Creating a physicalization that uses Vibration and Temperature to convey SDG data

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Abstract

In 2015, all members of the United Nations adopted the 2030 agenda for Sustainable Development. A total of seventeen goals were created that should provide peace and prosperity for people and the planet. However, concerns have been raised about whether these sustainable goals can be achieve by 2030. To create more awareness about the Sustainable Development Goals, a physical representation of data, in short physicalization, was made. A design process was developed to structure the phases that were followed in this graduation project. The phases that were followed were 1. Ideation, 2. Specification, 3. Realization and 4. Evaluation. Based on the ideation, a physicalization was made that uses vibration and temperature as modalities to convey information. For a physicalization to be useful, it's efficiency, effectiveness and enjoyability was evaluated. Overall the use of vibration and temperature was perceived enjoyable. Both the modalities were efficient, however, where vibration as modality was also effective, temperature did not appear to be an effective modality to convey information.

Acknowledgement

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I would also like to thank all the participants that helped me evaluating the physicalization. Your participation confirmed my expectations, but also led to new insights.

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Introduction

The main objective of this thesis is to create a physicalization that conveys data about one of the Sustainable Development Goal of the United Nations. There has not yet been a lot of research on physicalization, especially not in combination with the Sustainable Development Goals. Moreover, the goal is to convey data in an innovative way, that is effective and efficient at the same time. This innovate way is with the use of non-visual feedback and to be more precise, with the use of vibration and temperature. This chapter will begin with background information on data physicalization and the Sustainable Development Goals, followed by defining the objectives, formulating research questions and a report outline.

1.1 Background

In 2015, all members of the United Nations adopted the 2030 agenda for Sustainable Development. This agenda was to provide peace and prosperity for people and the planet, not only now, but also in the future. However, the progress at achieving these goals has not been going as well as intended. As a result, concerns have been raised about whether these sustainable goals can be achieved by 2030. Partly due to the recent global pandemic, the possibility that governments are prioritizing SDGs is smaller, even though sustainability will benefit society.

To create more awareness for the Sustainable Development Goals, a data physicalization will be made and evaluated.

1.2 Objectives

For a data physicalization to be useful, it must be effective, efficient, and enjoyable. Effectiveness could be defined as how well users are able to receive the information that is being conveyed, while efficiency could be defined as how quickly users are able to receive the information. The aim of this thesis is therefore to see whether vibration and temperature are good methods of feedback to convey information.

1.3 Research questions

The main research question for this thesis will be the following: *Are vibration good modalities to convey information?* The address the main research question, the following sub-questions have been formulated:

1) *What is the current state of the art for physicalization that use vibration and temperature?*
2) *How effective and efficient is the use of vibration and temperature to convey information*
3) *Are vibration and temperature perceived as enjoyable by users of the physicalization*

1.2 Report outline

This paper is structured as follows. Chapter 2 will regard the current state of the art in data physicalization. It will answer the question what physicalizations are and will state the use cases of physicalizations. It will also present the current state of the art when it comes to physicalizations in combination with non-visual feedback, to answer the first sub-question: What is the current state of the art for physicalizations that use vibration and temperature. Chapter 3 will describe the methodology used in this project. Chapter 4 will state the results of the ideation phase of the project. A Sustainable Development Goal will be picked, a first list of important things that need to be considered will be made, some first design sketches will be made, and the initial project idea is described. The findings of the ideation phase are discussed in chapter 5: specification. This chapter will state the requirement for this physicalization. With all the collected information, the initial design for the physicalization will be made. Then, the interaction and hardware will be specified. Chapter 6 will describe the building process of the physicalization. It will describe the electronic components and the code that were used. In chapter 7, the prototype created in the previous chapter will be evaluated. The user study and its results are described here. Finally, the conclusion will give answer to the main research question 'Are vibration and temperature good modalities for conveying information?', some recommendations are made, and challenges of the project are described.

State of the Art

2.1 Literature review

To design a physicalization, some research Is required. First, the word physicalization had been mentioned a couple times already, but what exactly is a physicalization and what are the use cases of a physicalization. Then, a more in-depth review will be done for physicalizations that already use non-visual feedback. This chapter aims to answer the first sub-question: What is the current state of the art for physicalization that use vibration and temperature?

2.1.1 What is a data physicalization?

According to Jansen et al [2], a data physicalization is a physical artifact whose geometry properties encode data. Physicalization emerged from the visualization research area, a research area that has been around for a long time. The main challenge for data visualization was to create a technique that turns abstract data into more easily understandable representations [3].

Current physicalization can have a lot of benefits over visualization. Among those benefits are active perception, depth perception, non-visual senses, intermodal perception, making data accessible, cognitive benefits, bringing data into the real world, and engaging people [2].

2.1.2 Use cases of data physicalizations

Physicalizations can have multiple use cases. Dragicevic et al [3] describe some of these cases for which physicalizations are currently being used. Among others, they mention analytics and communication, and education as use cases.

The first use case is physicalization for analytics is used to help people reason with and about data. It should help people to do tasks more effectively. A lot of physicalizations involve 3D data, so the use of 3D models has proven to be beneficial. These physicalizations are easy to manipulate and rearrange, which is helpful for the understanding of the data. An example of a physicalization for analytics is a physically generated landscape of “pain phenotypes”. This physicalization made dimensional structures more understandable for experts in the field [3]. A limitation of 3D models as physicalization is that they cannot update themselves, the physicalizations are static.

The second use case is physicalization for communication and education is used to communicate insights that the data gives. For this type of use, storytelling that guides the user to the insights that the designer wants to communicate is an important aspect. This type of physicalization has been used to give data-driven presentations. The presenter uses data representations composed of elements so that the data can be manipulated while being explained. A physicalization for communication and education can also be used in places like museums, galleries, and other public places. The main difference is that in that case, the storytelling must be implemented in the design of the physicalization. An example where a physicalization was used in a public place is the project Cairn, installed in Paris. The system replaced questionnaires about activities done in the lab. Visitors would encode how often they visited the lab and how much time they spent there with the use of wooden tiles [4].

Interaction with the physicalization is important. According to Baumer et al [5], nuanced reflection can only be achieved by synthesizing data, instead of by solely encountering data. There are multiple ways to create interaction with the physicalization. Karyda et al [6] researched the use of narrative physicalizations, which would enable people to form meaningful descriptions around data. Moretti and Marrozzi [7] suggested the use of participatory data physicalization, whereas, in addition to tangible and experienceable data in public spaces, data is collected and returned to the user.

2.1.3 Non-visual data cues

The data that is returned to the user does not have to be visual, it can also be non-visual. Non-visual feedback is all the feedback that the installation gives that cannot be seen. Examples are sonification and haptics. This form of feedback is especially useful when there is a visual overload on the display. In that case, non-visual feedback can be used as guidance. Guidance, in the context of visual analytics, is a computer-assisted process that aims to actively resolve a knowledge gap encountered by users during an interactive visual analytics system.

A way to make the feedback non-visual is with the use of vibrotactile interfaces. It is a method that has not been used enough yet in computer interfaces, even though it is known to be an effective way to transfer data. Especially visually impaired and blind people use this method of data transformation. Vibrotactile interfaces are becoming common in everyday objects, like mobile phones or game controllers. According to research done by [8], some vibrotactile cues, and their combination with visual cues, outperformed visual cues alone. However, they also showed that continuous vibrotactile feedback could be distracting and stressful. Some basic vibrotactile parameters, described by [9] , are frequency of the signal, amplitude, waveform, duration, and rhythm. They further explored the use of roughness and rhythm of a signal and found that participants were able to differentiate between different signals.

2.2 Conclusion

This chapter discussed the state of the art in physicalizations.

When designing a physicalization, multiple aspects are of importance. Firstly, the use case of the physicalization must be considered. This determines the interaction that the user has with the physicalization. Interaction is important, so a way to get people to engage with the system is important. The use of non-visual guidance can be beneficial for the physicalization if it isn't distracting or stressful. Non-visual feedback could be achieved by using vibrotactile cues, where users would be able to recognize the difference between different signals. Parameters that could be used for vibrotactile cues include frequency and amplitude of the vibration.

In contrast to vibration, no information was found on the use of temperature for data physicalization.

Based on the literature review, the first sub-question 'What is the current state of the art for physicalization that use vibration and temperature?' can be answered. Currently, vibration is used in physicalizations. Vibration is mostly used as guidance. It is also used to assist in situations where there is a visual overload. Furthermore, vibration is currently used in mobile phones and game controllers to give vibrotactile cues.

Now there is nothing out there that described the use of vibration in data physicalization.

Methods & Techniques

This section describes the methods used throughout this graduation project. The applied approach is based on The Design Methods of Creative Technology [10].

3.1 Design process

To develop the physicalization, the Design Methods of Creative Technology [10] will be used. This method consists of four stages: Ideation, Specification, Realization and Evaluation. In figure 3.1, the Creative Technology Design Process can be seen. After the introduction and the literature review, there is a concept of what the project should look like. The idea is to create a physical installation that represents Sustainable Development Goal data about energy. The goal for the ideation phase is to further define the concept of the project. This contains ideas for what the physicalization should look like and what the interaction with the physicalization should be. The ideation is done by brainstorming of different designs. The ideation phase can be found in chapter 4.

The next phase is the specification phase. During this phase, the concept is further specified. A final design for the physicalization is chosen. Additionally, the components that could be used are specified and a list of requirement is set up. The specification phase can be found in chapter 5.

In the realization phase, the components and requirements are used to build the prototype. This prototype is the physicalization that will be used to physicalize Sustainable Development Goal 7. The realization of the prototype can be found in chapter 7.

The next phase is the evaluation phase. During this phase, the prototype will be evaluated with the help of user tests. User tests consist of two parts. For the first part, users must perform information retrieval tasks using the physicalization. This is done with the help of a survey, in which users get information about the task and where users can give answers to the question. The second part of the user study consists of an structured interview with the participant, where more insights about the users' opinion is gathered.

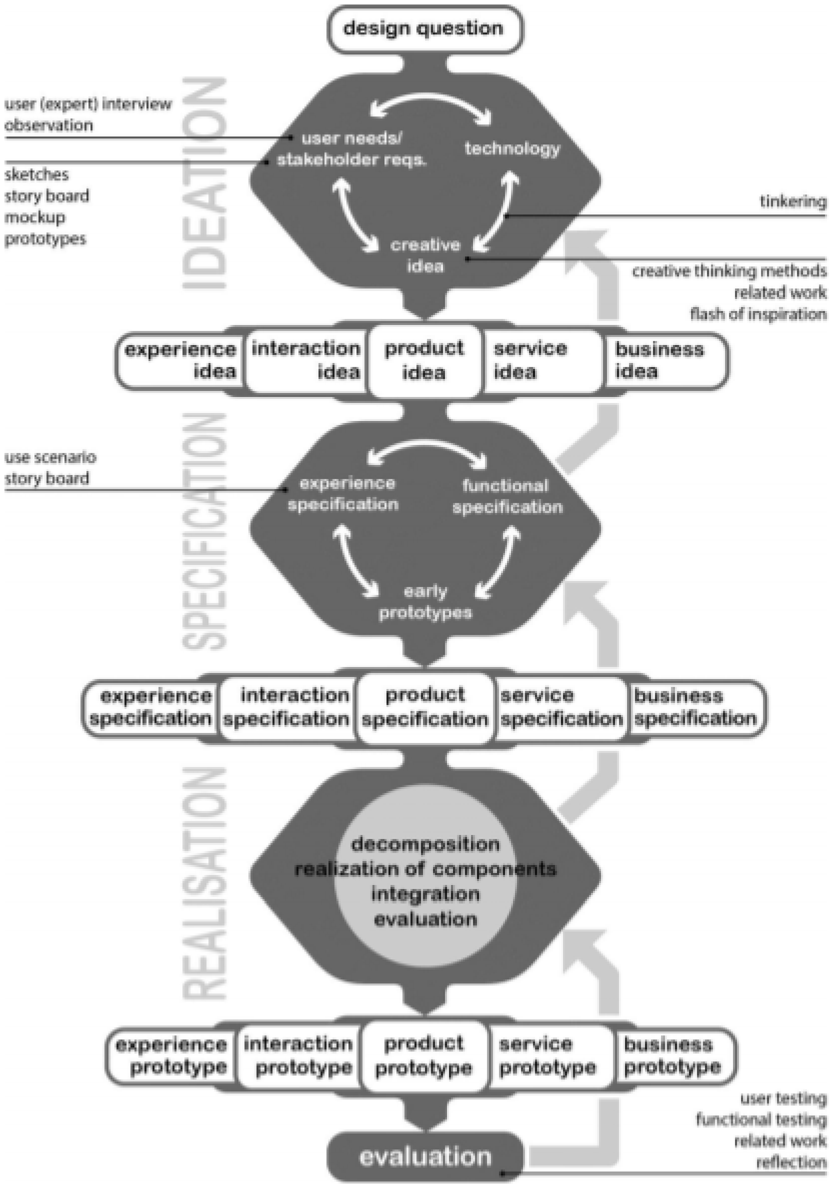


Figure 1 - Creative Technology Design Process

Ideation

This chapter describes the ideation phase of the project. Several design options and interactions will be explored, and a final design option will be chosen.

4.1 Brainstorming

The goal of the project was to create a physicalization that would communicate interesting facts regarding sustainable development worldwide to citizens. The project consisted of three main tasks: 1) pick an SDG goal or indicator; 2) develop a physicalization of this data; and 3) evaluate the physicalization with users.

4.1.1 Pick an SDG

The first main task was to pick an SDG. The first step to pick one, was to have an overview of all the 17 goals that were created. With a simple search on the internet, this overview was made. The Sustainable development goals, that also can be seen in Figure 4.1 are:

No Poverty

Zero Hunger

Good Health and Well-Being

Quality Education

Gender Equality

Clean Water and Sanitation

Affordable and Clean Energy

Decent Work and Economic Growth

Industry, Innovation, and Infrastructure

Reduces Inequalities

Sustainable Cities and Communities

Responsible Consumption and Production

Climate Action

Life Below Water

Life on Land

Peace, Justice and Strong Institutions

Partnerships for the Goals

To me, some of the goals were more familiar than others. For this physicalization, I wanted the goal to be less familiar to most people, so that the information conveyed by the physicalization would have more impact. Therefore, the first five goals would not be used for the project.

While doing research, I found the paper by Asadikia, A, Rajabifard, A. and Kalantari, M.: "Systematic prioritisation of SDGs: Machine learning approach." [1] This paper described a way to prioritize the Sustainable Development Goals. The goal of the paper was to find the more synergetic SDGs, the SDGs that would have a greater impact on other SDGs when they were further in their achievement. This paper concluded that the SDGs that were more synergetic, were SDG 3, SGD4, and SDG 7. As mentioned before, goals 3 and 4 were disregarded, so SDG 7 had my interest.

This goal lined up with my own interest. My high school research was about ways to heat the top floor of our high school, using smart heating solutions and clean energy. Therefore, the goal that I chose to use for the project was SDG 7: Affordable and Clean Energy.

Figure 2 - Sustainable Development Goals [11]

Within this goal, there were multiple targets, from which one or two had to be chosen to be compared using the physicalization. The targets for SDG 7, according the website of the United Nations [12], are:

7.1: By 2030, ensure universal access to affordable, reliable, and modern energy sources

7.2: by 2030, increase substantially the share of renewable energy in the global mix

7.3: by 2030, double the global rate of improvement in energy efficiency

7.a: by 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology

7.b: by 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support

4.1.2 Inspiration

The next step was to brainstorm on what type of physicalization I was going to make. In weekly brainstorm sessions, possibilities for types of physicalization that could be created were discussed. From the beginning, the idea was to create something that was out of the box. To do so, examples of physicalizations with unconventional interaction were evaluated and used as inspiration. Examples of these physicalizations are:

Unnatural Language [13]

"Unnatural Language is a network of electronic organisms ("Datapods") that create sonic improvisations from physical sensors in the natural environment."

