierarchical positioning of reason above and more important than emotion. They state that the absence of chartjunk reinforces this idea that data visualizations are neutral and truthful, when really, all knowledge is situated (Haraway, 1988), and we really can only understand a data visualization if we recognize the powers and structures that frame it and purport its objectivity (D'Ignazio & Klein, 2020).

Fundamentally, D'Ignazio and Klein disagree with Tufte about what gets labeled chartjunk. The idea of chartjunk is valuable in the design process, but, as pointed out by D'Ignazio and Klein, Tufte's definition is flawed. Again, he claims that chartjunk is anything that "does not tell the viewer anything new" (Tufte, 2018). To Tufte, emotional "embellishment" is chartjunk. To D'Ignazio and Klein (2020) this emotional framing *is* new information for the viewer — the graphic becomes positioned from the perspective of the data practitioner, rather than showcasing the information from the impossible view of "no body".

This idea of chartjunk can be extended to data sonifications as well. As discussed above, Geere and Quick (2021b) talk about how they add ambient noises like the sounds of cars driving past or the squawk of birds to create a specific sonic experience as their audience listens to *The End of The Road*. They want their listeners to feel a certain way, and they leverage non-data elements to do so. These ambient sounds would be considered chartjunk by Tufte, yet their inclusion in the sonification adds context to the data and brings out the deeper sentiment that Geere and Quick are trying to convey.

Within Local Warming, the inclusion of speeches from specific time periods might be considered chartjunk since they are added to frame the graphic in a certain way and, as Tufte might describe, emotional embellishment. Local Warming makes use of three distinct voice overs to add context to the sonification: an environmental protest on Earth Day in 1970 (Reuters, 2020), remarks on hurricane Katrina relief efforts from President George W. Bush in 2005 (Bush, 2005), and a hopeful yet urgent note

about the coming of change by Greta Thunberg in 2020 (PBS NewsHour, 2019). These speeches are overlaid with the sonification in the year they were originally delivered. The inclusion of these speeches contributes to the emotional response of Local Warming because they add a social-political context to the temperature and carbon dioxide data. Moreover, due to the overlaying of these audio clips, Local Warming becomes a critical visualization because it taps into historical memory and contextualizes contemporary events (Hall, 2008).

4.2 Accessibility and Data Literacy

Accessibility is sometimes an overloaded (in the technical sense of having multiple definitions) term both in this work and in the broader literature (Sawe et al., 2020; Lundgard et al., 2019; Rassler, 2016; Costanza-Chock, 2020). Rassler (2016) positions sonification as a tool to make scientific data accessible to the broader public since most people don't read scientific journals. Sawe et al. (2020) discuss how sonification is used to overcome science literacy, which also increases accessibility. Lastly, Lundgard et al. (2019) discuss the pitfalls of accessible data visualization, specifically examining accessibility as it relates to people with disabilities and, in the context of data visualization, those who are blind or visually impaired. In this paper, I often use the term accessibility and its variations in multiple contexts. In this section, I will unpack what I mean by accessibility and elaborate on the ways that Local Warming both is and is not accessible by being intentional and specific about who is referred to and who is included in these uses of the term accessible. Specifically, I will discuss the core principles of design justice and how they inform the liberatory perspective I try to take in my work, distinguish accessibility from data literacy, discuss how Local Warming contributes to the project of data literacy, and talk about feedback on the Local Warming exhibit as it relates to accessibility and data literacy.

When I first began researching sonification and design – long before I started to even create my first iterations of the Local Warming sonifications – I read the introduction to Sasha Costanza-Chock's book, *Design Justice*, which informed the ways I thought about accessible design in relation to this project (Costanza-Chock, 2020). I want to frame this discussion of accessibility with some core principles (specifically the second, third, and sixth principles) of design justice that Costanza-Chock puts forth in her work:

> *2. We center the voices of those who are directly impacted by the outcomes of the design process.*
> *3. We prioritize design's impact on the community over the intentions of the designer.*
> *6. We believe that everyone is an expert based on their own lived experience, and that we all have unique and brilliant contributions to bring to a design process.*

To practice design justice then is to align with these and the other principles of the design justice network. As a technologist, I ideologically align myself with these principles. In the context of accessible data visualization, designing for justice means actively including blind and visually impaired people in the design process. It means that even well intentioned designers can cause further harm to marginalized communities. I want to acknowledge my own positionality and the inherent limitations of my work. I am a sighted person and haven't yet been able to work alongside blind and visually impaired people on the Local Warming data sonification. I hesitate to claim that Local Warming is more accessible to blind and visually-impaired folks folks since they were not included in its design.

