CST + Design Fiction: TempHarmonics

Ryan Dreher
University of Victoria
CSC 413
Victoria, Canada
rdreher@uvic.ca

Baz Cox
University of Victoria
CSC 413
Victoria, Canada
bcox@uvic.ca

Dewei Yu
University of Victoria
CSC 413
Victoria, Canada
bouyu@uvic.ca

ACM Reference Format:
Ryan Dreher, Baz Cox, and Dewei Yu. 2024. CST + Design Fiction: TempHarmonics. In *Proceedings of CST + Design Fiction: TempHarmonics (TempHarmonics).* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Our Creativity Support Tool (CST) addresses the human challenge of understanding and perceiving temperature differences[8] in a future impacted by global warming, where rising temperatures and an expanded equator lead to a homogenized climate, making it difficult for people to distinguish between "cold" and "warm" environments. To solve this, our CST translates temperature variations into auditory cues, using music[14] as a medium to teach temperature distinctions: high-pitched, intense beeps represent hot[4] temperatures, while low-pitched, soothing tones signify cold temperatures. This system is motivated by the need to reintroduce the concept of temperature diversity in a future where such differences may no longer be intuitive. The system fosters creative engagement by mapping abstract temperature sensations to tangible auditory signals, empowering users to explore and learn through sensory interaction. This integration of technology and creativity to address a pressing environmental issue positions our design as a true Creativity Support Tool.

2 AIM

Our project aims to create the Creativity Support Tool, which uses the ability to perceive by ear to understand temperature distinctions. In a future where global warming[8] becomes the predominant factor, with increased temperatures having expanded the equator, we can hardly speak about perception differences in "cold" and "warm" climate zones.

Our CST addresses this challenge by translating temperature variations into musical[10] sounds: high-pitched, intense beeps represent hot temperatures, while low-pitched, soothing tones signify cold temperatures. We will seek to remap these abstract temperature sensations to more concrete auditory signals to bring back the notion of temperature diversity and create creative engagement through sensory interaction.

TempHarmonics, 2024-12-02, Victoria, Canada

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM
https://doi.org/10.1145/nnnnnnn.nnnnnnn

3 MOTIVATION

This work is human-centred in motivation because of the growing need to adapt to environmental and sensory changes expected due to global warming[8]. When climate differences are reduced, humans will intuitively not understand and react well to changes in temperature, affecting daily life and well-being. Our CST uses music[10] as a pedagogical and engaging medium to offer an innovative solution for people to relearn and appreciate temperature diversity. Such a strategy will not only improve the sensory perception of users but also empower them through creative exploration, putting technology in service of human experience to solve one of the significant environmental issues.

4 RELATED WORK

Our project, *TempHarmonics*, intersects several domains, including data sonification, educational technology, and multisensory learning tools designed to enhance understanding of climate change. This section reviews existing projects and research similar to our CST and discusses how our approach advances beyond previous work.

4.1 Data Sonification of Climate Data

Data sonification has been employed to represent complex datasets through auditory means, providing an alternative to visual representations [9]. One notable project is "A Song of Our Warming Planet" by Daniel Crawford, where global temperature records are translated into musical notes played on a cello[13]. Each note represents a year, and the pitch corresponds to the average annual temperature, creating a haunting melody that reflects the global warming trend. Similarly, the Climate Symphony project transforms climate data into orchestral music to make the data more emotionally resonant[3].

While these projects effectively raise awareness about climate change through music, they provide a static representation of data without interactive elements. TempHarmonics extends this concept by offering an interactive platform where users can manipulate temperature inputs and experience real-time auditory feedback. This interactivity fosters a deeper engagement, allowing users to explore and understand temperature variations through personal experimentation.

4.2 Educational Tools Utilizing Multisensory Learning

Multisensory learning tools have enhanced educational outcomes by engaging multiple senses and improving memory retention and understanding[17]. Projects like "Listen to the Data" use sonification to teach complex subjects such as astronomy and physics by converting data into sound. In the context of climate education, the "Sound of the Earth" installation allows users to listen to environmental data streams, providing an immersive experience.

However, these tools often lack customization and adaptability to individual learning needs. TempHarmonics differentiates itself by incorporating user-controlled parameters, enabling educators and learners to tailor the experience to specific educational goals. By integrating adjustable sound mappings and collaborative features, our CST supports various learning styles and encourages active participation.

4.3 Interactive Musical Instruments with Environmental Sensors

There have been developments in creating musical instruments that respond to environmental inputs. For instance, the Theremin is an early electronic instrument controlled without physical contact, using the proximity of the performer's hands to antennae[6].