This project used the input from physical sensors to create improvised sounds. These physical sensors were for example electrodes that could sense a difference in electricity in leaves or plants.

This project only used sonification, the use of sounds to convey data, rather than visual cues.

Sonaqua [14]

"This is a site-specific interactive sound installation where users can "play" vials of water from live readings water quality."

This project makes use of the fact that each water sample contained different minerals. The electrical current each of these minerals conducts varies. The more electrical current in a sample, the more polluted the sample is with heavy metals. With the use of sounds, differences between samples are made clear. Therefore, also this project is an example of a physicalization that uses sonification.

Augmented Reality and Data Physicalization [15]

" We add interactivity to physicalizations through the use of computer graphics, augmented reality headsets, high-accuracy tracking systems, and custom touch input devices. These technologies provide a means of displaying and interacting with diverse types of data."

This project uses augmented reality (AR) to give extra depth to physical models. For example, on a 3D printed model of bathymetric data, with the use of AR, they projected ocean currents along the southern coast of Africa.

4.1.3 Consideration

After investigating some state of the art, brainstorming about the interaction with the physicalization continued. For the interaction, several things needed to be considered:

4.1.3.1 Countries

The first thing to decide was which countries should be used for the physicalization. The county that would make the most sense to add was the Netherlands. The Netherlands was chosen as the project is created in the Netherlands and the probability was that mostly Dutch people would interact with it. They would probably most interest in seeing where the Netherlands stand compared to other countries.

Then, decided was to limit the possible countries to European countries. This would bring the comparison a bit closer to home, seeing how neighboring countries, or countries that are close performed.

To be able to compare countries in different places in Europe, the following four countries besides the Netherlands were chosen:

- Sweden, a wealthier a northern European country
- Estonia, a north-east European country
- Ukraine, a country in the eastern bloc
- Spain, a southern European country

4.1.3.2 Datasets

For the brainstorming of the physicalizations, it was important to also look at possible datasets that would be used. The datasets that would be used should have data for multiple countries, should contain recent data to be interesting for users and should be connected to SDG 7. Two datasets were chosen:

- The share of energy from renewable energy sources
- The amount of electricity generated from solar power

These datasets were chosen as they have a good relation to the development goal.

4.1.3.3 Feedback

The types of feedback had to be considered. There were two types of feedback that were particularly interesting to investigate, visual- and non-visual feedback. Most of the physicalizations make use of some type of visual cues. Therefore, more information about those types of physicalizations is known. On the other hand, there was the opportunity to explore something that has not been used a lot, the non-visual elements in the feedback.

The types of non-visual feedback that were considered were sonification, the use of sound, and haptics, the use of touch.

- Ideas related to audio were:
  - Sounds of what energy source is most common
  - Amount of noise related to how clean the energy is
  - The higher the volume of the sound, the higher the proportion of people in a country with access to clean energy
  - Slower music as the energy source gets “greener”

- Ideas related to touch were:
  - The use of the intensity of a vibration
  - Use of different materials for countries
  - Use of temperature

4.2 First design sketches

4.2.1 Design 1

The first design, that can be seen in Figure 4.2, compares values between two countries. Several different blocks represent different countries. Each block contains an RFID tag for the system to identify them. The participant can choose two countries to compare and places them in the dedicated slots on the installation. Then, the participant can choose which dataset and feedback method should be active. The blocks rise to a height according to their value in the dataset. If it is activated, the blocks also vibrate accordingly. This design combines the visual feedback of the risen block and non-visual feedback the vibration.

The prototype would make use of RFID scanners and vibrating motors that would be controlled by a microcontroller like an Arduino.

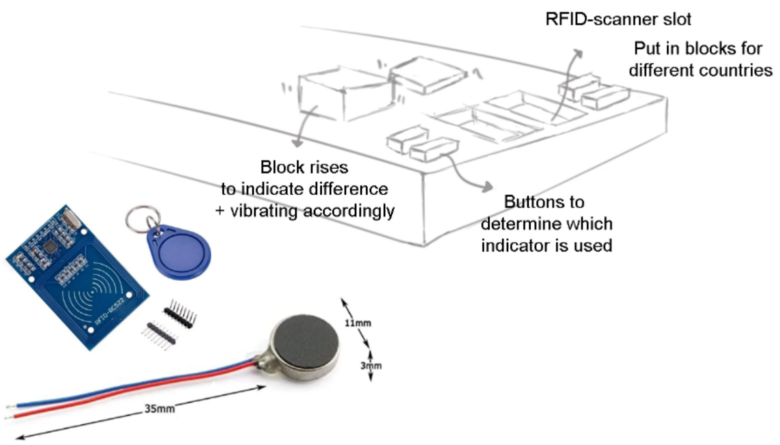


Figure 3 - Sketch of the first design

4.2.2 Design 2

The second design, that can be seen in Figure 4.3, is like the first design. The main difference is that this design only makes use of visual feedback, in the form of colored dots on an LED panel. The LED panel functions as a bar graph, where the height of the bar resembles that data.

The prototype would, just like design 1, make use of RFID scanners and vibrating motors. This prototype would also be controlled by a microcontroller like an Arduino.

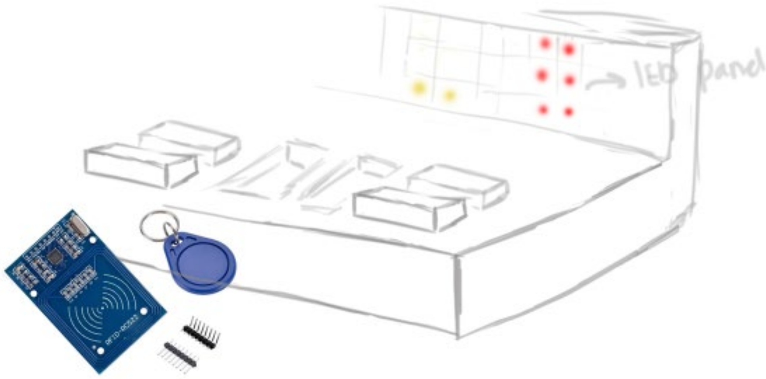


Figure 4 - Sketch of the second design

4.2.3 Design 3

The third design, that can be seen in Figure 4.4, only uses non-visual feedback. It is a flat surface with on one axis different countries and on the other axis different years. This physicalization would only physicalize one dataset, but over multiple years. The participant can move a block over the surface to different countries and different years. The block would vibrate according to the value of the dataset.

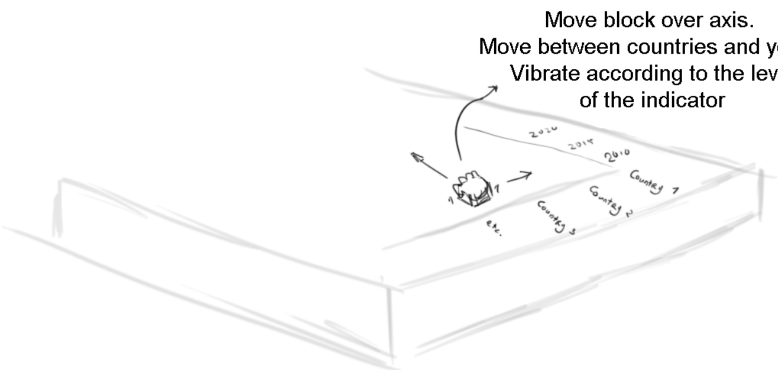


Figure 5 - Sketch of the third design

4.3 Initial project idea

The idea for his project is to create a physicalization of Sustainable Development Goal 7: Affordable and Clean Energy. The physicalization will convey the information using non-visual feedback, like sonification or haptics, as this could enhance the experience of energy. Users would be able to compare data points of two counties.

4.4 Conclusion

In this chapter, different aspect of the project idea has been described. The first choice that had to be made was which development goal would be used for this project. SDG 7 was chosen based on three characters: 1) the goal is less familiar to most people; 2) According to Asadikia, A. et al. goal 7 is one of the most synergetic goals; and 3) SDG7 was in line with my own interest.

Then, some inspiration was gained by looking at other physicalizations that have an interaction that is out-of-the-box. To think about what the physicalization should look like and what the interaction should be, things that were of influence for the projects had to be considered. Requirements for the dataset were created. It had to be newer data, preferably of 2020, and it should be connected to SDG 7. Also, the type of feedback was important to think about. Some ideas for the use of sonification and haptics were listed.

Three designs using possible interactions were created and evaluated with the supervisors. The initial project idea will look as follows: the project will be a physicalization that uses non-visual feedback like haptics and sonification to convey information about SDG 7: Clean and Affordable Energy. Users will be able to compare data from two countries with each other.

Specification

After the ideation phase in chapter 4, it is time to specify the concept, the design of, and the interaction with the physicalization. Furthermore, requirements for the prototype are listed.

5.1 Requirements

A list of requirements for the project is set up. These requirements are split into two groups, system requirements and functional requirements. System requirements are requirements for the operation of the physicalization. The functional requirements are requirements of how users should feel about the physicalization and how they should be able to interact with the physicalization.

5.1.1 System Requirements

- The physicalization should be a physical representation of data
- The physicalization should be able to turn on and off
- The physicalization should be able to reset
- The physicalization should display the countries in Europe

5.1.2 Functional Requirements

- The physicalization should let participants choose which type of feedback they wish to receive
- The physicalization should let participant choose which dataset they want to use
- The physicalization should let participants activate and deactivate countries in their comparison
- The physicalization should be engage users to interact with SDG data
- The physicalization should be efficient and effective
- The physicalization should be enjoyable

5.2 Initial Design

The initial drawing of the design can be seen in figure 5.1. This image displays the external design of the physicalization and part of the interaction with the components. The components that have been chosen will be further explained in section 5.4. What can be seen is that the installation will be a box. The top of the box will display the map of Europe. Countries that will be included in the comparison will be cut out from this top. Buttons will be placed underneath the country and with the use of springs, the country will be able to move back up when it is pressed.

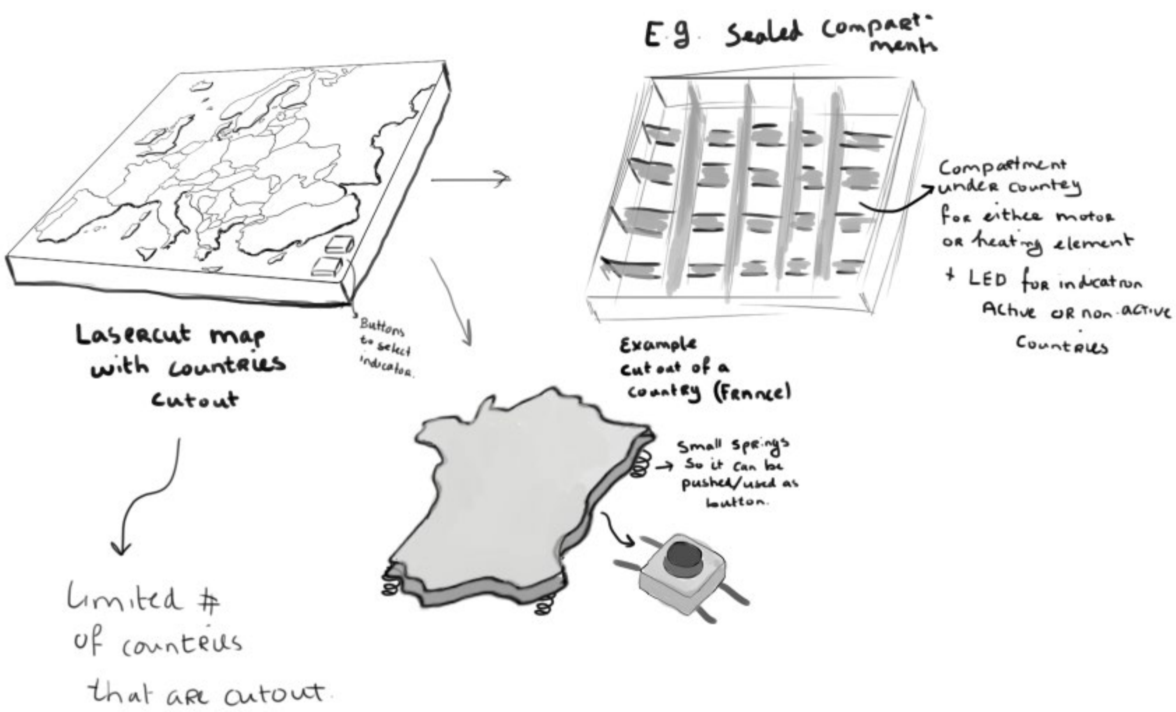


Figure 6 - Initial design

5.3 Interaction Specification

The goal of the project is for people to interact with SDG 7 data, through a physicalization. There will be two modalities that can convey the data, vibration, and temperature. The physicalization should allow for people to choose one of the two modalities and to choose one of two datasets. Besides, users should be able to activate and deactivate a country by pushing on the country. If the user has chosen a dataset, a modality and has activated a country, the users should be able to touch the county and receive information about the data in the form of the modality chosen. So, the user should either feel the country vibrate or feel the country getting warmer. The interaction of the two modalities, will be further discussed in 5.3.1: vibration and 5.3.2: temperature.

5.3.1 Vibration

The first modality is vibration. In a physical project, vibration can be implemented by using vibrating motors. For the project, five countries will be compared to each other on two different datasets. To do this, user should be able to identify the different datapoints. This means that the vibration of different countries should be different. A good method to distinguish different vibrational signals is the amplitude or intensity of the signal. The higher the amplitude of a signal, the higher the datapoint in the dataset is. A way to do this is by mapping the datapoints to intensities of the vibrating motors.

5.3.2 Temperature

The second modality is temperature. In the project, temperature can be implemented using heating elements. The difference between the datapoint of the five counties can be represented by the temperature of the country. The warmer a country feels, the higher the datapoint in the dataset. However, the interaction with the physicalization should be safe. It is not safe for humans to touch very warm or very cold surfaces as it could result in getting burnt. Like vibration, the datapoints can be mapped to temperatures. In this mapping, the highest point should not get warmer than 45 degrees Celsius and the lowest datapoint should not get colder than 10 degrees Celsius.

5.4 Hardware specification

This project makes use of two modalities, vibration, and temperature. To use these modalities, vibrating motors and heating elements will be used. However, that is not the only hardware that is needed. To control these components, a microcontroller is needed. For this project, that is the Arduino Mega 2560. The intensity of the vibration can be controlled with this Arduino. The temperature will be a bit more difficult. Besides heating element, a relay is needed to turn the heating element on and off whenever necessary. To determine when it needs to be turned on and off, a temperature sensor is needed. Lastly, to select the modality, dataset or county, buttons are needed.

5.4.1 Arduino Mega

The "heart" of the physicalization will be an Arduino Mega [16], which can be seen in Figure 5.2. An Arduino is a microcontroller that is used a lot in DIY projects. It is used to control a wide range of electrical components, for example LEDs, motors, and sensors. A board has in- and output pins to which these electrical components can be attached. The code that you use to control these components can be written in the open-source Arduino IDE [17]. Once the code is finished, it can be uploaded as a sketch to the Arduino. As long is the Arduino is powered, it will run this sketch.

Arduino has multiple different boards. Boards that are used a lot in projects are the Arduino Nano [18], which is a very small board and is therefore useful in smaller projects and wearables, the Arduino Uno [19], which is used for small to medium sized projects and the Arduino Mega, which is used when more in- and output pins are needed. For this project, a lot of output pins are needed. Each of the five countries needs a button, a motor, a relay, and a temperature sensor. Therefore, the most suitable Arduino is the Arduino Mega.

5.4.2 Heating elements

Heating elements will be used to heat up the countries. The heating elements will be connected to the relay, which can turn the heating element on or off. The heating elements that will be used for this project, will be ceramic heating elements. These heating elements are safe and reliable, as the surface of the element is isolated. Besides, these elements are easy to install, one of the wires must be connected to a positive wire, and the other wire must be connected to a ground wire. The elements work on 12 Volt and will thus need an external power supply.

