Friction and Resistance as modalities for Physicalizing Data

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Bachelor thesis Creative Technology

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ABSTRACT

The field of data Physicalization is a novel field which aims to study the physical representation of data. Existing research in the field indicates several benefits of data Physicalizations compared to conventional data visualization, including increased cognition and perception of the data. Data Physicalization also shows potential in making data more accessible to users that struggle with visualization, as its physical nature is perceptible by a broad group of users. Research into the physical modalities, modes in which data is experienced or expressed, was found to be lacking. This thesis aims at studying two modalities, resistance, and friction, which could potentially be effective in communicating data to users. To study these modalities, a Physicalization was designed by following the Creative Technology design process, a framework for designing novel solutions using existing technologies. The process includes the phases ideation, specification, realization, and evaluation. The effectiveness of both modalities was evaluated with users in terms of accuracy and effectiveness, while the entire Physicalization was validated in terms of user experience, fatigue, and task load. Neither modality was found to be significantly more accurate or efficient. Most users preferred reading data through resistance, although the concepts for both modalities will need to be re-evaluated for a more accurate result. Overall, the Physicalization as a whole was very well received.

ACKNOWLEDGEMENT

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CONTENTS

LIST OF FIGURES

List of Tables

1 INTRODUCTION

Data Physicalization, also known as physical visualization, is an emerging field of study aimed studying the use of physical representations for communicating and exploring data. A data Physicalization can be defined as a physical artifact whose geometry and material properties encode data. Data Physicalization has shown potential in being a more efficient tool in communicating data than conventional visualization methods [30]. The main benefits are found in the ability to utilize motor skills, depth perception, and non-visual senses such as touch. Another major advantage is that data Physicalization, compared to data visualization, is able to take an intermodal approach to conveying data [1], meaning multiple data output devices providing a cohesive multisensory experience.

Important will be to understand how data Physicalization can be effectively utilized for communicating data. For this reason, the modalities with which the data is conveyed need to be studied, as there is an inherent lack of research on this. Here it is necessary for the accuracy and efficiency of the modalities need to be studied and compared. Further representational context, meaning factors relating to the Physicalization built around the modalities, need to be evaluated in order to validate the concept. These factors can include subjective experience, task load, and fatigue.

1.1 OBJECTIVE AND RESEARCH QUESTIONS

The objective of this research is to study two physical modalities for encoding data on which no research currently exists: friction and resistance. A data Physicalization was constructed to test these modalities for their effectiveness, meaning accuracy, efficiency, and user experience. A comprehensive evaluation was also conducted to validify the Physicalization built based on a number of subjective mental and physical factors as experienced by the user.

The research question for this thesis is then:

Which of the modalities of friction and resistance is more effective when conveying data?

With sub-questions:

- *Which of the modalities of friction and resistance is more accurate when conveying data?*
- *Which of the modalities of friction and resistance is more efficient when conveying data?*
- *Which modality do users prefer when interacting with data?*

1.2 THESIS OUTLINE

The thesis will provide a detailed overview of how the Physicalization was conceptualized, built, and evaluated. In chapter 2, an overview will be provided of the state of the art and relevant frameworks within data Physicalization, in order to provide a better understanding of which principles the field is built upon. The methods and techniques used for the development of the solution as well as for the evaluation of this solution are discussed in chapter 3. To give a better understanding of how the solution was conceptualized, built, and evaluated, the entire process will be discussed, including ideation, specification, and realization. Chapter 4 covers the initial brainstorming phases and the concepts that were developed, along with a final concept that was chosen. In chapter 5, the concept was further specified based on requirements, both functional and non-functional. These requirements were developed through initial prototyping and scenario-based design. The interaction flow of the Physicalization is already detailed in this chapter. Chapter 6 details the installation built, its functions, and components. The installation was evaluated with users, a process which chapter 7 discusses. The results of this evaluation are covered in chapter 8, with additional discussion points and recommendations for future research considered in chapter 9. Finally, a conclusion will be drawn based on the research and its results.