While innovative, these instruments primarily focus on artistic expression rather than educational objectives. TempHarmonics bridges this gap by using environmental sensors—in our case, temperature sensors—not only for creative expression but also as a medium for education about climate change and sensory perception. Our CST is designed with pedagogical principles, aiming to facilitate learning through creative interaction.

4.4 Advancements Beyond Existing Work

TempHarmonics advances beyond previous projects by combining real-time interactivity, educational focus, and collaborative capabilities in a single platform. Unlike static sonification projects, our CST allows users to engage actively with temperature data, adjusting inputs and immediately experiencing the effects through auditory feedback. This immediacy enhances the learning experience, as users can experiment and observe outcomes in real-time.

Moreover, by incorporating collaborative features, TempHarmonics supports social learning environments where multiple users contribute to a shared soundscape. This collective interaction is not commonly found in existing sonification tools and adds a unique dimension to the educational experience.

In summary, while previous projects have explored the sonification of climate data and the use of environmental inputs in musical instruments, TempHarmonics uniquely integrates these concepts into an interactive educational tool that promotes creative exploration and collaborative learning. Our CST raises awareness about climate change and provides a means for individuals to experientially understand temperature variations, addressing a critical gap in climate education tools.

5 DESIGN FICTION

In the year 2174, Earth's climate has undergone irreversible transformations after centuries of unchecked global warming. The equatorial zone has expanded dramatically, enveloping much of the globe in unrelenting heat. Seasonal changes have vanished, and temperatures have stabilized at uncomfortably high averages. This new climatic normal has erased the once-rich diversity of seasonal experiences. Generations have grown up knowing only a singular, monotonous warmth. For many people who live on planet Earth, "cold" and "warm" are not just forgotten—they are unimaginable.

5.1 Scenario: Recreating the Sensations of a Lost Climate

Maria was a climate historian, 24, living in Neo-São Paulo, an equatorial megacity of ceaseless heat. She was supposed to teach students about Earth's climatic past, but it hardly ever works. How do you describe the feeling of "cold" to people if they have never felt a winter breeze? How do you describe the gentle warmth of spring to people who have only known oppressive, stagnating heat? Even with Maria using historical data and describing with her best effort, her students still cannot understand these concepts.

She turns to TempHarmonics for a novel solution. A Creativity Support Tool (CST), TempHarmonics uses advanced sensors that scan and record in real-time to capture temperature data and then process it by simulating contrasting climates through different musical sounds. TempHarmonics digitally converts the temperature readings into audible forms, which evoke sensations from both "cold" and "warm" temperature surroundings. These auditory cues can then be played back through different mediums of her choice: headphones, laptop speakers, or even surround sound systems.

Maria initiates the process by scanning an ice cube with the device's integrated sensors. After processing the data, the system generates a low-pitched, soft hum that fills the room through her laptop speakers, evoking the calm stillness of a cold winter's day. Maria and her students close their eyes, imagining the biting chill of frosty air brought to life through the sound. Next, she lights a match and scans the warmth of the flame. The system responds with high-pitched, rapid tones reminiscent of the intense heat of standing near a roaring bonfire on a summer night. As the students relate the musical cues to cold and warm sensations, they mimic the stillness of a snow-covered forest and the intense heat of a desert at midnight, making the once abstract concept of temperature feel vividly real.

Through TempHarmonics, Maria and her students creatively explore and understand the sensations of "cold" and "warm" by associating distinct musical cues with temperature variations. The CST empowers them to engage with abstract thermal concepts through a multisensory learning process, where low-pitched, soothing sounds evoke the calmness of cold, and high-pitched, dynamic tones simulate the intensity of heat. This auditory-thermal mapping fosters a deeper appreciation for the diversity of Earth's climatic past. Whether through individual exploration or collaborative soundscapes, TempHarmonics reconnects humanity with a lost sensory world—offering both education and hope in the face of a homogenized climate.

6 DESIGN

Our Creativity Support Tool (CST), *TempHarmonics*, is designed to reintroduce the concept of temperature diversity to individuals in a future where global warming has homogenized global climates. By translating temperature variations into auditory cues, we leverage music as an educational medium to foster creative engagement and sensory learning.

6.1 Design Rationale

6.1.1 Bridging Sensory Gaps Through Multisensory Learning. The homogenization of global temperatures presents a unique educational challenge: conveying the concept of temperature variation to individuals who lack direct sensory experience. Multisensory learning enhances comprehension and retention by engaging multiple senses simultaneously[17]. Shams and Seitz highlight that integrating auditory stimuli can effectively compensate for the absence of other sensory inputs. By mapping temperature differences to auditory cues, TempHarmonics provides an alternative sensory experience that facilitates understanding through sound, bridging the sensory gap created by environmental changes.