5.4.3 Relays

To turn the heating elements on and off a relay will be used. Relays are electronical switches. With a signal from the Arduino, the switch can be open or closed. This is ideal if you want to control the temperature of the heating element. When the temperature is not high enough, the electrical circuit can be closed, resulting in the heating element warming up. As soon as the heating element has reached its target temperature, the switch can be opened, so that the heating element is turned off. Then, when the temperature falls below the target temperature again, the circuit will be closed again, and the element will start heating again. This results in the temperature floating around the target temperature.

A relay has two sides, the front and back, that need to be connected. The front connections are for the relay to work and has three connections, VCC, GND and IN. For relays to work, they must be powered by 5V. Luckily, the Arduino can prove this power by connecting the 5V pin of the Arduino to the Vcc pin of the relay. Besides power, the relay has an input pin, which can receive a signal from the Arduino, resulting in opening and closing the system. The third connection is the ground. The ground of the Arduino must be connected to the ground of the relay.

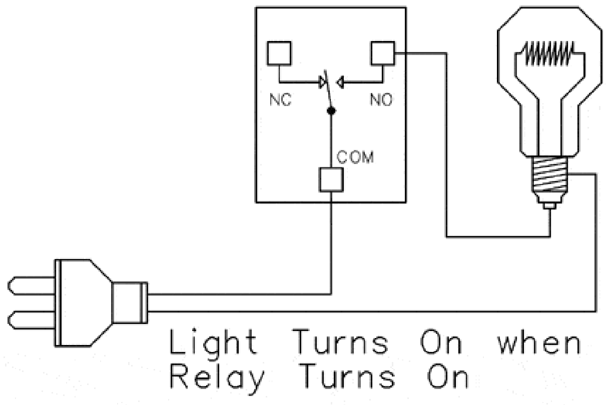
On the back of the relay, there are three possible connections for wires: Normally open (NO), common (COM) and normally closed (NC). A relay can have two settings, normally open and normally closed. When the setting normally open is used, the electrical circuit will be open until it receives a signal from the Arduino. When the setting normally closed is used, the electrical circuit will be closed until it receives a signal from the Arduino.

I hope to clarify these two setting with an example, someone uses a relay to switch on a lamp:

- When the setting NO is used, the lamp will be turned off as the circuit is opened. No current flows through the circuit. When the relay receives a signal from the Arduino, the circuit will close, resulting in current flowing through the circuit. The lamp will turn on.
- When the setting NC is used, the lamp will be turned on as the circuit is closed. Current flows through the circuit. When the relay receives a signal from the Arduino, the circuit will open, resulting in the lamp turning off. This setting can be seen in figure 5.3.

The main difference is, do you want the electrical component (in the example the lamp) to be turned on or turned off by default.

For the project, the NO setting will be used. By default, the heating element should be turned off. Only when a signal is received from the Arduino, the heating elements should turn on. The COM will always be connected to the electrical component that is used.

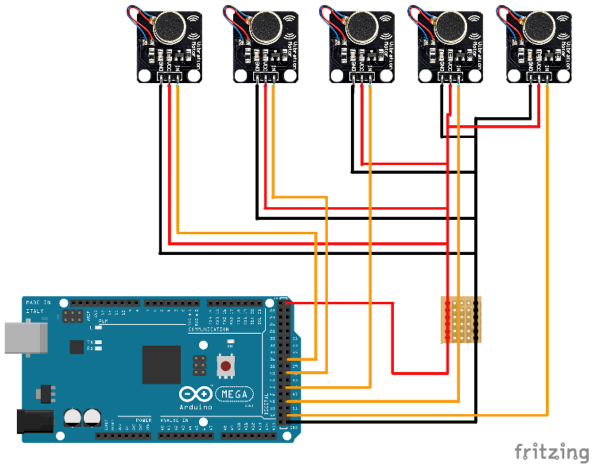


5.4.4 Temperature sensors

The temperature sensors keep track of the temperature of the heating element. The sensors that will be used are of the type LM35 When the temperature sensor senses a temperature lower than the target value, it will send a signal to the Arduino asking to turn on the heating element. When the temperature the sensor measures is higher than the target value, the sensor will send a signal to the Arduino to turn off the heating element. A temperature sensor has three connections, VCC, GND and OUT. The VCC is connected to the 5V pin on the Arduino, the GND is connected to the ground of the Arduino and the OUT is connected to an analog input pin on the Arduino.

5.4.5 Buttons

The buttons are used for selecting a modality, a dataset and for activating and deactivating countries. When a button is pressed, a signal is sent to the Arduino. The Arduino knows what this signal is and can act upon it automatically.



5.5 Conclusion

This chapter described the specification phase of the project. First, system and functional requirements were listed. The system requirements include that the physicalization should be a physical representation of data, that the physicalization should be able to be turned on and off and be rest, and that it should display the countries in Europe. The list of functional requirements mentions that users should be able to choose which modality they want to use, vibration or temperature. The users should also be able to choose the dataset. The physicalization also should be efficient, effective, and enjoyable. Based on these requirements, a sketch of the initial prototype was made. Then, the interaction and components were specified. When the user chooses vibration as feedback method, the countries should start to vibrate with different intensities. When the user chooses temperature as feedback method, the countries should warm up. This is done by using vibrating motors and heating elements respectively.

Realization

With the components specified in chapter 5: Specification, the physicalization can be build. This chapter will explain how that is done.

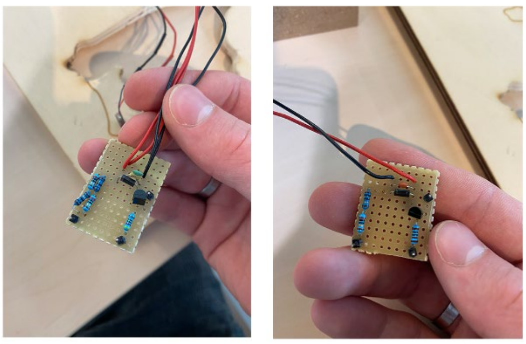
6.1 Electrical components

For the prototype, a variety of electrical components were used. The electrical components used include vibrating motors, temperature sensors, relays, heating elements and buttons.

6.1.1 Vibration Motors

First, the installation was made using the vibrating motors defined in the previous chapter. However, these motor modules behaved inconsistently. Sometimes they would work like expected, but sometimes they did not or hardly work. Therefore, modules for the motors were created using an example from techZeero [21]. These motors performed a lot more consistent. However, still was chosen to not use the intensity of the motors as differentiating factor. Instead, the frequency of the vibration was used to distinguish differences in the data, as these differences were easier to notice.

The vibrating motors are used for the first modality: Vibration. The motors that are used can be seen in Figure 6.1. The motors are placed underneath the country, in a way where they touch the bottom of the cutout of the country. The placement of the motor can be seen in Figure 6.2.



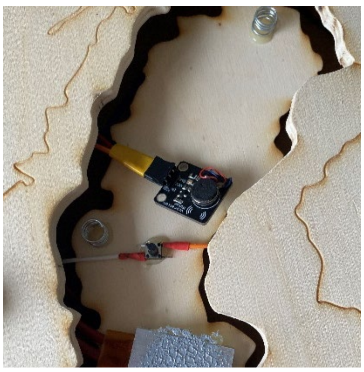


Figure 12 - Position of the motor, button, and heating element under Sweden

The motors need 5V to work properly and need 90mA of current. To make sure that they get enough current, the motors are soldered in parallel and have their own 5V pin on the Arduino Mega. The schematic of the motors connected to the Arduino can be seen in Figure 6.3. The motor for Sweden is connected to Arduino pin D37, the motor for Estonia is connected to pin D41, the motor for the Netherlands is connected to pin D45, the motor for Ukraine is connected to pin D49 and the motor for Spain is connected to pin D53.

6.1.2 Temperature Sensors

The temperature sensors that have been used are the LM35 by Texas Instruments. These sensors were chosen because they are easy in use, and don't need calibration. The sensors have three pins, 5V, GND and OUT. To make the wiring more organized, the sensors were soldered onto a PCB board. 5V from the sensor it was connected to the 5V output of the Arduino. The GND of the sensor was connected to the GND of the Arduino. The OUT of the sensor for Sweden was connected to pin A0 on the Arduino, the output of the sensor for Estonia was connected to pin A1, the output for the Netherlands was connected to pin A2, the output of the sensor for Ukraine was connected to pin A3 and the output of the sensor for Spain was connected to pin A4. The connections can also be seen in Figure 6.4. The sensors were place next to the heating element so that it would immediately notice a difference of temperature when a heating element was turned on.

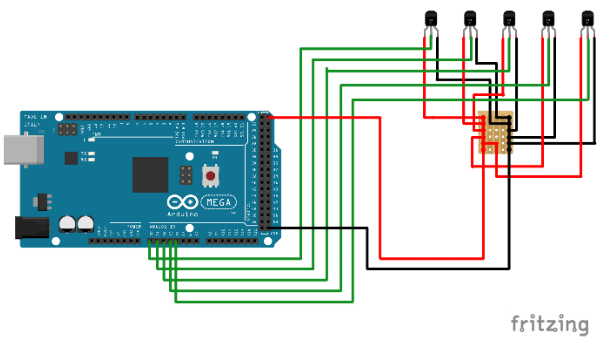


Figure 13 - Five temperature sensors connected to an Arduino Mega

6.1.3 Relays

To switch the heating elements on and off, 5V relays were used. The chosen relays were cheaper relays from China. On the front, the relays have three pins. To make the wiring more organized and the motors more easily changeable, the wires for the power, ground and signal were soldered to female connectors. The relays are soldered in parallel, so that they all get the same voltage from a single 5V output from the Arduino. The 5V of the relays was connected to the 5V of the Arduino, the GND of the relay was connected to the GND of the Arduino and the signal pin of the relay for Sweden was connected to pin D34 of the Arduino, the signal for Estonia was connected to pin D38, the signal for the Netherlands was connected to pin D42, the signal for Ukraine was connected to pin D46 and the signal for Spain was connected to pin D50. The connections of the relays with the Arduino can be seen in Figure 6.5.

6.1.4 Heating Elements

The heating elements that were used had to be able to become warm enough to feel a difference. The heating element that was chosen were 12V PTC heating elements with a maximum temperature of 80 degrees Celsius. The main reason why these were chosen was the small size of the heating elements. Size of the heating element was important as the element had to be able to fit underneath the countries. For the Netherlands and Estonia, the smaller countries, only half of the heating element fitted. Because the heating elements require 12V, and external power supply had to be used. The heating elements had two wires, one for the power and one for ground. The power wires were all connected in parallel to the power wire from the power supply, so all the elements would get 12V. The ground wire of the elements was connected to the NO port of the relay. From the COM port of the relay a wire was connected, in parallel to the ground wire of the external power supply. The heating elements were placed underneath each country, where possible completely, but otherwise, as mentioned, only half. The connection of the heating elements can be seen in Figure 6.5. The position of the heating element under a country can be seen in Figure 6.2.

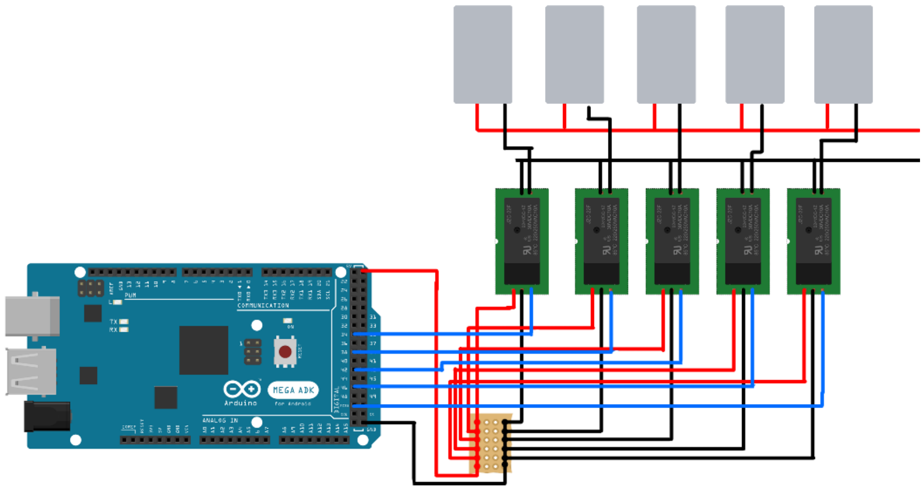


Figure 14 - Relays and heating elements connected to an Arduino Mega

A total of nine buttons were needed for the system. Each country needed a button so that it could be activated or deactivated by the user. The other four buttons were needed for choosing the modality and the dataset. To reduce the number of wires that were needed to connect all the buttons (For nine buttons, you would need nine wires for power and nine for ground, so a total of 18 wired), a 3x3 button grid was used. The wiring of such a grid can be compared to the wiring of a keypad. By using a button grid, only six wires must be used. The pins that are used to connect the rows are D22, D24 and D26. The pins on the Arduino that are connected to the columns are D28, D30 and D32. The wiring of the buttons can be seen in Figure 6.6. The buttons that were used were tactile push buttons. These buttons are easy to use and very responsive.

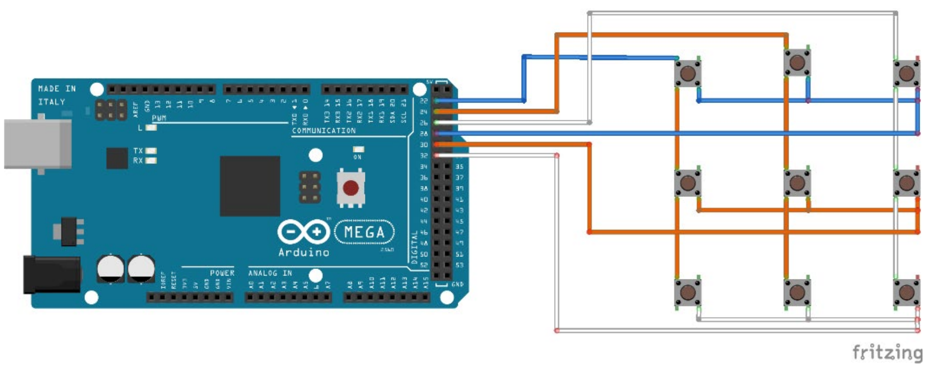


Figure 15 - 3x3 Button grid connected to an Arduino Mega

6.2 Electrical circuit

The entire circuit drawing can be seen in Figure 6.7. The five motors are connected in parallel and have their own 5V pin. The five relays and temperature sensors share another 5V pin. The schematic of the entire installation can be seen in Appendix A.

6.3 Housing

All the components and wires needed to be secure. A box was made using MDF wood. The box is 50 centimeters in width, 50 centimeters in length and 10 centimeters in height. The box was also made to support the top.

6.3.1 Top

The top, or front plate, was created using a laser cutter. On the front plate, the map of Europe had to be engraved and the countries that could be compared, Sweden, Estonia, the Netherlands, Ukraine, and Spain, had to be cut-out. The design of the front plate was created in Adobe Illustrator. To have engrave counties, lines must have a width and need to be filled with a color on the grayscale. The darker the color, the darker the engravement. To cut out countries, the lines need to be red and hair thin. The front plate can be seen in Figure 6.6.

For the countries to fit in the cutouts, the cutouts had to be made wider. This was done using sanding paper and wood rasps. This was a precise job as the top still had to look good, while the countries would be able to fall through the holes.