2 BACKGROUND RESEARCH AND RELATED WORK

2.1 WHAT IS DATA PHYSICALIZATION?

There are multiple definitions of data Physicalization that can influence the interpretation for design. The most common definition is "a physical artifact whose geometry or material properties encode data." [1], which can be broadly interpreted as any physical object which represents data. Another broad interpretation is given by Danyluk et al. [2], defining data Physicalization as a representation of data with real objects in physical spaces. This is a more general view of any physical object being designed for or used as a representation of data. López García & Hornecker [3] define it focussed more specifically on the ability to physically interact with the object, allowing for touching, holding, feeling, and moving around it. In this way, a data Physicalization is explicitly designed for physical interaction, while also representing the data. In all definitions a data Physicalization is a physical object which represents data.

2.2 WHAT ARE THE MAIN CHALLENGES OF DATA PHYSICALIZATION?

While data Physicalization borrows in many ways from existing fields of research, such as tangible interfaces and data visualization, and uses many existing enabling technologies, such as shape-changing interfaces, fabrication technology and haptics, it is very much its own field of research [1]. Unlike solutions within these fields, data Physicalization allows for more active interaction in exploring the data. Designing for physical interaction such as hand, head and body movements make this active perception possible [8]. While guidelines exist for designing both visualizations (see [8] for a comprehensive overview) and to a limited extent for haptic representation of data [10], understanding how data can be encoded and effectively represented by a range of physical modalities is a challenge specific to data Physicalization, and one that this paper aims to explore.

2.3 WHAT ARE THE MAIN BENEFITS OF DATA PHYSICALIZATION?

The most agreed on benefits of data Physicalization are in cognition and perception [3]. mentions that the Physical form allows strengthens motor memory and affordances. Likewise, Danyluk et al. [2] point to memorability and effectivity of interaction as advantages of data Physicalization. Expanding on this, Jansen et al. [1] discuss possible societal benefits such as making data more accessible and engaging large audiences. It is worth noting however that the amount of research supporting these benefits is lacking but does show potential.

2.4 SHAPE-CHANGING INTERFACES

Many Physicalizations are static, meaning they are able to physically represent the data, but this data cannot be modified after it is created. Controlling the geometry of a Physicalization would allow for a more dynamic way to show data, for example by showing different variables or showing the same variable over time. The research area of shape-changing interfaces provides an insight into how interacting with a system can be less abstract and more dynamic, as well as give a good overview of enabling technologies that can be used to convey data through shape-changing properties in a Physicalization.

Similar to data Physicalization, many shape-changing interfaces attempt to communicate information. Other functional purposes for using shape-changing interfaces are dynamic affordances, allowing for more possibilities of interaction, and haptic feedback. Hedonistic purposes, such as aesthetics and emotion, and explorative purposes, for conceptual experimentation into shape and material, are also reasons for using shape-changing interfaces [11].

There are a number of examples where deformable material properties are used as interface. Jamming user interfaces [12] introduces a malleable user interface where the stiffness of a material is used for haptic feedback and deformation as input. Materiable [13], as shown in figure 1, utilizes bars which emulate the physical properties of the material is representing, allowing for an enhanced experience in the presentation of spatial data. More common are interfaces which can control its shape or geometry, such as inForm [14], which through motorized bars guides by dynamically constraining users, which facilitates interaction, and can manipulate external physical objects. PneUI [15] uses pneumatically actuated soft composite materials to develop concepts which can both sense input and dynamically change its shape.

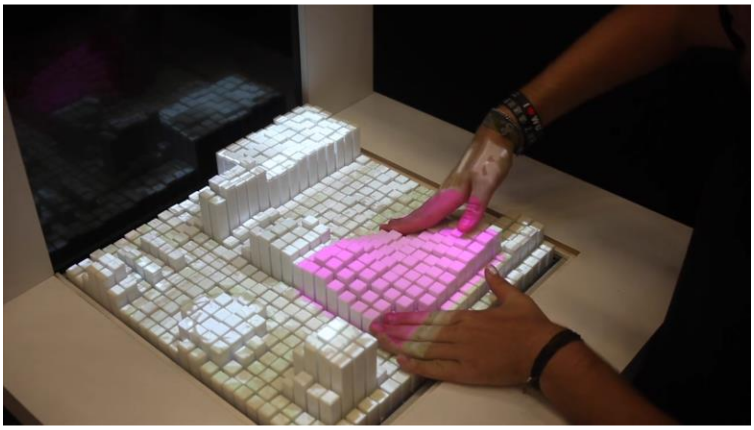

Figure 1: Materiable emulates properties of materials [13]

2.5 Non-visual physicality of data

Through Physicalization, data can be represented in a way that is comprehensible without visual cues or can enhance the existing visual element with a physical one. Common examples of where non-visual data representation already exist are found within sonification and haptics. Within haptics, feedback is given from a system to the user such that it is comparable to physical interaction that it represents.