6.1.2 Utilizing Music for Emotional and Cognitive Engagement. Music profoundly impacts human emotions and cognitive processes, making it an effective educational tool [7]. Hallam discusses how music influences mood, arousal levels, and physiological responses, enhancing learning and memory retention. Cross-modal perception studies suggest a natural association between musical elements and thermal sensations—high pitches often correlate with warmth, while low pitches are associated with cold [5]. By leveraging these inherent associations, our CST uses high-pitched, rapid tones to simulate heat intensity and low-pitched, soothing sounds to represent the cold's calmness. This auditory representation helps users internalize temperature variations cognitively and emotionally.

6.1.3 Promoting Creative Exploration and Learning. Transforming abstract temperature data into tangible auditory experiences encourages users to engage creatively with the material. This approach aligns with constructivist learning theories, where individuals build knowledge through active exploration and personal experience[15]. By allowing users to manipulate temperature inputs and observe corresponding auditory outputs, TempHarmonics fosters a hands-on learning environment. Such creative engagement is crucial for deep learning and long-term retention, promoting curiosity and personal investment in the educational process.

6.1.4 Addressing Climate Education Through Innovative Tools. Educating future generations about climate change impacts is essential for fostering environmental stewardship [11]. Traditional methods may not suffice in conveying global warming's severity, especially when direct sensory experiences are lacking. TempHarmonics offers an innovative solution that makes climate education more accessible and impactful through multisensory engagement. Experiencing simulated temperature differences via auditory cues enables users to deeply understand climate issues, potentially motivating participation in environmental conservation efforts.

6.2 Design Principles Applied

6.2.1 Low Threshold, High Ceiling. TempHarmonics is designed to be accessible to beginners while offering depth for advanced exploration [16]. The hardware setup uses standard components like the LM35 sensor and Arduino microcontroller, making it approachable for individuals with minimal technical background. The accompanying software provides an intuitive interface for fundamental interactions, such as experiencing predefined temperature simulations. Advanced users can customize sound mappings and create new auditory scenarios, offering a high ceiling for creative exploration.

6.2.2 Support for Exploration and Multiple Paths. The CST encourages open-ended exploration, supporting the principle of providing multiple pathways for users to engage with the content[12]. Users can experiment with different temperature inputs, adjust parameters, and observe the resulting auditory outputs. This design fosters divergent thinking and creativity, as there is no correct way to interact with the system. Such flexibility is essential in creativity support tools, empowering users to take ownership of their learning process.

6.2.3 Support for Collaboration. Collaborative learning enhances understanding and retention, as social interaction plays a significant role in cognitive development[18]. TempHarmonics facilitates collaborative experiences by allowing multiple devices to send data to a central application. In a classroom setting, students can contribute individual temperature inputs to a collective soundscape, promoting teamwork and communication. This collaborative aspect aligns with social learning theories and enhances the educational value of the CST.

6.2.4 Integration of Technology and Art. By combining technology with artistic expression, TempHarmonics embodies the STEAM (Science, Technology, Engineering, Arts, Mathematics) approach to education[19]. This integration promotes holistic learning and appeals to a broader range of learners. The fusion of scientific data with musical interpretation aids in understanding complex concepts and fosters appreciation for the arts, supporting interdisciplinary education.

6.3 Application of Design Principles

6.3.1 Low Threshold, High Ceiling. The straightforward hardware assembly and user-friendly software interface ensure that beginners can quickly use TempHarmonics. As users become more comfortable, they can delve into advanced features like adjusting the mapping of temperature to sound frequencies, experimenting with different sound synthesis techniques, and integrating additional sensors. This scalability aligns with the principle of providing a low barrier to entry while offering complex possibilities for advanced users [16].

6.3.2 Support for Exploration and Multiple Paths. TempHarmonics allows users to simulate various temperature scenarios, including historical climate data. By manipulating these inputs, users can explore how temperature variations affect the auditory output, promoting an interactive and engaging learning experience. This open-ended interaction encourages learners to approach the concept of temperature in ways that resonate with their interests and learning styles[12].

6.3.3 Support for Collaboration. TempHarmonics enables multiple users to collaborate to create complex soundscapes in group settings. For example, each student can represent a different geographic location's temperature data, contributing to a global auditory representation of climate variations. This collaborative creation enhances understanding of global warming's diverse impacts and fosters a sense of community and shared purpose[18].