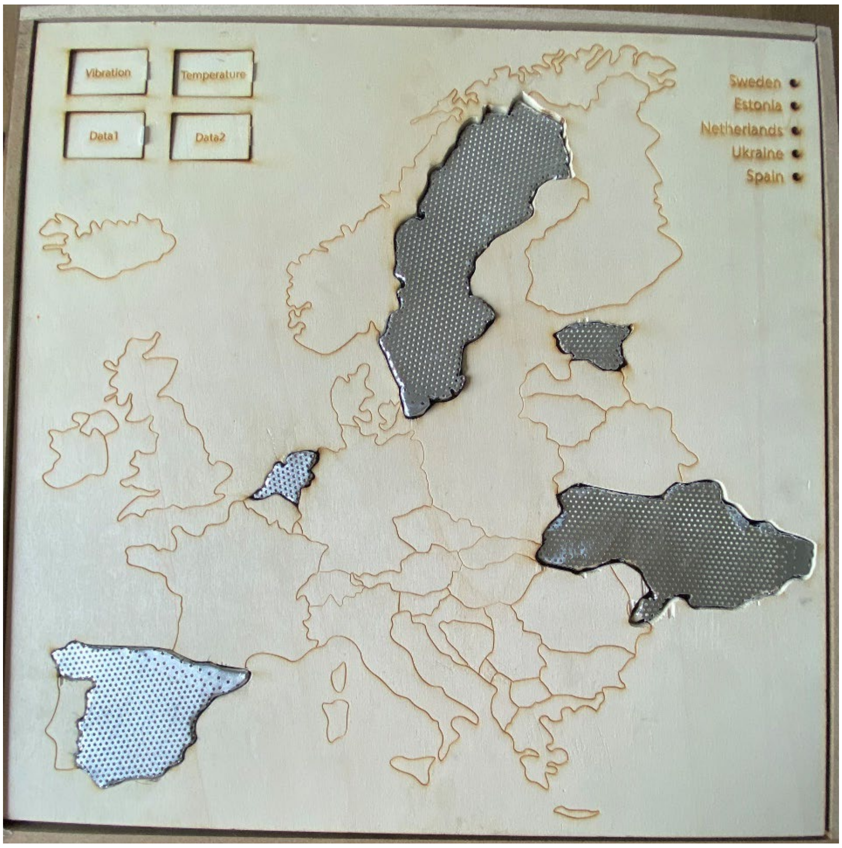


Figure 16 - Front plate

6.3.2 Countries

The countries were cut out of the front plate using the laser cutter. One of the modalities was temperature, the idea was to heat up the countries. As wood does not conduct heat, I had to think of another method. I decided to cover the countries in metal, so that the heat would be conducted. This was done with the use of a perforated aluminum plate. This plate had to be thin to be able to bend it in shape over the county. I traced the country on the metal and cut the piece of metal using tin scissors. I placed to wooden country and the piece of metal on a vice and started bending the metal over the edges of the county. With the use of a metal file, the metal was shaped in the contour of the country. The metal had to be around the edges of the country very tightly, as this would make sure the country was still identifiable. This was also done so that the amount that the holes for countries had to be widened was minimalized. The result of the countries can be seen in Figure 6.7.

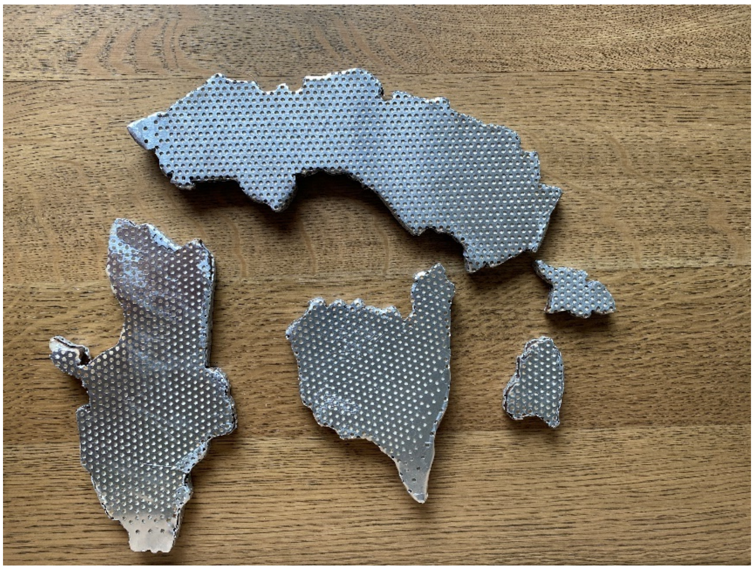


Figure 17 - Countries covered in metal

6.4 Code

A big part of this prototype was the software. The software was created using the Arduino IDE [17]. Multiple functions had to be created to have the prototype do everything it had to do. The first interaction that users do is push buttons. A function was created to check whether buttons were pressed. Based on the modality that was chosen, different electrical components had to turn on. For each modality, two functions were created. For vibration, the functions were vibrationOn and vibrationOff, and for temperature, the function were temperatureOn and temperatureOff. Then, two more functions were created, mapVibration and mapTemperature, to map the values of the data to values that the Arduino could use for the frequency of the vibration and for the target temperature. With the use of these functions, the loop function could be created. The loop starts with checking if buttons were pressed. If buttons were pressed, it would keep track of the state of these buttons. Dependent on the modality that was active the Arduino would start to let the motors of the active countries vibrate or would start to heat up the active countries.

6.4.1 Buttons

The function checkButton was created to check if buttons were pressed. The buttons, that were connected in a 3x3 grid used a library [22] to be identified. The layout of the buttons and their corresponding identification can be seen in Figure 6.10. When a certain button is pressed, the system checks the state of that button. This is done using Booleans. Each button has his own Boolean variable, xxIsAcitve (where the xx stands for either the country, the modality, or the dataset). If that button is already active (the Boolean is set to true), the push of the button will deactivate the button. If the button is not active yet, the push of the button will make the button active. For the buttons for the modality and dataset there is one small difference. When the button is not yet active, the push of the button will make it active. However, if the button is active, pushing the button will not deactivate that button. This is to prevent that the system is turned on without a modality or dataset.

6.4.2 vibration

The function vibrationOn is the function that is called when the modality vibration is active, and a country is pushed (and thus activated). The function receives two variables when it is called: the county that is activated, and a value for the frequency of the vibration. For a certain combination of country and dataset, the motor gets turned on and will start vibrating. With the user of a timer of a certain duration (based on the position of the country in the dataset) the motor will turn on and off, resulting in a perceivable interval.

The function vibrationOff does exactly what is says, it turns off a motor. When this function is called, the intensity of the vibration of the country which should be tuned off is set to 0, meaning it is off.

6.4.3 temperature

The function temperatureOn is the function that is called when the modality temperature is active. The function receives two variables, similar as the function vibrationOn, when it is called: the country, and the value. When the function gets called for a certain country, the temperature sensor will measure the current temperature of the heating element. Based on the dataset and the value of the temperature sensor, the heating element can be turned on or off. When the measured temperature is below the target temperature, the element gets turned on, then the measure temperature is above the target temperature, the heating element will be turned off. Turning the heating element on and off is done using the relay.

When the function temperatureOff is called for a certain country, it will turn off the relay and thus turn off the heating element.

6.4.4 Mapping

The mapping of data was done differently than originally planned. The plan was to use a linear mapping scale, where the value of the dataset was transformed to a value that the Arduino could use as value for the timer for the vibration or target for the temperature. Two functions would be created, a mapping function for the vibration and one for the temperature.

The function mapVibration can be split into two parts, a mapping for values in dataset 1 and a mapping for values in dataset 2. Arduino provides a mapping function [23], which looks as follows:

map(value, fromLow, fromHigh, toLow, toHigh);

It transforms a certain value that lies between fromLow and fromHigh to a newly defined interval toLow, toHigh.

For vibration, the maximum value that a motor can have is 255. After testing, a lower value was found at 150. Below the lower value, the motor did not work. The lowest value for a country in dataset 1 was 10%, the lowest from value was therefore set to 9. The highest value of a country in dataset 1 was 67.6%, the fromHigh value was therefore set to 70. For vibration in combination with dataset 1, the following function was used:

float mappedValue = map(value, 9, 70, 150, 255);

For datset 2, the lowest value was 0.04 and the highest value of a country was 20.8. That resulted in the following function for dataset 2:

float mappedValue = map(value, 0, 21, 150, 255);

The mapping function for temperature is like the mapping function of vibration. The only differences are the fromLow and fromHigh values. For temperature, the maximum value was set at 45 degrees. A higher temperature then that would be unsafe to use and interact with. The lowest value that could be used was set at 10 degrees. This led to the following mapping functions for dataset 1 and dataset 2 respectively:

float mappedValue = map(value, 9, 70, 15, 45);

float mappedValue = map(value, 0, 21, 15, 45);

However, when testing the prototype, found was that this mapping function with small differences in the values of the data, influenced the intensity of one of the motors to point where it was hardly noticeable. A different mapping was chosen. The goal of the physicalization with the data was that users would know the order of the countries. So, users should be able to tell which country has the highest and which country has the lowest value in the dataset. To do so, the countries were given a rank, from 1 to 5. This rank represents the order of the countries from highest to lowest. For example, Sweden was the country with the highest share of energy from renewables, therefore Sweden would get ranked as number 1. For both vibration and temperature, this rank corresponded to a predefined value. For vibration, this value could be 0 (no delay), 500 (0.5 second delay), 1000 (1 second delay), 1500 (1.5 second delay) or 2000 (2 second delay). For temperature, the value could be 21 degrees, 27 degrees, 33 degrees, 39 degrees or 45 degrees Celsius.

6.4.7 loop

The loop function is the main function of the system and the one that is continuously executed. The function starts with checking the buttons for changes in active buttons. As a default, vibration is set to active. Therefore, the loop function proceeds as follows:

- The function checks which dataset is active
- For each country, the function will check if it is active
- If a country is active, the vibrationOn function is called, if a country is not active, the vibration of the country will be turned off.

When the temperature button is pressed, the following will happen:

- All vibration will be turned off
- The function will check which dataset is active
- For all the countries, the temperatureOn function is called. When temperature is active, users won't be able to turn off countries individually. When the modality temperature is active, the system needs time to warm up the countries.

Evaluation

This chapter focusses on the evaluation of the in chapter 6 described prototype. Evaluation of the prototype was done using a user study with sixteen participants.

7.1 User study

The goal of the user study was to measure the level of the enjoyability of participants in information-gathering tasks of Sustainable Development Data, using a physicalization with two types of non-visual feedback (vibration and temperature).

7.1.1 Hypotheses

Expected was that participants would prefer one of the two types of non-visual feedback.

7.1.2 Variables

The Independent variables of the study were: The different types of non-visual feedback from the same physicalization (vibration feedback and temperature feedback) and the different tasks to perform (as described below). The dependent variables included: Efficiency (the time needed to complete the tasks), effectiveness (number of correct answers) and the subjective preference of one of the two types of feedback.

7.1.3 Tasks

All the tasks need to be done using the provided physicalization.

1. What is the country with the highest share of electricity production from renewables?
2. What country/countries has/have a higher share of electricity production than the Netherlands?
3. What country has the lowest share of electricity production from renewables?
4. What country generated the most energy from solar power?
5. What country/countries generated more electricity from solar power than the Netherlands?
6. What country generated the least amount of electricity from solar energy?

Finally, the participants are asked what type of non-visual feedback they preferred for these tasks and what type of feedback they liked most in general.

The tasks can be divided into two task sets, where the first task set includes questions 1, 2 and 3, and the second task set includes questions 4, 5 and 6.

To limit the learning effect of interacting with the physicalization, four versions of the user study can be distinguished. These four versions differentiate in the order of the modality and the task set that must be used. The layout for the task sets will be the following:

Participant 1: Vibration [Data 1, Task set 1] => Temperature [Data 2, Task set 2]

Participant 2: Temperature [Data 1, Task set 1] => Vibration [Data 2, Task set 2]

Participant 3: Vibration [Data 2, Task set 2] => Temperature [Data 1, Task set 1]

Participant 4: Temperature [Data 2, Task set 2] => Vibration [Data 1, Task set 1]

7.1.4 Procedure

1. First, the participant will get an introduction to the objective and procedure of the study by the moderator. The participants will also be asked to sign a consent form. The information brochure and consent form can be found in Appendix C.

2. The participant will get some time to get familiar with the installation, using a “fake dataset”.

3. A camera will be turned on to record the participants' interaction with the physicalization.

4. The user can start with the interaction and will receive one task at a time. The survey can be found in Appendix D.

5. After completion of a task, the participant is asked to enter the answer on the laptop that is provided. The participant will then receive the next task. When the three questions of one task set are completed, the participant is asked to rate the enjoyability of the interaction of the used modality on a 1-to-5-point scale. Then, the participant continues with the next task set.

6. After all the tasks are completed, a short interview will be conducted to ask the participant a few more questions about the installation.

When the participant is asked to use temperature, and the button for temperature is pressed, the researcher starts a timer for 3 minutes. This time is needed for the heating element to warm up the countries. When the timer is done, the participant can continue the interaction.

7.1.5 Participants

The user study will be conducted with 16 participants. The participants don't need special requirements regarding their age, gender, nationality, or experience with SDG data. Recruitment will be done through by asking people to participate.

7.1.6 Data collection

The interaction the participant has with the physicalization will be recorded. The video footage allows the researcher to analyze the interaction after the test is done. Furthermore, the answers of the questionnaire will be collected, just as the answers from the interview.

7.2 Results

The full list of results of the user study can be found in appendix E. The interview and answers to the questions can be found in Appendix F. The independent variables of the study, as described above, were the type of non-visual feedback (vibration or temperature) and the different tasks to perform. The dependent variables were the efficiency, the effectiveness, and the subjective preference. The results are therefore structured in the following way: First we will look at the efficiency of using vibration against the efficiency of using temperature. Then, the efficiency will be compared based on the different tasks. The same will be done for effectiveness, first the effectiveness of using vibration will be compared to the effectiveness of using temperature and then the effectiveness of the different tasks will be compared.

7.2.1 Efficiency

The efficiency of the physicalizations is determined by the time it took participants from reading the question to answering it.

7.2.1.1 Vibration vs Temperature

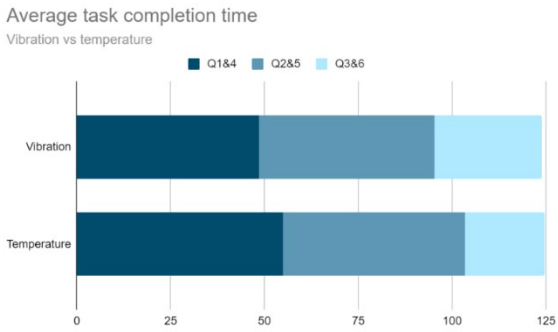


Figure 18 - Average task completion time for vibration and temperature (in seconds)

In figure 7.1, the average task completion time can be seen for both vibration and temperature. The average time it took participants to complete the tasks using vibration was 124 seconds. The average time it took participants to complete the tasks using temperature was 125 seconds. On average, it took the participants only 1 second less to complete the tasks using vibration than temperature.

Figure 7.1 also shows how these average times are broken down per task. For task 1&4, the average time to complete the task, using vibration, was 49 seconds. For temperature, the average time was 55 seconds, a difference of 6 seconds. For tasks 2&5, the average time it took participants was 47 seconds. For temperature this was 48 seconds, a one second difference. For task 3&6, the average completion time using vibration was 29 seconds, while for temperature, this was only 21 seconds.

7.2.1.2 Task 1 vs 4

For task 1, the user had to find the country with the highest share of electricity production from renewables. For task 4, participants had to find the country which generated the most amount of energy from solar power.

	Mean	Std. Deviation
Efficiency Question 1 (seconds)	50.81	15.342
Efficiency Question 4 (seconds)	52.63	32.035

Table 1 - Means and standard deviation for task completion times questions 1 and 4

Table 7.1 shows the statistical comparison of question 1 to question 4. What can be seen is that on average, it took participants almost two seconds more to answer question 4. What also can be seen is that the answering times of question 1 lie closer together, whereas the answering times for question 3 are more spread.

7.2.1.3 Task 2 vs 5

For task 2, the user had to find the countries with a highest share of electricity production from renewables than the Netherlands. For task 5, participants had to find the countries which generated more energy from solar power than the Netherlands.

	Mean	Std. Deviation
Efficiency Question 2 (seconds)	49.75	16.184
Efficiency Question 5 (seconds)	45.31	19.942

Table 2 - Means and standard deviation for task completion times questions 2 and 5

In table 7.2, the statistical comparison of question 2 to question 5 can be seen. It shows that on average, it took participants over four seconds more to answer question 2. However, the answering times for question 2 are more consistent than the answering times of question 5.