For presenting non-visual information through haptics, vibrotactile messages can be used. They can be used where vision is not possible or not the most optimal solution. Structured vibrotactile messages, also called “tactons”, can be encoded by manipulating the parameters of the vibration. Both rhythm and location have shown to be effective stimuli for communication [4], as well as different waveforms when designing for texture [5].

Multiple studies show the effect that non-visual representation of data can have on a number of factors. DataBox, a wireless cube device that was built using haptics and auditory feedback to represent air pollution, facilitated more discussion about the message behind the data than a conventional visualization [6]. Vital + Morph translates physiological data into a concept which combines a shape changing tangible interface with a haptic Physicalization for social impact [7].

2.6 Modalities of friction and resistance

Research exists which utilizes friction and resistance in representing data, but not as direct representation of the data itself. Fabricated, static Physicalizations could allow for these modalities, for example by using springs or gravity, but there is no existing research. Dynamic Physicalizations often use force to position a data representation in a certain way, for example when using physical bar-charts. Madgets [16] used moveable and configurable tabletop magnets that can be used for actuation through force-feedback and vibration. This concept can be observed in figure 2. As discussed, stiffness, which is closely related to resistance, has been studied in the context of shape-changing interfaces. However, there is no research on the ability of these modalities to directly convey data, such that a user can perceive a certain pressure or resistance and gain insights into a topic. There are informal guidelines for these modalities, which propose that friction and resistance are likely only suitable for ordinal data, and that representing nominal data would be inappropriate [10].

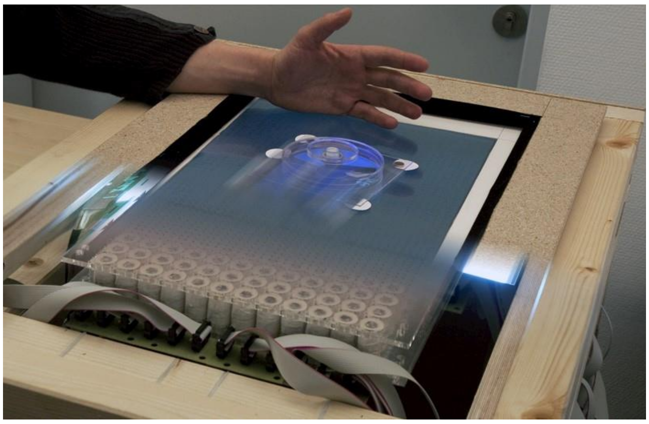

Figure 2: Madgets concept, magnets used for actuation [16]

2.7 CONCLUSION

An overview was given of data Physicalization and its related fields. Examples of Physicalizations and relevant enabling technologies were given to illustrate the possibilities within the field. In understanding how to design a Physicalization, it is important to be aware of these technologies. It is also important to understand the potential benefits of data Physicalization and the current challenges within the field.

Many technologies and research within fields such as shape-changing interfaces and haptics point to the benefits non-visual data presentation can have, data Physicalization provides an interesting option to achieve this. While the non-visual technologies within the fields of haptics and shape-changing interfaces are built for feedback and interaction respectively, the same manipulation of material properties can be used to represent data. For the modalities that this project aims to explore, namely friction and resistance, no existing research exists within data Physicalization. Studying the effectivity, as well as other factors such as engagement and memorability, should give a clearer perspective on when these modalities can be employed to portray data.

3 METHODS AND TECHNIQUES

Building on the knowledge from the background research and the related work, a Physicalization can be built. Using the design process for Creative Technology [17], which can be utilized to make use of existing technology and combine it in novel solutions, designing the Physicalization is structured into three distinct phases.