6.3.4 Integration of Technology and Art. The CST bridges the gap between quantitative analysis and qualitative experience by translating scientific data into musical expressions. This approach aids in learning scientific concepts and fosters appreciation for the arts, supporting interdisciplinary education critical for developing well-rounded individuals in the 21st century [19].

7 IMPLEMENTATION

Our implementation of the *TempHarmonics* Creativity Support Tool (CST) integrates both hardware and software components to translate temperature data into auditory experiences. This section explains how the system works, including step-by-step instructions on building the hardware, an explanation of the software components, and the rationale behind our design choices. We also explicitly state what was implemented and discuss any parts that were not fully realized, providing justification for these decisions.

7.1 Hardware Implementation

7.1.1 Components Used. The hardware setup consists of the following components from the **UNO R3 Super Starter Kit**:

- **Arduino UNO R3**: Microcontroller board used for processing sensor data and serial communication.
- **NTC Thermistor (10kΩ)**: A temperature-sensitive resistor used to measure ambient temperature changes.
- **10kΩ Resistor**: Used in conjunction with the thermistor to create a voltage divider circuit.
- **Breadboard Mini**: A small breadboard for assembling the circuit without soldering.
- **Jumper Wires**: Used to connect components and the Arduino on the breadboard.
- **USB Cable**: Connects the Arduino to a computer for programming and serial communication.

7.1.2 Circuit Design and Assembly. To measure temperature using the thermistor, we constructed a voltage divider circuit. The thermistor's resistance changes with temperature, affecting the voltage at the analog input pin, which we read using the Arduino.

Wiring Instructions:

(1) **Thermistor Connection:**
  - Connect one end of the **thermistor** to the **5V** pin on the Arduino.
  - Connect the other end of the thermistor to the **analog input pin A0** and one end of the **10kΩ resistor**.

(2) **Resistor Connection:**
  - Connect the other end of the **10kΩ resistor** to the **GND** pin on the Arduino.

Circuit Diagram: This configuration forms a voltage divider where the voltage at point A0 varies according to the thermistor's resistance, which changes with temperature.

7.1.3 Arduino Code. The Arduino code reads the analog voltage from the voltage divider, calculates the corresponding temperature, and sends the temperature data to the computer via serial communication.

The full Arduino code is provided in **Appendix A**

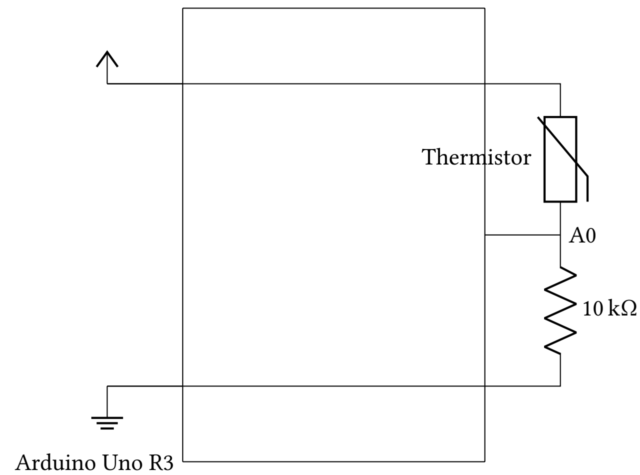

Figure 1: Voltage Divider Circuit with Thermistor and Resistor

Hardware Implementation Notes.

- **Component Selection Rationale:**
  - The **NTC thermistor** was chosen for its sensitivity and responsiveness to temperature changes within the desired range.
  - The **10kΩ resistor** matches the thermistor's nominal resistance, optimizing the voltage divider for mid-range temperatures.
- **Calibration Considerations:**
  - The thermistor requires calibration to ensure accurate temperature readings due to its non-linear resistance-temperature relationship.
  - We used standard values for the **beta coefficient** and **nominal resistance**, which are suitable for common 10kΩ NTC thermistors.
- **Limitations:**
  - The thermistor's accuracy decreases outside its optimal temperature range.
  - Environmental factors like self-heating or rapid temperature changes can affect readings.

7.2 Software Implementation

The software component is a Python script that communicates via serial with the Arduino, processes temperature data, maps temperatures to sound files, plays the corresponding sounds, and provides a graphical user interface (GUI) for visualization.

Python Script Overview. **Key Functionalities:**

(1) **Serial Communication and Data Processing**
(2) **Temperature to Sound Mapping**
(3) **Sound Playback**
(4) **Graphical User Interface (GUI)**
(5) **Data Logging**
(6) **Multithreading for Concurrent Operations**

The full Python script is provided in **Appendix A**.