7.2.1.4 Task 3 vs 6

For task 3, the user had to find the country with the lowest share of electricity production from renewables. For task 6, participants had to find the country which generated the least amount of energy from solar power.

	Mean	Std. Deviation
Efficiency Question 3 (seconds)	23.81	11.333
Efficiency Question 6 (seconds)	26.06	12.391

Table 3 - Means and standard deviation for task completion times questions 3 and 6

In table 7.3, the statistical comparison of question 3 to question 6 can be seen. It shows that on average, it took participants over two seconds more to answer question 6. The spread of the answering times between question 3 and question 6 is similar.

7.2.2 Effectiveness

The effectiveness of the of the physicalization is determined by the number of correct answers participants gave on the questions. Derived from the number of correct answers is the accuracy of answering correctly.

7.2.2.1 Vibration vs Temperature

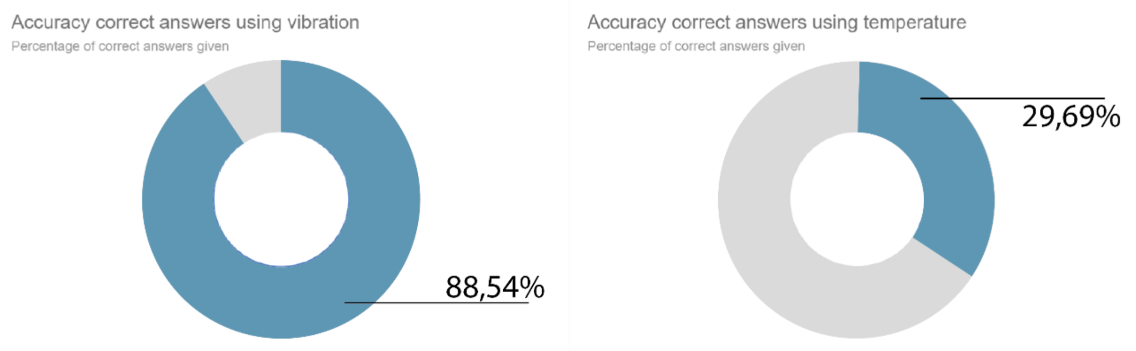


Figure 19 - Accuracy of correct answers for vibration (left) and temperature (right)

In figure 7.2, the accuracy of correct answers on the tasks for vibration and temperature can be seen. It shows a big difference, as the accuracy of the prototype is 88.54% when using vibration and only 29.69% when temperature is being used.

In figure 7.3 can be seen that the accuracy for the number of correct answers on the questions is very different when using vibration and temperature. For the first question of the task set, all the participants gave the correct answers when using vibration. However, when using temperature, only 12.5% of the given answers was correct. For the second question, with the use of vibration, 96.88% of the answers the participants gave were correct. With the use of temperature, this percentage was 51.56%. Finally, for the third question of the task set, 68.75% of the answers the participants gave, with the use of vibration, were correct. When participants had to use temperature for the same question, only 25% of the answers were correct.

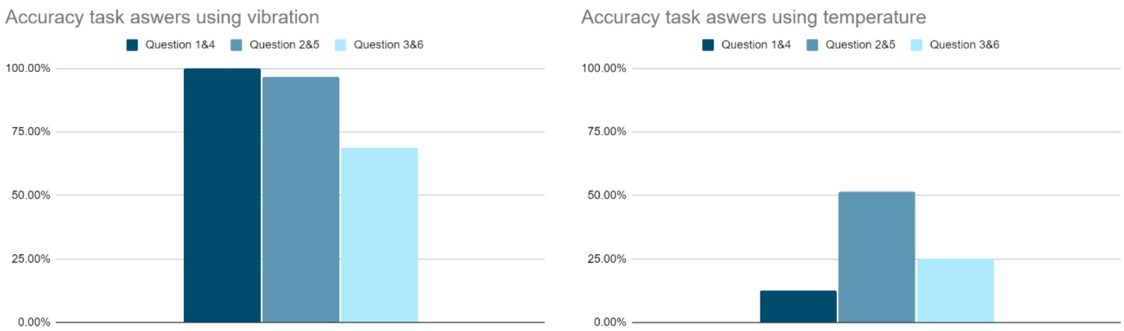


Figure 20 - Accuracy of correct answers for Q1&4, Q2&5, and Q3&6 for vibration (left) and temperature (right)

7.2.2.2 Task 1 vs 4

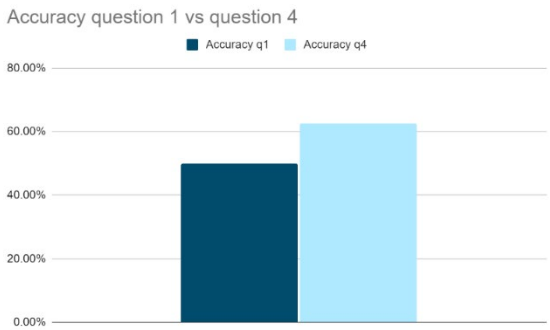


Figure 21 - Accuracy of correct answers for Q1 vs Q4

Figure 7.4 shows the accuracy of correct answers on question 1 vs question 4. The accuracy of question 1 is 50%, where the accuracy of question 4 is 62.5%.

7.2.2.3 Task 2 vs 5

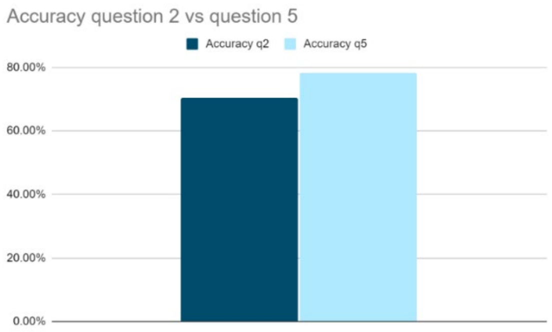


Figure 22 - Accuracy of correct answers for Q2 vs Q5

Figure 7.5 shows the accuracy of correct answers on question 2 vs question 5. The accuracy of question 2 is 70.31%, where the accuracy of question 5 is 78.13%.

7.2.2.4 Task 3 vs 6

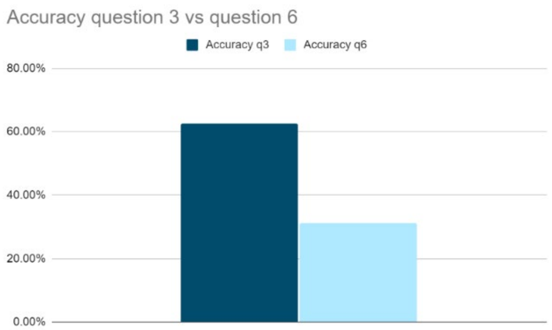


Figure 23 - Accuracy of correct answers for Q3 vs Q6

Figure 7.6 shows the accuracy of correct answers on question 3 vs question 6. The accuracy of question 3 is 62.5%, where the accuracy of question 5 is 31.25%.

7.2.3 Subjective preference

This section evaluates the subjective preference of the participants. After each task set, the participants got asked to rate the enjoyability of the interaction with the feedback method they just used. In the interview, the participants got asked whether they preferred the interaction with vibration or with temperature.

7.2.3.1 Score enjoyability

During the user study, after each task set, the participants were asked to rate the enjoyability of the interaction with the type of feedback they used. This was done using 5-point Likert scale. Eleven of the sixteen participants enjoyed (4) using vibration as a feedback method. Four people really enjoyed (5) the interaction with vibration. One person did not enjoy, nor unenjoyed (3) the interaction. When it came to temperature, nine out of the sixteen participants indicated they enjoyed (4) the interaction. Three participants really enjoyed (5) the interaction, three people did not enjoy, nor unenjoyed (3) the interaction and one person unenjoyed (2) the interaction with temperature. On average, the enjoyability of vibration scored a 4.19 out of 5 and temperature scored 3.88 out of 5.

7.2.3.2 Subjective preference interview

In the interview, the participants got asked to give their preference for one of the two feedback methods. 12 out of the 16 participants indicated that they preferred vibration as non-visual feedback method. The other 4 participants preferred temperature as a feedback method.

When asked why the participants preferred vibration, most participants gave the same answer: *"The difference was more clear and easier to distinguish."* Almost all the participants that chose vibration as their preferred feedback method also added that they found it harder to detect.

The four participants that chose temperature as their preferred feedback method did so for different reasons:

> *"Temperature, because it's very new"*

> *"Temperature, it's more absolutely scaled, as in, one is warmer than the other. For vibration the pattern or intensity could change."*

> *"Temperature, it's new and it's nice that it's more investigative. You must really look and search for the answer. It also lends itself more for physicalization, because you could also listen to the motors instead of feeling them vibrate."*

"I enjoyed the subtle feeling of the temperature."

7.2.3.3 Comparing the score to subjective preference

For seven participants, the score they gave to the questions 'How much did you enjoy interacting with the installation when the feedback was set to vibration?' and 'How much did you enjoy interacting with the installation when the feedback was set to temperature?' corresponded to the subjective preference they gave during the interview. Six participants gave the enjoyability of interacting with vibration and interacting with temperature the same score. Of these six people, four later indicated they preferred vibration, whilst two of the participants indicated they preferred temperature. For three participants, the score they gave to the questions about the enjoyability of the interaction with the prototype did not correspond to the subjective preference they later gave during the interview. Two participants chose the feedback method they enjoyed (4) rather than the one they really enjoyed (5). However, one participant scored the enjoyability of using vibration and temperature 4 and 2 respectively but indicated in the interview that the subjective preference was temperature.

7.3 Conclusion

The evaluation checks the efficiency and effectiveness of using vibration and temperature as feedback methods. Secondly, this evaluation sees whether participants prefer either of the feedback methods.

7.3.1 Efficiency and effectiveness

The efficiency and effectiveness are determined by the time participants needed to answer the question and the correctness of the answers they gave respectively. The efficiency and effectiveness were compared for both the two feedback methods, vibration, and temperature, and for the different tasks.

The efficiency of using vibration was almost like the efficiency of using temperature, while, on average, it took participants 124 seconds to finish the task set using vibration and 125 seconds to finish the task set using temperature. Therefore, can be concluded that the type of feedback does not have an impact on the efficiency of the physicalization.

When comparing the different tasks, no big differences can be seen. When comparing task 1 to task 4, a difference of two seconds was seen. When comparing task 2 to task 5, a four second difference could be seen. And finally, when comparing task 3 to task 6, a two second difference could be seen. It can be concluded that the different tasks do not have an impact on the efficiency.

Whereas there were no big differences in the efficiency of using vibration or temperature, big differences were seen in the effectiveness of the two feedback methods. The accuracy of correct answers given using vibration was 88.54%, where the accuracy of correct answers given using temperature was only 29.69%. This indicates that the use of vibration is far more effective. It can be concluded that the type of feedback does have an impact on the effectiveness of the physicalization.

When comparing the different tasks, differences could be seen. When comparing task 1 to task 4, a difference in accuracy of 12.5% could be seen, in favor for task 4. When comparing task 2 to task 5, a difference in accuracy of 7.8% could be seen in favor of task 5. When comparing task 3 to task 6, a difference in accuracy of 31,5% could be seen. The accuracy of task 3 was twice as high as the accuracy of task 6.

7.3.2 Participant preference

The preference of the user is determined by the score the participant gave to the interaction with vibration and the interaction with temperature, and the preference they indicated in the interview. When comparing the scores the participants gave to the interactions, a slight preference towards vibration could be seen (4.19/3.88). This preference was confirmed by the answers the participants gave in the interview. From the sixteen participants, twelve preferred vibrations. The main reason participants preferred vibration was that it was easier to compare the counties. This can be seen back in the effectiveness of vibration as feedback method.

Discussion

The aim of this chapter is to describe recommendations when continuing this project. It describes challenges regarding the use of vibration and temperature as feedback methods and changes that can be made to the prototype. It also describes what can be done in the future.

8.1 Challenges

The use of vibration and temperature as feedback methods brought a lot of challenges. Below, the challenges for both feedback methods are described.

8.1.1 Challenges vibration

It was a design choice to let the face of the physicalization be the map of Europe. To make sure the map was recognizable for most people, chosen was to keep the countries the sizes they are on the map, also the countries that would be included in the interaction. As a result, Sweden, Ukraine, and Spain, were big in comparison to the other countries, the Netherlands and Estonia. This brought two challenges with it. Firstly, with the room underneath the Netherlands and Estonia being limited, the position of the vibrating motors was dependent on where there was room for the motor to be glued to the country. This resulted in the participants feeling the vibration in different places underneath the different countries. Secondly, the motors were small, but the vibration had to be felt om the entire surface of the country. For the bigger countries, to be able to feel the vibration on the entire surface, two motors had to be used. However, these two motors did have to vibrate at the same frequency, without delay.

Another challenge for the use of vibration was the intensity of the vibration. At first the idea was to have the intensity of the vibration differ, rather than the frequency. The vibrating motors that were used did not all perform the same. Some motors, regardless of the power or current that was used, vibrated with a higher intensity than others. This made it unable to use the intensity of the vibration as differentiating factor.

A fourth challenge of the vibrating motors was that when they were glues to the county, the vibration produced a lot of noise. This resulted in participants not only basing their answers on what they felt, but also on what they heard. One participant did not feel the countries at all when, but solely based the answers on the sound the motors produced.

8.1.2 Challenges temperature

The first challenge for the use of temperature was the distribution of temperatures. To make the physicalization safe to touch, for a longer period, the temperature should not be below 10 degrees Celsius and not above 50 degrees Celsius. With a small safety margin, the available distribution was 15 to 45 degrees Celsius. The heating elements do not cool, so any temperature below room temperature could not be used. This resulted in only having a range from 20 to 45 degrees Celsius to use. Because small differences in temperature are hard to notice, only a small number of different countries can be compared using temperature. There is no room to scale up the number of countries that are included into the physicalization.

The design choice to have the countries their original size, as described above, also brought challenges for the use of temperature. As the countries were covered in metal, the size of the country was connected to the size of the metal surface of the country. Thus, for the bigger countries, the heating element had a bigger surface that needed to be warmed up. This resulted in the bigger countries needing more time to heat up.

The time that the heating element needed to heat up was dependent on more factors. For example, the position of the heating element underneath the country, the position of the temperature sensor, the space below the country and how the element was glued on all influenced the heating of the country. The distance of the temperature sensor to the heating element influenced the measured temperatures. The smaller countries did not have the room to fit the entire heating element, so only part of the heating element was touching the country. And less touching area meant less area to glue to element to the country. When the element was not glued to the country, it took very long to get warm, without ever reaching it’s target temperature.

Ther following example explains the challenges described above for the use of temperature:

At one point, Spain should have gone to 45 degrees Celsius and Ukraine to 33 degrees Celsius. However, in the time that Ukraine got to 30 degrees, Spain only got to 26 degrees Celsius.

8.2 Recommendations

For this bachelor project, a first prototype was created. The prototype was tested in a user study and from this user study, several recommendations can be made for further improvement of the prototype.

Most participants preferred the use of vibration as differences were easier to feel. Most of the participant found it difficult to feel the difference with temperature. One participant suggested the use of a solid metal country, rather than a wooden country covered in metal. This should improve the thermal conductivity, which theoretically would result in the countries heating up faster and getting warmer. It would also result in the country heating up more evenly, rather than in one spot.

In the interview, multiple participants indicated they missed some feedback on whether a country was turned on or off. Some suggested that the addition of an LED that would indicate if the country were on or off would solve this problem.

The vibrating motors that were used were of a poor quality. Therefore, vibrating intensity could not be used as a differentiating factor in the comparison of data. Expected is that higher quality motors perform more consistent and can thus be used to have the vibrating intensity as a differentiating factor.