Moreover, I want to challenge the notion that the change in medium offered by data sonification inherently makes it a more accessible form of data representation to blind or visually impaired people. Blind, visually impaired, and sighted people all have different lived experiences which impacts the way they consume knowledge and thus interpret all representations of data including sonifications. In fact, sighted and blind users have been shown to have different interpretations of pitch polarity (Walker & Lane, 2001; Walker and Mauney, 2010) –meaning the relationship between pitch and a variable. A positive pitch polarity means that as the variable increases in value, so does the pitch (Walker & Nees,

2011). A negative pitch polarity means that as the variable decreases in value, the pitch increases (Walker & Nees, 2011). Both polarities are used within sonificiation, and the polarity used often depends on what data is being represented. For example, in *The End of the Road*, Geere and Quick (2021b) use a negative pitch polarity to represent insect size. Larger insects correspond to lower pitched sounds, while smaller insects correspond to higher pitched sounds. However, in *The Natural Lottery*, Geere and Quick (2021a) use a positive pitch polarity to map increasing atmospheric carbon dioxide levels to sounds of increasing pitch, which is the same mapping used in Local Warming. This use of a positive polarity in Local Warming could be critiqued as a "visual-first" approach to accessibility (Lundgard et al., 2019). Data sonifications are not automatically more accessible to blind and visually impaired people, and accessibility needs to be considered in the design of sonifications just as much as visualizations.

Instead, I want to position Local Warming as a creative experiment that contributes to the larger project of data representation with the potential for greater accessibility. Local Warming was about imagining new possibilities and trying to create them. Data sonification presents a novel and hopefully more accessible way to engage with data; however, before data sonification can claim to be an inherently accessible medium, more work — that centers the experiences of blind and visually impaired people — needs to be done to understand how data sonification might be used to increase accessibility to data for people with disabilities.

The term accessibility can also be used to describe data literacy and the process of making data available to people who previously didn't have access to it (not because of a disability but rather due to hegemonic structures which control the presentation and public availability of data). For example, Rassler (2016) discusses how the sonification of climate data makes the data available to a broader public since most people don't read or engage with scientific literature outside of academia. Sawe et al. (2020) similarly position data sonification as a tool through which scientists can balance complexity and comprehensibility in the public sharing of their data and results. Despite this conversation of accessibility, Sawe et al. (2020) use different Western orchestral instruments to sonify several different variables in their sonficiation, which I find hypocritical because I don't find that sonification accessible at all. What audience has the musical background, ability to recognize and pick out specific instruments from a cacophony of sounds, and a prior knowledge of Western musical instruments? To whom does Sawe et al. (2020) make their data available? These are important questions to ask ourselves as we make claims about technology and accessibility. In Local Warming, I specifically used electronic synths and sounds that did not require background information that I couldn't explain in the narrative lead-up to the sonification in the hopes that Local Warming would not require additional musical background to be understood.

The use of data visualizations is so widespread and the ability to interpret them is so important that they are an integral part of our system of education (Franconeri et al., 2021). As a kid attending public school in the United States, I was taught how to create and interpret various basic forms of data visualizations from a young age. While many of us can easily dissect and interpret bar, line, and pie charts, we are also exposed to new and unfamiliar data visualizations all the time online (Lee et al., 2015), whether through works of data journalism published by *The New York Times*, *The Washington Post*, or *The Guardian* or through social media like Twitter and Instagram. The ubiquity of information visualizations is at the heart of the issue of data and graphical literacy. How do you streamline the process of data interpretation? How do you encourage people to engage with new and unfamiliar representations of data?