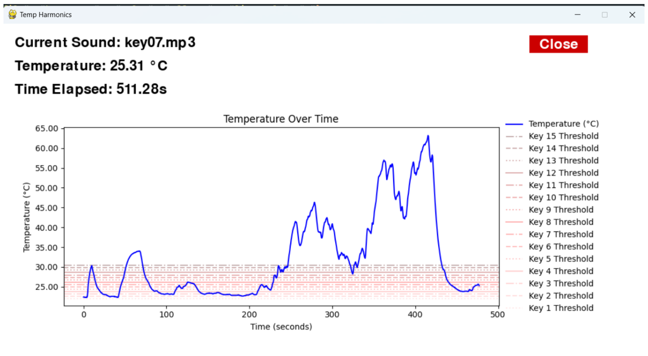

Figure 2: Graphical User Interface (GUI) in action

Graphical User Interface (GUI). The GUI displays:

- **Current Temperature**
- **Current Sound File**
- **Elapsed Time**
- **Real-Time Temperature Graph**

Multithreading. We use Python's `threading` module to handle different tasks concurrently:

- **Serial Data Reading Thread**
- **Temperature Data Processing Thread**
- **GUI Thread**

This approach ensures the GUI remains responsive while data is being read and processed in the background.

Software Implementation Notes.

- **Sound Files:** We used pre-recorded MP3 files (`key01.mp3` to `key15.mp3`) representing musical notes. These files correspond to the temperature zones and are played when the temperature falls within a specific zone.
- **Data Queue and Thread Synchronization:**
  - We use a `Queue` to safely pass temperature data between threads.
  - Locks are used to synchronize access to shared variables.
- **Error Handling:**
  - The script includes exception handling for serial communication errors, data processing issues, and user interruptions.
  - Graceful shutdown procedures are implemented to close threads and release resources.

7.2.1 *Implemented vs. Mocked Components.*

Implemented Components.

- **Hardware Setup:** Complete assembly of the voltage divider circuit with the thermistor and resistor.
- **Arduino Code:** Fully functional code that reads temperature data and sends it via serial communication.
- **Python Script:**
  - Serial communication and data processing.
  - Temperature to sound mapping.
  - Sound playback using `pygame`.
  - GUI with real-time temperature display and graph.
  - Data logging to a file.

Mocked or Not Implemented Parts.

- **Real-Time Sound Synthesis:** Instead of generating sounds programmatically based on temperature values, we used pre-recorded sound files.
- **User Customization in GUI:** The ability for users to adjust temperature zones, thresholds, or sound mappings through the GUI was not implemented.
- **Wireless Communication:** Communication between the Arduino and the computer is wired (USB). Wireless options like Bluetooth were not explored due to time constraints.
- **Advanced Data Analysis:** While data is logged, no additional data analysis or visualization beyond the real-time graph is performed.

7.3 Rationale for Not Implemented Parts

Our primary goal was to create a working prototype that demonstrates the core functionality of *TempHarmonics*. Implementing real-time sound synthesis or advanced user customization would have required significant additional development time and possibly more complex hardware. These features are identified as potential enhancements for future work, as they would improve user engagement and system flexibility.

7.4 Building the System: Step-by-Step Instructions

Step 1: Assemble the Hardware.

(1) **Prepare the Components:**
  - Gather the Arduino UNO R3, thermistor, 10kΩ resistor, breadboard mini, and jumper wires.

(2) **Construct the Voltage Divider Circuit:**
  - Place the thermistor and resistor on the breadboard according to the circuit diagram.
  - Use jumper wires to connect the thermistor to the **5V** pin and **analog pin A0** on the Arduino.
  - Connect the resistor between the thermistor and the **GND** pin on the Arduino.

(3) **Verify Connections:**
  - Ensure all connections are secure and match the schematic.

Step 2: Upload the Arduino Code.

(1) **Install the Arduino IDE:**
  - Download and install the Arduino IDE from https://www.arduino.cc/en/software.

(2) **Load the Arduino Sketch:**
  - Open the Arduino IDE.
  - Copy and paste the Arduino code provided in Appendix A into a new sketch.

(3) **Configure the Serial Port:**
  - Connect the Arduino to your computer using the USB cable.
  - In the Arduino IDE, go to **Tools** > **Port** and select the port corresponding to your Arduino.

(4) **Set the Baud Rate:**
  - Ensure the baud rate in the code matches the one in the Python script (**115200**).