8.3 Future work

There is still a lot of improvement possible to this prototype. When using better quality motors, the intensity of the vibration could tried as differentiating factor again. There is also a lot of improvement possible for the temperature. As mentioned by one of the participants, the use of a solid metal country would improve the interaction. As there is no information out there about the use of temperature in data physicalization, more research could be done into that. What are qualities of the use of temperature that could be useful for conveying data. There could also be opportunities to investigate the use of non-visual feedback for physicalization in general.

This research only compared the use of vibration with the use of temperature; however, this gives no indication how these modalities perform against what is already there. The performance of this prototype could be compared to physicalizations that do use visual feedback and physicalization that use a combination of visual- and non-visual feedback.

Conclusion

The goal of this bachelor thesis was to create an innovative physicalization that would convey SDG data. The physicalization had to be effective, efficient, and enjoyable. At the beginning of the project, the main research question was formulated, this chapter aims to answer that question.

The main research question was the following:

Are vibration good modalities to convey information?

To answer the main research question, the sub-questions need to be answered first.
The first sub-question was:

What is the current state of the art for physicalization that use vibration and temperature?

This sub-question was answered in Chapter 2: State of the Art. To answer this question, it is first necessary to understand what a physicalization is. According to Jansen et al. [2], a data physicalization is a physical artifact whose geometry properties encode data. Research to physicalizations that use vibration is limited. Currently, vibration is used in physicalization. Vibration is used when there is a visual overload or as guidance. Vibrotactile cues are also used in mobile phones or game controllers.

Temperature, in contrast to vibration, has not been used at all in the context of data physicalization.

How effective and efficient is the use of vibration and temperature to convey information

This sub-question was answered in chapter 7. When comparing the efficiency of using vibration or temperature, it found was that there is hardly any difference. On average it took participants 124 seconds to finish the task set using vibration and 125 seconds using temperature. Also, the different tasks did not have a great impact on the different tasks.

When looking at the effectiveness of the physicalization, found was that the feedback method does have a big impact. Where the accuracy of correct answers was 88.54% for vibration, it was only 29.69% for temperature. For question 1&4 and 2&5 the effectiveness was close to each other, however, the accuracy of correct answers on question 3 was twice as high as the accuracy of correct answers on question 6. It can be concluded that the different tasks did not have a large impact on the effectiveness and effectivity of the physicalization. And where the used modality did not have an impact on the efficiency, it did have a large impact on the effectiveness of the physicalization.

Are vibration and temperature perceived as enjoyable by users of the physicalization

This sub-question was also answered in chapter 7. After completing a task set, participants got asked to rate the enjoyability of the interaction with the used modality on a 1-to-5 scale, where 5 indicated they really enjoyed the interaction. On average, vibration scored a 4.19 out of 5 and temperature scored a 3.88 out of 5. Concluded can be that participants enjoyed both the use of vibration, as the use of temperature to perform the tasks. Nevertheless, the survey showed that 75% of the participants did prefer the use of vibration.

Solely based on the results, it can be concluded that users enjoy the use of vibration and temperature as modalities to convey data and that the type of modality has hardly any impact on the efficiency of the physicalization. However, the effectiveness of temperature was, compared to the high effectiveness of vibration, very low. This would make temperature a lesser modality to convey data.

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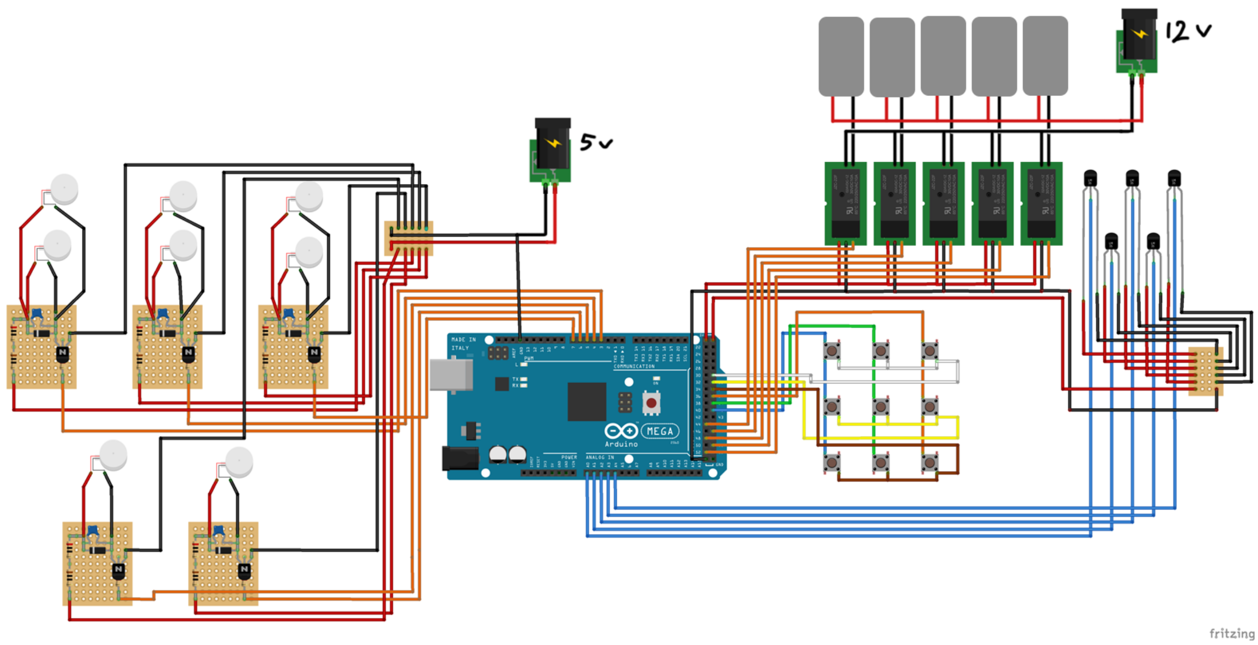
Appendix A: Schematic of entire installation



Appendix B: Arduino code

```
/* v5 of the final Graduation Project Arduino Code

The Arduino code is uploaded to the Arduino used for the graduation project
Physicalizing SDG 7

The program does the following:
- Checks whether buttons are pressed and thus countries are active and should
do something
- if a country is active, check whether it should vibrate or heat up, and
use the correct values to do so.


Made by: Rick van Loenhout, s2142104

*/


//----------Buttons----------//
#include "Adafruit_Keypad.h"
const byte ROWS = 3; //rows
const byte COLS = 3; //columns
char keys[ROWS][COLS] = {
  {'1', '2', '3'},
  {'4', '5', '6'},
  {'7', '8', '9'}
};
byte rowPins[ROWS] = {41, 39, 37}; //connect to the row pinouts on the arduino
byte colPins[COLS] = {35, 33, 31}; //connect to the col pinout on the arduino

//initialize an instance of class NewKeypad
Adafruit_Keypad customKeypad = Adafruit_Keypad( makeKeymap(keys), rowPins,
colPins, ROWS, COLS);

// At first, all buttons are inactive
boolean swedenIsActive = false;
boolean estoniaIsActive = false;
```

```
boolean netherlandsIsActive = false;
boolean ukraineIsActive = false;
boolean spainIsActive = false;
boolean vibrationIsActive = true;
boolean temperatureIsActive = false;
boolean data1IsActive = false;
boolean data2IsActive = false;

//----------Vibration----------//
int motorSweden = 7;
int motorEstonia = 6;
int motorNetherlands = 5;
int motorUkraine = 4;
int motorSpain =  3;

unsigned long previousMillisSweden = 0;
unsigned long previousMillisEstonia = 0;
unsigned long previousMillisNetherlands = 0;
unsigned long previousMillisUkraine = 0;
unsigned long previousMillisSpain = 0;

//----------Temperature----------//
int relaySweden = 44;
int relayEstonia = 47;
int relayNetherlands = 48;
int relayUkraine = 51;
int relaySpain =  52;

int tempSensorSweden = A0;
int tempSensorEstonia = A1;
int tempSensorNetherlands = A2;
int tempSensorUkraine = A3;
int tempSensorSpain = A4;

int tempValueSweden;
int tempValueEstonia;
int tempValueNetherlands;
int tempValueUkraine;
int tempValueSpain;
```

```
void setup() {
  Serial.begin(9600);

  //----------Buttons----------//
  customKeypad.begin();


  //----------Vibration----------//
  pinMode(motorSweden, OUTPUT);
  pinMode(motorEstonia, OUTPUT);
  pinMode(motorNetherlands, OUTPUT);
  pinMode(motorUkraine, OUTPUT);
  pinMode(motorSpain, OUTPUT);

  vibrationOff('Sweden');
  vibrationOff('Estonia');
  vibrationOff('Netherlands');
  vibrationOff('Ukraine');
  vibrationOff('Spain');

  //------------Temperature------------//
  pinMode(relaySweden, OUTPUT);
  pinMode(relayEstonia, OUTPUT);
  pinMode(relayNetherlands, OUTPUT);
  pinMode(relayUkraine, OUTPUT);
  pinMode(relaySpain, OUTPUT);

  pinMode(tempSensorSweden, INPUT);
  pinMode(tempSensorEstonia, INPUT);
  pinMode(tempSensorNetherlands, INPUT);
  pinMode(tempSensorUkraine, INPUT);
  pinMode(tempSensorSpain, INPUT);

  temperatureOff('Sweden');
  temperatureOff('Estonia');
  temperatureOff('Netherlands');
  temperatureOff('Ukraine');
  temperatureOff('Spain');

}
```

```
void loop() {
  checkButtons();

// In the beginning, vibration is activated. Turn off the temperature for all
countries
  if (vibrationIsActive && !temperatureIsActive) {
//     temperatureOff('Sweden');
//     temperatureOff('Estonia');
//     temperatureOff('Netherlands');
//     temperatureOff('Ukraine');
//     temperatureOff('Spain');


// When neither dataset 1 as dataset 2 is acitve, test data is active
    if (!data1IsActive && !data2IsActive) {
      //sweden
      if (swedenIsActive) {
        vibrationOn('Sweden', mapVibration('1'));
        //Serial.println("data1 sweden is vibrating");
      } else if (!swedenIsActive) {
        vibrationOff('Sweden');
      }

      //estonia
      if (estoniaIsActive) {
        vibrationOn('Estonia', mapVibration('2'));
        //Serial.println("data1 estonia is vibrating");
      } else if (!estoniaIsActive) {
        vibrationOff('Estonia');
      }
      //netherlands
      if (netherlandsIsActive) {
        vibrationOn('Netherlands', mapVibration('3'));
        //Serial.println("data1 netherlands is vibrating");
      } else if (!netherlandsIsActive) {
        vibrationOff('Netherlands');
      }
      //ukraine
      if (ukraineIsActive) {
        vibrationOn('Ukraine', mapVibration('4'));
        //Serial.println("data1 ukraine is vibrating");
```

```
  } else if (!ukraineIsActive) {
    vibrationOff('Ukraine');
  }
  //spain
  if (spainIsActive) {
    vibrationOn('Spain', mapVibration('5'));
    //Serial.println("data1 spain is vibrating");
  } else if (!spainIsActive) {
    vibrationOff('Spain');
  }
}

if (data1IsActive && !data2IsActive) {
  //Serial.println("Checking vibration, dataset1");

  //sweden
  if (swedenIsActive) {
    vibrationOn('Sweden', mapVibration('1')); //67.7 | 1
    //Serial.println("data1 sweden is vibrating");
  } else if (!swedenIsActive) {
    vibrationOff('Sweden');
  }

  //estonia
  if (estoniaIsActive) {
    vibrationOn('Estonia', mapVibration('3')); //3
    //Serial.println("data1 estonia is vibrating");
  } else if (!estoniaIsActive) {
    vibrationOff('Estonia');
  }
  //netherlands
  if (netherlandsIsActive) {
    vibrationOn('Netherlands', mapVibration('4')); //4
    //Serial.println("data1 netherlands is vibrating");
  } else if (!netherlandsIsActive) {
    vibrationOff('Netherlands');
  }
  //ukraine
  if (ukraineIsActive) {
    vibrationOn('Ukraine', mapVibration('5')); //5
    //Serial.println("data1 ukraine is vibrating");
```

```
  } else if (!ukraineIsActive) {
    vibrationOff('Ukraine');
  }
  //spain
  if (spainIsActive) {
    vibrationOn('Spain', mapVibration('2')); //2
    //Serial.println("data1 spain is vibrating");
  } else if (!spainIsActive) {
    vibrationOff('Spain');
  }
} else if (data2IsActive && !data1IsActive) {
  //Serial.println("Checking vibration, dataset2");

  //sweden
  if (swedenIsActive) {
    vibrationOn('Sweden', mapVibration('4')); //0.41 | 5
    //Serial.println("data2 sweden is vibrating");
  } else if (!swedenIsActive) {
    vibrationOff('Sweden');
  }
  //estonia
  if (estoniaIsActive) {
    vibrationOn('Estonia', mapVibration('5')); //0.04
    //Serial.println("data2 estonia is vibrating");
  } else if (!estoniaIsActive) {
    vibrationOff('Estonia');
  }
  //netherlands
  if (netherlandsIsActive) {
    vibrationOn('Netherlands', mapVibration('2')); //7.91
    //Serial.println("data2 netherlands is vibrating");
  } else if (!netherlandsIsActive) {
    vibrationOff('Netherlands');
  }
  //ukraine
  if (ukraineIsActive) {
    vibrationOn('Ukraine', mapVibration('3')); // 1.00 | 50
    //Serial.println("data2 ukraine is vibrating");
  } else if (!ukraineIsActive) {
    vibrationOff('Ukraine');
  }
```

```
      //spain
      if (spainIsActive) {
        vibrationOn('Spain', mapVibration('1')); // 20.71
        //Serial.println("data2 spain is vibrating");
      } else if (!spainIsActive) {
        vibrationOff('Spain');
      }
    }
  } else if (temperatureIsActive && !vibrationIsActive) {
    vibrationOff('Sweden');
    vibrationOff('Estonia');
    vibrationOff('Netherlands');
    vibrationOff('Ukraine');
    vibrationOff('Spain');
    if (data1IsActive && !data2IsActive) {
      //Serial.println("Checking temperature, dataset1");
      temperatureOn('Sweden', mapTemperature('1')); //67.7
      temperatureOn('Estonia', mapTemperature('3')); //35.2
      temperatureOn('Netherlands', mapTemperature('4')); //25.2
      temperatureOn('Ukraine', mapTemperature('5')); //10.0
      temperatureOn('Spain', mapTemperature('2')); //43.5


    } else if (data2IsActive && !data1IsActive) {

      temperatureOn('Sweden', mapTemperature('4')); //0.41
      temperatureOn('Estonia', mapTemperature('5')); //0.04
      temperatureOn('Netherlands', mapTemperature('2')); //7.91
      temperatureOn('Ukraine', mapTemperature('3')); //1.00
      temperatureOn('Spain', mapTemperature('1')); //20.76
    }
  }
  delay(100);
}


void checkButtons() {
  customKeypad.tick();
  while (customKeypad.available()) {
    keypadEvent e = customKeypad.read();
    char number = (char)e.bit.KEY;
```

```
//if button sweden is pressed
if (number == '3' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (swedenIsActive) {
    swedenIsActive = false;
  } else if (!swedenIsActive) {
    swedenIsActive = true;
    Serial.println("sweden");
  }
}

//if button estonia is pressed
if (number == '2' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (estoniaIsActive) {
    estoniaIsActive = false;
  } else if (!estoniaIsActive) {
    estoniaIsActive = true;
    Serial.println("estonia");
  }
}

//if button netherlands is pressed
if (number == '4' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (netherlandsIsActive) {
    netherlandsIsActive = false;
  } else if (!netherlandsIsActive) {
    netherlandsIsActive = true;
    Serial.println("netherlands");
  }
}

//if button ukraine is pressed
if (number == '1' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (ukraineIsActive) {
    ukraineIsActive = false;
  } else if (!ukraineIsActive) {
    ukraineIsActive = true;
    Serial.println("ukraine");
  }
}
```

```
//if button spain is pressed
if (number == '7' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (spainIsActive) {
    spainIsActive = false;
  } else if (!spainIsActive) {
    spainIsActive = true;
    Serial.println("spain");
  }
}

//if button vibration is pressed
if (number == '9' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (vibrationIsActive) {
    temperatureIsActive = false;
    vibrationIsActive = true;
  } else if (!vibrationIsActive) {
    temperatureIsActive = false;
    vibrationIsActive = true;
    Serial.println("vibration");
  }
}

//if button temperature is pressed
if (number == '6' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (temperatureIsActive) {
    vibrationIsActive = false;
    temperatureIsActive = true;
  } else if (!temperatureIsActive) {
    vibrationIsActive = false;
    temperatureIsActive = true;
    Serial.println("temperature");
  }
}

//if button data1 is pressed
if (number == '8' && e.bit.EVENT == KEY_JUST_PRESSED) {
  if (data1IsActive) {
    data2IsActive = false;
    data1IsActive = true;
  } else if (!data1IsActive) {
    data1IsActive = true;
```

```
        data2IsActive = false;
        Serial.println("data1");
      }
    }

    //if button data2 is pressed
    if (number == '5' && e.bit.EVENT == KEY_JUST_PRESSED) {
      if (data2IsActive) {
        data1IsActive = false;
        data2IsActive = true;
      } else if (!data2IsActive) {
        data2IsActive = true;
        data1IsActive = false;
        Serial.println("data2");
      }
    }
  }
  delay(10);
}

void vibrationOn(int country, float value) {

  // The value should not change the intensity of the motors, but the timing
interval in which the country will vibrate
  // The analogWritw is replaced by digitalWrite for testing purpose, the
255's and 0's are replaced by HIGH's and LOW's

  if (country == 'Sweden') {
    unsigned long currentMillisSweden = millis();
    if (currentMillisSweden - previousMillisSweden >= value) { //so the 0
will be changed by the value
      digitalWrite(motorSweden, HIGH); // and the value here will be changed
by 255 (the max intensity of the motor). Perhaps for Sweden as the motors
vibrated with such a strong intensity, set the intensity a bit lower.
      previousMillisSweden = currentMillisSweden;
      delay(1);
    } else {
      digitalWrite(motorSweden, LOW);
    }
  }
```

```
else if (country == 'Estonia') {
  unsigned long currentMillisEstonia = millis();
  if (currentMillisEstonia - previousMillisEstonia >= value) {
    digitalWrite(motorEstonia, HIGH);
    previousMillisEstonia = currentMillisEstonia;
    delay(10);
  } else {
    digitalWrite(motorEstonia, LOW);
  }
}

else if (country == 'Netherlands') {
  unsigned long currentMillisNetherlands = millis();
  if (currentMillisNetherlands - previousMillisNetherlands >= value) {
    digitalWrite(motorNetherlands, HIGH);
    previousMillisNetherlands = currentMillisNetherlands;
    delay(1);
  } else {
    digitalWrite(motorNetherlands, LOW);
  }
}

else if (country == 'Ukraine') {
  unsigned long currentMillisUkraine = millis();
  if (currentMillisUkraine - previousMillisUkraine >= value) {
    digitalWrite(motorUkraine, HIGH);
    previousMillisUkraine = currentMillisUkraine;
    delay(1);
  } else {
    digitalWrite(motorUkraine, LOW);
  }
}

else if (country == 'Spain') {
  unsigned long currentMillisSpain = millis();
  if (currentMillisSpain - previousMillisSpain >= value) {
    digitalWrite(motorSpain, HIGH);
    previousMillisSpain = currentMillisSpain;
    delay(1);
  } else {
    digitalWrite(motorSpain, LOW);
```

```
    }
  }
}


void vibrationOff(int country) {
  if (country == 'Sweden') {
    digitalWrite(motorSweden, LOW);
  } else if (country == 'Estonia') {
    digitalWrite(motorEstonia, LOW);
  } else if (country == 'Netherlands') {
    digitalWrite(motorNetherlands, LOW);
  } else if (country == 'Ukraine') {
    digitalWrite(motorUkraine, LOW);
  } else if (country == 'Spain') {
    digitalWrite(motorSpain, LOW);
  }
}

void temperatureOn(int country, float value) {

  if (country == 'Sweden') {
    unsigned long currentMillisSweden = millis();
    if (currentMillisSweden - previousMillisSweden >= 10000) {
      Serial.println("sweden tempsensor 10s interval active");

      int sum = 0;
      for (int i = 0; i < 100; i++) {
        sum += analogRead(tempSensorSweden);
      }
      tempValueSweden = (sum / 100);
      float mv = (tempValueSweden / 1023.0) * 5000;
      float celcius = (mv / 10);
      Serial.print("Sweden target value: ");
      Serial.print(value);
      Serial.print(" " );
      Serial.print("Sweden temp: ");
      Serial.println(celcius);

      if (celcius < value) {
        digitalWrite(relaySweden, LOW);
```

```
    } else if (celcius >= value) {
      digitalWrite(relaySweden, HIGH);
    }
    previousMillisSweden = currentMillisSweden;
  }
}

else if (country == 'Estonia') {
  unsigned long currentMillisEstonia = millis();
  if (currentMillisEstonia - previousMillisEstonia >= 10000) {
    Serial.println("Estonia tempsensor 10s interval active");

    tempValueEstonia = analogRead(tempSensorEstonia);
    float mv = (tempValueEstonia / 1023.0) * 5000;
    float celcius = (mv / 10);
    Serial.print("Estonia target value: ");
    Serial.print(value);
    Serial.print(" " );
    Serial.print("Estonia temp: ");
    Serial.println(celcius);


    if (celcius < value) {
      digitalWrite(relayEstonia, LOW);
    } else if (celcius >= value) {
      digitalWrite(relayEstonia, HIGH);
    }
    previousMillisEstonia = currentMillisEstonia;
  }
}

else if (country == 'Netherlands') {
  unsigned long currentMillisNetherlands = millis();
  if (currentMillisNetherlands - previousMillisNetherlands >= 10000) {
    Serial.println("Netherlands tempsensor 10s interval active");

    int sum = 0;
    for (int i = 0; i < 100; i++) {
      sum += analogRead(tempSensorNetherlands);
    }
    tempValueNetherlands = (sum / 100);
```

```
    float mv = (tempValueNetherlands / 1023.0) * 5000;
    float celcius = (mv / 10);
    Serial.print("Netherlands target value: ");
    Serial.print(value);
    Serial.print(" " );
    Serial.print("Netherlands temp: ");
    Serial.println(celcius);

    if (celcius < value) {
      digitalWrite(relayNetherlands, LOW);
    } else if (celcius >= value) {
      digitalWrite(relayNetherlands, HIGH);
    }
    previousMillisNetherlands = currentMillisNetherlands;
  }
}

else if (country == 'Ukraine') {
  unsigned long currentMillisUkraine = millis();
  if (currentMillisUkraine - previousMillisUkraine >= 10000) {
    Serial.println("Ukraine tempsensor 10s interval active");

    int sum = 0;
    for (int i = 0; i < 100; i++) {
      sum += analogRead(tempSensorUkraine);
    }
    tempValueUkraine = (sum / 100);
    float mv = (tempValueUkraine / 1023.0) * 5000;
    float celcius = (mv / 10);
    Serial.print("Ukraine target value: ");
    Serial.print(value);
    Serial.print(" " );
    Serial.print("Ukraine temp: ");
    Serial.println(celcius);

    if (celcius < value) {
      digitalWrite(relayUkraine, LOW);
    } else if (celcius >= value) {
      digitalWrite(relayUkraine, HIGH);
    }
    previousMillisUkraine = currentMillisUkraine;
```

```
      }
    }

    else if (country == 'Spain') {
      unsigned long currentMillisSpain = millis();
      if (currentMillisSpain - previousMillisSpain >= 10000) {
        Serial.println("Spain tempsensor 10s interval active");

        int sum = 0;
        for (int i = 0; i < 100; i++) {
          sum += analogRead(tempSensorSpain);
        }
        tempValueSpain = (sum / 100);
        float mv = (tempValueSpain / 1023.0) * 5000;
        float celcius = (mv / 10);
        Serial.print("Spain target value: ");
        Serial.print(value);
        Serial.print(" " );
        Serial.print("Spain temp: ");
        Serial.println(celcius);

        if (celcius < value) {
          digitalWrite(relaySpain, LOW);
        } else if (celcius >= value) {
          digitalWrite(relaySpain, HIGH);
        }
        previousMillisSpain = currentMillisSpain;
      }
    }
  }

  void temperatureOff(int country) {
    if (country == 'Sweden') {
      digitalWrite(relaySweden, HIGH);
    } else if (country == 'Estonia') {
      digitalWrite(relayEstonia, HIGH);
    } else if (country == 'Netherlands') {
      digitalWrite(relayNetherlands, HIGH);
    } else if (country == 'Ukraine') {
      digitalWrite(relayUkraine, HIGH);
    } else if (country == 'Spain') {
```

```
    digitalWrite(relaySpain, HIGH);
  }
}

float mapVibration(int rank) {
  if (rank == '1') {
    float mappedValue = 0;
    return mappedValue;
  } else if (rank == '2') {
    float mappedValue = 500;
    return mappedValue;
  } else if (rank == '3') {
    float mappedValue = 1000;
    return mappedValue;
  } else if (rank == '4') {
    float mappedValue = 1500;
    return mappedValue;
  } else if (rank == '5') {
    float mappedValue = 2000;
    return mappedValue;
  }
}

float mapTemperature(float rank) {
  if (rank == '1') {
    float mappedValue = 45;
    return mappedValue;
  } else if (rank == '2') {
    float mappedValue = 39;
    return mappedValue;
  } else if (rank == '3') {
    float mappedValue = 33;
    return mappedValue;
  } else if (rank == '4') {
    float mappedValue = 27;
    return mappedValue;
  } else if (rank == '5') {
    float mappedValue = 21;
    return mappedValue;
  }
}
```