In my conversation with Dr. Michele Claibourn about the opening ceremony of the Picturing Climate Justice exhibit, she recounted how the Local Warming story was well received, especially among youth. It's hard to say for sure what drew the younger attendees to the Local Warming story, but I would argue that the combined representation of data through sight and sound is what attracted them. The multisensory nature of the project was potentially more engaging for youth. Hopefully, this increased engagement among youth will actually lead to increased memorability or recall of the data or shape how they think about the climate crisis in the future. Dr. Claibourn described many of the youth jockeying for the ability to play with the sonification and be the one to actually press play. Jokingly, she said she could

still hear the siren playing long after the event had ended because the Local Warming piece was playing almost constantly during the opening ceremony.

This point about youth engagement was echoed by Dr. Brown Wilson. She thought the ending to Local Warming, which featured a voice over of Greta Thunberg speaking about the climate crisis, was powerful given that the Picturing Climate Justice exhibit sought to center Charlottesville youth. Dr. Brown Wilson also noted that her daughter was particularly excited by the Local Warming story. Moreover, Dr. Brown Wilson recounted that her daughter said she felt that she really understood the point of the Local Warming exhibit. Her daughter compared the Picturing Climate Justice exhibit to other museums, galleries, and events that she attended with her mother, commenting that, at this exhibit, she actually "got it".

4.3 Reflections

One of the greatest technical challenges for me personally was the development of the background knowledge needed to create data sonifications. Before working on this project, I had little to no musical background or knowledge whatsoever, so a large part of my time at the beginning of this year was spent researching music theory and understanding things like minor and major keys, melodies and countermelodies, and chord progressions. I had to figure out how timbre, pitch, and loudness interact within a song and how to manipulate them electronically. Moreover, the electronic creation of music and sound is another discipline of knowledge that I did my best to pick up along the way. I struggled to effectively represent via sound the sentiment and overall feeling I was trying to convey. I was also relatively new to the tools that I ultimately used to create Local Warming, namely Svelte.js and Sonic Pi. Moreover, I struggled to get the visual and the sonification to fully sync up in the final Local Warming tool.

Beyond tools and technical issues, I realized the power of interdisciplinary, collaborative work through this project. Through my role at the UVA Equity Center, I was able to get feedback on the earlier designs of Local Warming from people of various academic backgrounds. In this thesis itself, I try to discuss the creation of technological and data-driven work that embodies feminist (D'Ignazio and Klein, 2016; D'Ignazio and Klein, 2020), liberatory (Costanza-Chock, 2020), and critical (Hall, 2008) frameworks. These theoretical lenses provide me with new ways to critique other representations of data and my own work. First, as discussed above, Costanza-Chock (2020) makes me hesitant to claim that sonification is more accessible even though other literature makes this claim without directly incorporating feedback and lived experience of people with disabilities. D'Ignazio, Klein, and Hall make me question what narrative I'm espousing through my work and what systems of power am I supporting or challenging.

4.4 Future Work

With Local Warming itself, I want to add tooltips on the carbon dioxide and final sonification charts to add context, particularly to explain the voice overs. Dr. Brown Wilson shared a neat idea of using images on the final sonfication tool instead of text. For example, you could imagine that as former President George Bush discusses hurricane Katrina, an image could appear to demonstrate the devastation and truly how much of New Orleans was underwater. It might be interesting to think more about interactivity as it relates to sonification. If there was a way to generate sonifications in the browser, you could enable users to add or remove certain sonic elements from a sonification like you might with a variable in a visualization.

Beyond Local Warming, I think a natural and very exciting avenue to build upon this work would be to delve deeper into the concept of visceralization by incorporating more senses into the representation or specifically looking to wield senses other than sight and sound to convey data. At the beginning of last semester, I remember talking with Dr. Claibourn about leveraging tactile sense and the radiation of heat the Picturing Climate Justice exhibit to explore surface temperature data in Charlottesville. Furthermore,

you might be able to create certain smells to represent air quality. Given the very real and physical nature of climate data, I think there are several, exciting possibilities to explore in the realm of visceralization.

5 Conclusion

As discussed above, Local Warming leverages the power of music to convey greater emotion than a standalone visual. The combination of sound and sight work together to *visceralize* global and local climate data to provide visitors at the Picturing Climate Justice exhibit with a way to experience and feel the data over simply seeing it. Informed by feminist, liberatory, and critical frameworks, Local Warming exists at the intersection of ethics and technology and as a creative experiment and exploration into new worlds of data representation that hopefully will one day lead to greater accessibility and understanding of represented data.

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