(5) **Upload the Code:**
   - Click the **Upload** button in the Arduino IDE to compile and upload the code to the Arduino.

Step 3: Prepare the Software Environment.

(1) **Install Python 3:**
   - Download and install Python 3 from https://www.python.org/downloads/.

(2) **Install Required Libraries:**
   - Open a terminal or command prompt.
   - Run: `pip install pyserial pygame matplotlib`

(3) **Place Sound Files:**
   - Ensure that the sound files (`key01.mp3` to `key15.mp3`) are in the same directory as the Python script.

(4) **Update Serial Port in Script:**
   - Open the Python script (`A3.py`) in a text editor.
   - Update the `serial_port` variable to match your Arduino's serial port (e.g., `'COM3'` on Windows or `'/dev/ttyACM0'` on Linux).

Step 4: Run the Python Script.

(1) **Execute the Script:**
   - Navigate to the directory containing the Python script.
   - Run: `python A3.py`

(2) **Interact with the GUI:**
   - The GUI window will display temperature readings, the current sound file, and a temperature graph over time.
   - Use the **End** button to stop data gathering or the **Close** button to exit the application.

Step 5: Test the System.

(1) **Verify Temperature Readings:**
   - Observe the temperature displayed in the GUI.
   - Compare it with a known temperature source to assess accuracy.

(2) **Trigger Temperature Changes:**
   - Gently warm the thermistor (e.g., by holding it) and observe changes in temperature readings and sound playback.
   - Allow the thermistor to cool and verify that the system responds appropriately.

(3) **Check Sound Playback:**
   - Ensure that different temperatures trigger the correct sound files according to the defined temperature zones.

7.5 Images

- **Figure 3**. is our TempHarmonics Prototype
- **Figure 4** is the internal components of TempHarmonics

7.6 Code Linkage

- **Arduino Code**: See **Appendix A** for the full Arduino code.
- **Python Script**: See **Appendix A** for the full Python script.

7.7 Conclusion

The implementation of *TempHarmonics* successfully demonstrates the concept of using temperature data to generate auditory experiences. By combining hardware sensing with software processing and visualization, we created an interactive tool that engages users in exploring temperature variations through sound and visual feedback. While some advanced features were not implemented due to time constraints, the project lays a solid foundation for future enhancements that could further enrich the educational and creative potential of the CST.

Figure 3: TempHarmonics Prototype

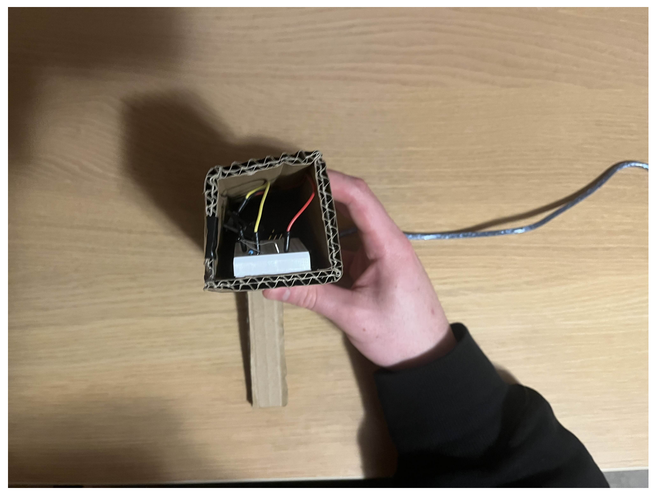

Figure 4: Interior of TempHarmonics

8 CRITIQUE

During our self-evaluation using the CSI calculation template [2], we calculated the Creativity Support Index (CSI) for *TempHarmonics* and obtained an aggregated score of approximately 210. As we did our calculation, the prototype indicates strong performance in fostering creativity and user engagement. *TempHarmonics* demonstrated notable strengths in promoting expressiveness, with high individual scores (10 and 8) reflecting users' ability to be creative during interactions. Similarly, immersion scored consistently well (7 and 8), highlighting the system's effectiveness in capturing users' attention. However, limitations were also identified, such as relatively low counts for exploration and collaboration, suggesting areas for improvement by incorporating more interactive or collaborative features. Overall, this CSI score highlights *TempHarmonics* as a powerful Creativity Support Tool, excelling in expressiveness and immersion while also offering opportunities to broaden its engagement across other dimensions like collaboration and exploration.