Appendix C: Information brochure & Consent form

Information brochure

The goal of this study is to find out the extent to which data physicalization can help users get information about Sustainable Development Goals (SDGs). The SDGs were adopted by all members of the United Nations in 2015. We want to compare different countries and the extent to which they meet the SDG goals in the domain of clean and affordable energy.

During this study you will be interacting with the installation you can see on the table. This

installation is a physical representation of data about Sustainable Development Goal (SDG) 7: clean andaffordable energy.

After you have finished the tasks, you will be asked to answer a couple more questions about thephysicalization.

- Researcher: Rick van Loenhout (r.p.v.vanloenhout@student.utwente.nl)
- Supervisor: Champika Ranasinghe (c.m.eparanasinghe@utwente.nl)
- University of Twente

Consent form

By signing this consent form I acknowledge that:

- I have read and understood all the information for participating in this study in the information brochure.
- I give permission for participating in this study and for collecting, storing, and using the data for this research.
- I give permission to make a video to capture data of me interacting with the physicalization.
- I am participating voluntarily and behold the right to withdraw from the research at any given time, without giving any reason.

If you have any advice complaints about this research, please contact the secretary of the EthicsCommittee (EC) of the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) of the University of Twente, P.O. Box 217, 7500 AE Enschede (NL), e-mail: ethicscommittee-cis@utwente.nl

Name participant:

…………………………………….

Signature:

…………………………………….

Date:

Name researcher:

…………………………………….

Signature:

…………………………………….

Date:

……………………………………… ………………………………………

Appendix D: Survey user study

D.1: User study V1

Section A: Task set 1: Using data 1 and vibration
For the following tasks, please select Dataset 1 and the feedback method Vibration.

A1. **What is the country with the highest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Vibration' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

A2. **What country/countries has/have a higher share of electricity production than the Netherlands?**

Use dataset 1 and the feedback method 'Vibration' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

A3. **What country has the lowest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Vibration' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

Section B: Enjoyability Vibration

B1. **How much did you enjoy interacting with the installation when the feedback was set to vibration?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Section C: Task set 2: Using data set 2 and temperature

For the following tasks, please select Dataset 2, and the feedback method Temperature.

C1. **What country generated the most energy from solar power?**

Use dataset 2 and the feedback method 'Temperature' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

C2. **What country/countries generated more electricity from solar power than the Netherlands?**

Use dataset 2 and the feedback method 'Temperature' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

C3. **What country generated the least amount of electricity from solar energy?**

Use dataset 2 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

Section D: Enjoyability Temperature

D1. **How much did you enjoy interacting with the installation when the feedback was set to temperature?**

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

D.2: User study V2

Section A: **Task set 1: Using data 1 and temperature**

For the following tasks, please select Dataset 1 and the feedback method Temperature. The five countries you can choose from are: Sweden, Estonia, Netherlands, Ukraine and Spain.

A1. **What is the country with the highest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

A2. **What country/countries has/have a higher share of electricity production than the Netherlands?**

Use dataset 1 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

A3. **What country has the lowest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

Section B: Enjoyability Temperature

B1. **How much did you enjoy interacting with the installation when the feedback was set to temperature?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Section C: Task set 2: Using data set 2 and temperature

For the following tasks, please select Dataset 2, and the feedback method Vibration. The five countries you can choose from are Sweden, Estonia, Netherlands, Ukraine, and Spain.

C1. **What country generated the most energy from solar power?**

Use dataset 2 and the feedback method 'Vibration' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

C2. **What country/countries generated more electricity from solar power than the Netherlands?**

Use dataset 2 and the feedback method 'Vibration' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

C3. **What country generated the least amount of electricity from solar energy?**

Use dataset 2 and the feedback method 'Vibration' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

Section D: Enjoyability Vibration

D1. **How much did you enjoy interacting with the installation when the feedback was set to vibration?**

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

D.3: User study V3

Section A: Task set 1: Using data set 2 and vibration

For the following tasks, please select Dataset 2, and the feedback method Vibration. The five countries you can choose from are Sweden, Estonia, Netherlands, Ukraine, and Spain.

A1. **What country generated the most energy from solar power?**

Use dataset 2 and the feedback method 'Vibration' to answer this question.

- [ ] Sweden
- [ ] Estonia
- [ ] Netherlands
- [ ] Ukraine
- [ ] Spain

A2. **What country/countries generated more electricity from solar power than the Netherlands?**

Use dataset 2 and the feedback method 'Vibration' to answer this question.

- [ ] Sweden
- [ ] Estonia
- [ ] Netherlands
- [ ] Ukraine
- [ ] Spain

A3. **What country generated the least amount of electricity from solar energy?**

Use dataset 2 and the feedback method 'Vibration' to answer this question.

- [ ] Sweden
- [ ] Estonia
- [ ] Netherlands
- [ ] Ukraine
- [ ] Spain

Section B: Enjoyability Vibration

B1. **How much did you enjoy interacting with the installation when the feedback was set to vibration?**

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

Section C: Task set 2: Using data 1 and temperature

For the following tasks, please select Dataset 1 and the feedback method Temperature. The five countries you can choose from are: Sweden, Estonia, Netherlands, Ukraine and Spain.

C1. **What is the country with the highest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

C2. **What country/countries has/have a higher share of electricity production than the Netherlands?**

Use dataset 1 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

C3. What country has the lowest share of electricity production from renewables?

Use dataset 1 and the feedback method 'Temperature' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

Section D: Enjoyability Temperature

D1. How much did you enjoy interacting with the installation when the feedback was set to temperature?

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

D.4: User study V4

Section A: Task set 1: Using data set 2 and temperature

For the following tasks, please select Dataset 2, and the feedback method Temperature. The five countries you can choose from are Sweden, Estonia, Netherlands, Ukraine, and Spain.

A1. What country generated the most energy from solar power?

Use dataset 2 and the feedback method 'Temperature' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

A2. What country/countries generated more electricity from solar power than the Netherlands?

Use dataset 2 and the feedback method 'Temperature' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

A3. What country generated the least amount of electricity from solar energy?

Use dataset 2 and the feedback method 'Temperature' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

Section B: Enjoyability Temperature

B1. **How much did you enjoy interacting with the installation when the feedback was set to temperature?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Section C: Task set 2: Using data 1 and vibration

For the following tasks, please select Dataset 1 and the feedback method Vibration. The five countries you can choose from are: Sweden, Estonia, Netherlands, Ukraine and Spain.

C1. **What is the country with the highest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Vibration' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

C2. **What country/countries has/have a higher share of electricity production than the Netherlands?**

Use dataset 1 and the feedback method 'Vibration' to answer this question.

Sweden ☐
Estonia ☐
Netherlands ☐
Ukraine ☐
Spain ☐

C3. **What country has the lowest share of electricity production from renewables?**

Use dataset 1 and the feedback method 'Vibration' to answer this question.

- Sweden ☐
- Estonia ☐
- Netherlands ☐
- Ukraine ☐
- Spain ☐

Section D: Enjoyability Vibration

D1. **How much did you enjoy interacting with the installation when the feedback was set to vibration?**

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

Appendix E: Results User Evaluation

E.1 vibration

Gender	Have people used physicalization before?	Modality	Q1&4 time (s)	Q2&5time (s)	Q3&6time (s)	Q1&4accuracy	Q2&5accuracy	Q3&6accuracy	Score enjoyability	subjective pref
M	Yes	V	39	60	47	100.00%	75.00%	100.00%	4.00	Vibration
M	Yes	V	38	6	17	100.00%	100.00%	100.00%	4.00	Temperature
M	No	V	35	34	37	100.00%	100.00%	100.00%	4.00	Vibration
M	Yes	V	51	57	26	100.00%	100.00%	100.00%	4.00	Vibration
M	Yes	V	38	38	25	100.00%	100.00%	100.00%	4.00	Temperature
F	Yes	V	52	54	45	100.00%	100.00%	0.00%	4.00	Vibration
F	Yes	V	38	54	52	100.00%	100.00%	100.00%	4.00	Vibration
M	Yes	V	41	61	30	100.00%	75.00%	0.00%	4.00	vibration
M	Yes	V	37	64	30	100.00%	100.00%	100.00%	4.00	Temperature
M	Yes	V	48	42	36	100.00%	100.00%	100.00%	3.00	Vibration
M	Yes	V	112	52	21	100.00%	100.00%	0.00%	4.00	Vibration
M	Yes	V	57	45	16	100.00%	100.00%	100.00%	4.00	Temperature
M	No	V	64	48	16	100.00%	100.00%	100.00%	5.00	Vibration
M	Yes	V	41	38	18	100.00%	100.00%	0.00%	5.00	Vibration
M	Yes	V	42	42	26	100.00%	100.00%	0.00%	5.00	Vibration
F	No	V	44	51	15	100.00%	100.00%	100.00%	5.00	Vibration
			48.56	46.63	28.56	100.00%	96.88%	68.75%	4.19	

E.2 Temperature

Gender	Have people used physicalization before?	Modality	Q1&4time	Q2&5time	Q3&6time	Q1&4accuracy	Q2&5accuracy	Q3&6accuracy	Score enjoyability	subjective pref
M	Yes	T	29	40	27	0.00%	50.00%	0.00%	5.00	Vibration
M	Yes	T	91	34	7	0.00%	50.00%	0.00%	4.00	Temperature
M	No	T	46	26	12	0.00%	75.00%	100.00%	3.00	Vibration
M	Yes	T	41	58	13	0.00%	75.00%	0.00%	4.00	Vibration
M	Yes	T	52	31	12	0.00%	75.00%	0.00%	4.00	Temperature
F	Yes	T	56	34	27	0.00%	0.00%	0.00%	3.00	Vibration
F	Yes	T	41	81	30	0.00%	25.00%	0.00%	4.00	Vibration
M	Yes	T	31	43	34	0.00%	50.00%	0.00%	4.00	vibration
M	Yes	T	31	25	12	0.00%	50.00%	0.00%	2.00	Temperature
M	Yes	T	61	54	46	0.00%	50.00%	0.00%	4.00	Vibration
M	Yes	T	70	76	17	0.00%	25.00%	0.00%	3.00	Vibration
M	Yes	T	27	75	18	100.00%	25.00%	0.00%	5.00	Temperature
M	No	T	139	38	34	100.00%	75.00%	0.00%	4.00	Vibration
M	Yes	T	30	35	14	0.00%	75.00%	100.00%	4.00	Vibration
M	Yes	T	47	32	23	0.00%	75.00%	100.00%	5.00	Vibration
F	No	T	86	93	15	0.00%	50.00%	100.00%	4.00	Vibration
			54.88	48.44	21.31	12.50%	51.56%	25.00%	3.88	

E.3 Efficiency per question

Time q1	Time q2	Time q3	Time q4	Time q5	Time q6
39	60	47	29	40	27
91	34	7	38	6	17
46	26	12	35	34	37
51	57	26	41	58	13
38	38	25	52	31	12
56	34	27	52	54	45
41	81	30	38	54	52
41	61	30	31	43	34
37	64	30	31	25	12
61	54	46	48	42	36
70	76	17	112	52	21
57	45	16	27	75	18
64	48	16	139	38	34
30	35	14	41	38	18
47	32	23	42	42	26
44	51	15	86	93	15
50.8125	49.75	23.8125	52.625	45.3125	26.0625

E.4 Statistics efficiency per country

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
Time Q1	16	30	91	50.81	15.342	235.363
Time Q4	16	27	139	52.63	32.035	1026.250
Valid N (listwise)	16					

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
Time Q2	16	26	81	49.75	16.184	261.933
Time Q5	16	6	93	45.31	19.942	397.696
Valid N (listwise)	16					

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
Time Q3	16	7	47	23.81	11.333	128.429
Time Q6	16	12	52	26.06	12.391	153.529
Valid N (listwise)	16					

E.5 Effectiveness per question

Accuracy q1	Accuracy q2	Accuracy q3	Accuracy q4	Accuracy q5	Accuracy q6
100.00%	75.00%	100.00%	0.00%	50.00%	0.00%
0.00%	50.00%	0.00%	100.00%	100.00%	100.00%
0.00%	75.00%	100.00%	100.00%	100.00%	100.00%
100.00%	100.00%	100.00%	0.00%	75.00%	0.00%
100.00%	100.00%	100.00%	0.00%	75.00%	0.00%
0.00%	0.00%	0.00%	100.00%	100.00%	0.00%
0.00%	25.00%	0.00%	100.00%	100.00%	100.00%
100.00%	75.00%	0.00%	0.00%	50.00%	0.00%
100.00%	100.00%	100.00%	0.00%	50.00%	0.00%
0.00%	50.00%	0.00%	100.00%	100.00%	100.00%
0.00%	25.00%	0.00%	100.00%	100.00%	0.00%
100.00%	100.00%	100.00%	100.00%	25.00%	0.00%
100.00%	100.00%	100.00%	100.00%	75.00%	0.00%
0.00%	75.00%	100.00%	100.00%	100.00%	0.00%
0.00%	75.00%	100.00%	100.00%	100.00%	0.00%
100.00%	100.00%	100.00%	0.00%	50.00%	100.00%
50.00%	70.31%	62.50%	62.50%	78.13%	31.25%

E.6 Statistics effectiveness per question

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Effectiveness Q1	16	.00	100.00	50.0000	51.63978
Effectiveness Q	16	.00	100.00	70.3125	31.90970
Effectiveness Q3	16	.00	100.00	62.5000	50.00000
Effectiveness Q4	16	.00	100.00	62.5000	50.00000
Effectiveness Q5	16	25.00	100.00	78.1250	25.61738
Effectiveness Q6	16	.00	100.00	31.2500	47.87136
Valid N (listwise)	16				

E.7 Preference participant

Participant	Enjoyability vibration	Enjoyability temperature	Subjective preference	corresponds
Participant 1	4	5	Vibration	-
Participant 2	4	4	Temperature	+/-
Participant 3	4	3	Vibration	+
Participant 4	4	4	Vibration	+/-
Participant 5	4	4	Temperature	+/-
Participant 6	4	3	Vibration	+
Participant 7	4	4	Vibration	+/-
Participant 8	4	4	Vibration	+/-
Participant 9	4	2	Temperature	-
Participant 10	3	4	Vibration	+
Participant 11	4	3	Vibration	+
Participant 12	4	5	Temperature	-
Participant 13	5	4	Vibration	+
Participant 14	5	4	Vibration	+
Participant 15	5	5	Vibration	+/-
Participant 16	5	4	Vibration	+
	4.19	3.88		

Appendix F: Interview questions and answers

Q1	Have you ever used a physicalization before?
	Probably projects of CreaTe
	Built one
	I don't think so. Maybe something that comes close was as a child that you had to feel what was in a box
	Yes, during bachelor CreaTe, Gogbot
	Yes, demo module 8
	Yes
	Yes, module 8 CreaTe, Gogbot
	Yes, Singapore science museum
	Yes, Module 8 CreaTe
	I thinks so, in the designlab or at Gogbot
	Yes, in a museum
	Yes, in a science museum
	No, not that I can think of
	Yes, during CreaTe module 8
	Yes
	No

Q2	Have you ever been interacting with data like this?
	Besides building one and participating in user studies, no
	No
	No
	No
	Not for data. I have interacted with both haptics and temperature, but it was more of a trigger
	Vibration probably yes, temperature no
	No

	No
	No
	Temperature not, vibration sort of
	No not really
	No
	No
	No
	No
	No

Q3	Which modality did you like most in general, why?
	Vibration, the difference between countries better noticeable
	Temperature, because it is very new
	Vibration, easier to distinguish
	Vibration, was more clear to identify differences. Small difference easier to distinguish with vibration
	Temperature. It is more absolutely scaled. One is warmer than the other, whereas with vibration pattern could change or intensity etc
	Temperature was nice, but difficult, Vibration was easier
	Vibration, temperature was hard to detect
	Vibration easier to distinguish, temperature more difficult
	Temperature, its new and its nice that it's more investigative, looking and searching for the answer. It also lends itself more for the physicalization, as motors is more listening than feeling
	Vibration, as temperature was more difficult and unclear
	Vibration, it was easier to feel than temperature
	Temperature, subtle feeling
	Vibration, more clear than temperature
	Vibration, you could feel more difference
	The vibration was a bit more clear. Temperature was a bit harder to feel
	Vibration, more clear and more fun to feel

Q4	What did you like most about the physicalization?
	The interaction when feeling the difference
	You really had to feel, it is more interaction than when you only see the difference
	Touching the surface and then something happens
	Looks nice, playful interaction. A table would be quicker to transfer data, but would be less playful
	Buttons as they stand out from the rest (metal surface), but when every country is a button you don't have that anymore. And it's nice it is an actual representation of europe. You know what it looks like and you see that before you.
	Playful way to compare. Temperature was nice to feel
	Removed the bias for both datasets
	Nice way of interacting with the data
	Vibration is a nice way of interaction between man and machine
	It was more investigative, which is more fun to do
	You can feel it, the temperature difference was surprising
	Feeling the differences between countries. Pressing a button and something happens
	Surprised by the vibration
	For the vibration that Spain was vibrating very hard. I like laser cuts
	Unique way to represent data
	To compare the countries, so touching two countries and feel a difference between the two.

Q5	Was there something that you missed while using the physicalization?
	Perhaps if you are not good at geography, it would be nice if on the country it said what country it was
	Perhaps some light, for fun and as an indication a country is active
	Not really
	Exact values and more information about the country, perhaps after the question
	Vibration: For me not clear it was a button instead of a trigger. Temperature: verification that the given country is correct. Confusion about what country was the hottest and what country was expected to be the hottest
	Kind of forgot about the data, or at least what dataset 1 and 2 were. The temperature difference was hard to feel

	Would have liked more difference for the temperature
	Overview of the data, maybe comparing more countries at the same time
	Sometimes unclear if I pushed a button or not, so something for that
	For me, the frequency of the vibration was a bit unclear. It took some time for me to realize that it was the frequency between vibrations
	The temperature difference was hard to feel
	Maybe some indication or feedback of when a country is turned on or off
	Not really
	Feedback on whether a country is on or off
	Explanation on the board on what dataset 1 & 2 are.
	Not really

Q6	Where would you like to see something like this?
	City hall, (tech) museum, a company (power plant for example)
	Exposition about energy
	Nemo, or in a zoo or something as those explanatory things
	Museum, exposition about climate. Data linked to location.
	Museum or at a company that works with energy. Fun/interesting to have a heat map like: "This is where we stand"
	Exposition, presentations about this topic. Also, just fun to hang a building somewhere.
	Conference or event about SDGs
	Museum, educate younger children on certain topics
	CreaTe demo market, interactive museum, or at a company as a fun showpiece
	Musea, temporary expositions about the topic
	Information points, elementary school, high school
	Museum, exhibitions, a conference about global warming
	A science museum for example
	Sustainable energy places
	At the entrance of a EU building to just show data. Exposition on climate change
	In a museum, for tours in technical companies, congresses, or open days

Q7	Do you think you know how these countries compared to each other by using the physicalization?
	Yes
	Yes
	I think I would quickly forget it. It was more interesting what you felt than what it meant
	Yes, that Ukraine performed poorly was no surprise
	Yeah think so, but it was not so much different than initially guessed.
	Yeah
	Yes, but kind of forgot which dataset was what. But the best performer was quite clear
	I think so
	Yes, but I expected Sweden to have a higher share of renewables (*which is true, but with temperature, it did not get the warmest*)
	A bit, but not entirely. Some things were a bit unclear and I had the feeling that I was missing some data. With some extra explanation about how to interpret the data, I would have known it better
	Yes
	Yes, Ukraine is a bit behind, Sweden is sustainable
	Yes
	Yes, especially the extremes were very clear
	Yes, surprised by the renewables value of Estonia (*it got the warmest in the 3 minutes)
	Yes, however, with temperature less than with vibration

Q8	Would you use such a physicalization again, why? Why not?
	Yes, I would. It’s a way better experience to understand data when you feel the difference
	Perhaps for different datasets
	When you see it somewhere then yes, but also more to see what it does
	Yes, interesting to interact in a playful way, When you see it, it gets your interest
	Once, but when you know the data, it loses its interest
	Yeah, it is nice to do. Easy way to learn facts about countries
	Yes, useful for people who can’t see

	Yes, interesting for users. Learning about something new in a more fun way, not only using the values
	Yes, nice that you can play with an installation. I do think it loses novelty quickly
	Yes, it is always fun to touch the stuff
	Yes, interactive, and easy/clear differences between countries
	Yes, if you can compare more countries, or use different datasets
	If it was something similar then yes, if it's the same one with the same datasets, no
	If you have done it once, no
	Yes, it's nice to interact with, especially if there are more datasets
	Yes, I think it's a good way of showing data. It was very clear, you could feel big differences

Q9	Do you have any other comments or remarks about the study of the prototype?
	The motor of Estonia behaved a bit differently. Maybe mention that you must press the country. Other than that, it's nice
	Nope, fun thing to interact with
	When using vibration I caught myself also listening to the vibration of the motors. The loudness of the vibration is not related to the frequency, but it might fool people.
	No, not really
	No
	No *for vibration used sound instead of feeling*
	People might be confused as people's senses are different.
	Vibration, especially the smaller countries, is sometimes hard to feel if it's on
	Sweden did not evenly get warm, which took me some time to figure out. At first, I thought it did not get warm until I touched the country a bit higher. For the motors, For me, it was more hearing than feeling.
	Touching a metal surface whilst it is plugged into a socket is always a bit sketchy. *Everything is checked and safe, no wires are touching or are close to the metal, besides, lower, and safe voltages and currents are used*. The intensity of the motors

	is a bit dependent on the tilt. For someone who is not that good at topography, maybe indicate which country is which.
	No
	Vibration pattern like it is now is easy to hear. Might have been better to change the frequency of the motor itself or else the intensity. For temperature maybe it would have been nicer to have the whole country out of metal, as it would more evenly get warm.
	Don't know if the heating was done after 3 minutes, perhaps if you waited a little longer the difference would have been a bit bigger
	Not really
	Did not know what to expect as to how warm the countries would get. But other than that, no.
	No