8.1 Strengths

(1) **Multisensory Engagement Enhances Learning**
TempHarmonics utilizes multisensory learning to convey abstract ideas of temperature diversity effectively. The mapping of temperature variations to auditory cues fills in sensory information gaps within the CST and allows better comprehension and retention. This emotional and cognitive link with music enhances the learning experience and makes the concept of temperature diversity accessible even for users without direct sensory exposure.

(2) **Enhanced Emotional Connection Through Music**
TempHarmonics leverages the inherent emotional and cognitive impact of music to create a meaningful and memorable user experience. The system fosters an intuitive understanding of abstract concepts by translating temperature data into auditory cues that align with natural associations, such as high-pitched tones for warmth and low-pitched sounds for cold. This emotional connection not only enhances user immersion but also deepens engagement with the tool, making the learning experience more impactful and resonant[1].

(3) **Interdisciplinary Integration**
TempHarmonics artfully integrates technology and art, embodying a STEAM approach that appeals to both technical and artistic learners in comprehending climate education. The auditory representation of data conveys an in-depth comprehension of temperature variation while cultivating an appreciation for musical creativity simultaneously.

8.2 Limitations

(1) **Limited Representational Depth**
While the prototype effectively translates temperature fluctuations into sound, the auditory cues may be too simple for complex data. Subtleties such as rate of change, extremes, or long-term trends in temperature may not be well captured, which can diminish educational value for advanced users seeking more detailed information.

(2) **Dependence on Predefined Associations**
The mapping of temperature to auditory cues is based on intrinsic associations, such as high pitches for warmth and low pitches for cold. Although intuitive for many, these associations may not be universally resonant, particularly across diverse cultural or personal conceptions of sound. This could make the CST less accessible and inclusive for a worldwide audience.

(3) **Technical and Hardware Limitations**
The system requires external sensors and microcontrollers, which may limit its use in resource-constrained environments. Real-time processing of higher complexity datasets involving many users collaboratively manipulating a virtual scene is difficult to realize and may require more advanced hardware.

9 FUTURE WORK

The development of *TempHarmonics* opens several avenues for future improvement and extension. Building upon the foundational concept of translating temperature data into auditory experiences for educational purposes, the following are three meaningful directions for future work:

9.1 Integration of Advanced Sensors for Enhanced Accuracy

9.1.1 Incorporate High-Precision Temperature Sensors. Upgrade the system by integrating more accurate and sensitive temperature sensors, such as the DS18B20 digital temperature sensor or thermocouple sensors. These sensors offer higher precision and a broader temperature range, enhancing the system's ability to detect subtle temperature variations.

9.1.2 Add Additional Environmental Sensors. Expand the sensory input by including other environmental sensors, such as humidity, air quality (e.g., CO_2 levels), or barometric pressure sensors. This would allow *TempHarmonics* to provide a more comprehensive representation of environmental conditions.

9.1.3 Multisensory Data Fusion. Implement data fusion techniques to combine readings from multiple sensors, creating more complex and nuanced auditory outputs that reflect a combination of environmental factors.

9.1.4 Justification. Enhancing sensor accuracy and incorporating additional environmental data will improve the educational value of *TempHarmonics* by providing users with richer, more detailed information. This aligns with the trend toward multimodal learning environments, which have been shown to enhance cognitive processing and retention [17].

9.2 Development of a Mobile Application for Increased Accessibility

9.2.1 Create a Cross-Platform Mobile App. Develop a mobile application compatible with iOS and Android devices to replace or supplement the desktop Python application. The app would communicate wirelessly with the hardware via Bluetooth or Wi-Fi, allowing for greater mobility and ease of use.

9.2.2 User-Friendly Interface. Design an intuitive user interface that enables users to customize sound mappings, adjust settings, and visualize data in real time. Incorporate interactive tutorials to guide new users through the system's features.

9.2.3 Cloud Integration and Data Sharing. Enable data logging and cloud synchronization features, allowing users to save their sessions, track changes over time, and share their soundscapes with others. This would facilitate collaborative projects and remote learning opportunities.

9.2.4 Justification. Developing a mobile app enhances the accessibility and portability of *TempHarmonics*, making it more convenient for users to engage with the tool in various settings, such as classrooms, museums, or outdoor environments. Mobile platforms are increasingly prevalent in educational technology, supporting the shift toward ubiquitous learning [19].

9.3 Incorporation of Machine Learning for Adaptive Sound Mapping

9.3.1 Implement Adaptive Algorithms. Utilize machine learning algorithms to analyze user interactions and preferences, enabling the system to adapt the sound mappings over time for a personalized experience.

9.3.2 Predictive Modeling. Incorporate predictive analytics to anticipate temperature trends based on historical data, allowing the system to generate anticipatory auditory cues that can enhance the learning experience.

9.3.3 Emotion Recognition and Response. Explore the use of affective computing to adjust the auditory outputs based on the user's emotional responses, creating a more engaging and empathetic educational tool.

9.3.4 Justification. By integrating machine learning, *TempHarmonics* can become a more intelligent system that personalizes the educational experience. Adaptive learning technologies have been shown to improve engagement and effectiveness by tailoring content to individual users' needs [11]. This advancement would position *TempHarmonics* at the forefront of innovative educational tools.

REFERENCES

[1] [n. d.]. Sounds of the Earth – Sonifications of Earth's vibrations. https://www.soundsoftheearth.ie/
[2] Erin Cherry and Celine Latulipe. 2014. Quantifying the Creativity Support of Digital Tools through the Creativity Support Index. *ACM Transactions on Computer-Human Interaction* 21, 4 (6 2014), 1–25. https://doi.org/10.1145/2617588
[3] ClimateMusic. [n. d.]. ClimateMusic | Science + Music + Action. https://climatemusic.org/
[4] Daniel G. Craig. 2005. An Exploratory Study of Physiological Changes during "Chills" Induced by Music. *Musicae Scientiae* 9, 2 (7 2005), 273–287. https://doi.org/10.1177/102986490500900207
[5] Zohar Eitan and Renee Timmers. 2009. Beethoven's last piano sonata and those who follow crocodiles: Cross-domain mappings of auditory pitch in a musical context. *Cognition* 114, 3 (12 2009), 405–422. https://doi.org/10.1016/j.cognition.2009.10.013
[6] Albert Glinsky. 2000. *Theremin.* University of Illinois Press.
[7] Susan Hallam. 2010. The power of music: Its impact on the intellectual, social and personal development of children and young people. *International Journal of Music Education* 28, 3 (8 2010), 269–289. https://doi.org/10.1177/0255761410370658
[8] James Hansen, Makiko Sato, Reto Ruedy, Ken Lo, David W. Lea, and Martin Medina-Elizade. 2006. Global temperature change. *Proceedings of the National Academy of Sciences* 103, 39 (9 2006), 14288–14293. https://doi.org/10.1073/pnas.0606291103
[9] Thomas Hermann. 2008. Taxonomy and definitions for sonification and auditory display. http://hdl.handle.net/1853/49960
[10] Richard A. McFarland. 1985. Relationship of skin temperature changes to the emotions accompanying music. *Biofeedback and Self-Regulation* 10, 3 (9 1985), 255–267. https://doi.org/10.1007/bf00999346
[11] Martha C. Monroe, Annie Oxarart, and Richard R. Plate. 2013. A role for environmental education in climate change for secondary science educators. *Applied Environmental Education & Communication* 12, 1 (1 2013), 4–18. https://doi.org/10.1080/1533015x.2013.795827
[12] Stephen Nachmanovitch. 1990. *Free Play: Improvisation in Life and art.* http://ci.nii.ac.jp/ncid/BA30761429
[13] Oc. 2016. A Song of Our Warming Planet: Cellist Turns 130 Years of Climate Change Data into Music. https://www.openculture.com/2013/07/a_song_of_our_warming_planet.html
[14] Leonid Perlovsky. 2012. Cognitive Function of Music. Part I. *Interdisciplinary Science Reviews* 37, 2 (6 2012), 131–144. https://doi.org/10.1179/0308018812z.00000000010
[15] Jean Piaget. 1976. *Piaget's Theory.* 11–23 pages. https://doi.org/10.1007/978-3-642-46323-5_2
[16] Mitchel Resnick and Brian Silverman. 2005. Some reflections on designing construction kits for kids. https://doi.org/10.1145/1109540.1109556
[17] Ladan Shams and Aaron R. Seitz. 2008. Benefits of multisensory learning. *Trends in Cognitive Sciences* 12, 11 (9 2008), 411–417. https://doi.org/10.1016/j.tics.2008.07.006
[18] L. S. Vygotsky. 1980. *Mind in society.* https://doi.org/10.2307/j.ctvjf9vz4
[19] Georgette Yakman. 2008. STEAM Education: an overview of creating a model of integrative education. *ResearchGate* (2 2008). https://www.researchgate.net/publication/327351326_STEAM_Education_an_overview_of_creating_a_model_of_integrative_education

A SOURCE CODE

The source code for this project can be found on the University's GitLab: https://gitlab.csc.uvic.ca/rdreher/csc413-assignment-3.
Note: *Repository requires an active UVic Netlink account*