The core of the Creative technology design process consists of ideation, specification, and realization, which combines converging and diverging designing with a semi-cyclic process. The structure of ideation leading to specification, which in turn leads to realization and finally evaluation, allows for backtracking between the stages. Results of evaluation in any stage can lead to adjustments in previous stages. The structure of the design process can be seen in figure 3.

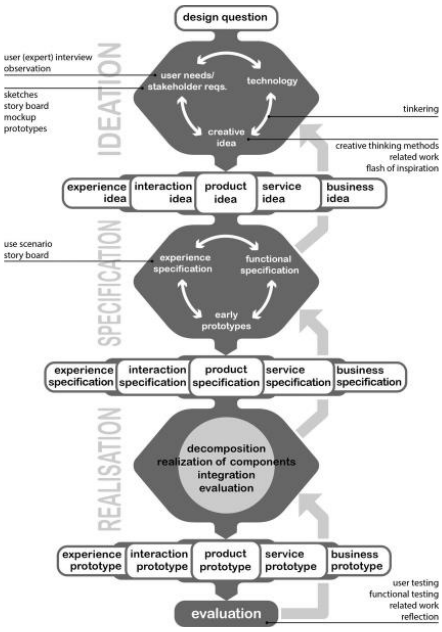

Figure 3: the Creative Technology Design process

For the ideation stage, novel applications are identified for conventional or innovative technologies. Here the existence of the technology enabling the application is the starting point for the design process, which is the case for data Physicalization as it combines existing technologies into a novel concept. During the ideation stage different ideas are brainstormed, and possibly already evaluated with users. The result of the ideation phase is an overview of what the solution could look like in the form of an elaborated project idea, where requirements, experience and interaction are all taken into consideration. The ideation phase of this project is covered in chapter 4 of the thesis.

In the specification phase early prototypes are built. For the Physicalization, multiple ideas can be explored for actuating for a certain modality. Evaluating the core of the user experience is main driving factor. These early prototypes can be evaluated with users and a final design for the Physicalization can be chosen.

After the product specification is given, a full prototype (or multiple full prototypes) can be built in the realization phase with the required components and requirements. Evaluation of whether this prototype meets the requirements from the specification phase used to ensure that the prototype is consistent with the preceding phases of the design process.

Finally in the evaluation phase, functional testing can be performed as well as testing whether the requirements that were discovered are met. User testing will be used to test how effective the modalities of friction and resistance are in terms of information retrieval how accurate they are. In addition, the evaluation will include testing on how both modalities are experienced by the user. The evaluation phase also includes reflection, both for academic and personal progress.

For data Physicalization, the additional dimensions of choice of modality, representation intent and human-data relations will be applied during the ideation and specification phases, as it allows for a more focused perspective for designing multisensory data representations [18]. Through these dimensions a design more specifically aimed at utilizing more than one sensory channel, in this case vision and touch, can be created.

4 IDEATION

For the ideation phase the Creative Technology design process [17] was used together with the design space that Hogan & Hornecker [18] discovered, which aligns itself along three axes: choice of modality, representation intent and human-data relations. These three axes are used to make design choices when creating multisensory data representations, considering the core of the data relating to the chosen modality and the intended interaction, and form the initial specification used before the concepts were developed.

Before this the dataset and other specifics were chosen based on initial brainstorming and discussion with supervisors.

4.1 BRAINSTORM

Before the concepts were developed, certain aspects of the design were already considered, such as the type of data, datasets, variables.

4.1.1 Type of data

The choice for geographic data was made based on the availability of existing visualizations and guidelines for visualizations that exist for this type of data, as well as the benefits that data Physicalization has shown to have relating to this type of data. When designing visualizations, in particular 2D maps, there is a huge base of knowledge on works and what does not, such as whether certain visual variables are suitable for qualitative or quantitative data [20]. There is also already a growing amount of data Physicalizations of geographic data that already exist, see for example [21][22][23]. The potential benefits of stimulating engagement, collaboration and reflection make data Physicalization a good method for conveying this sort of data.

4.1.2 Dataset

The central bureau for statistics in the Netherland (CBS) publishes a dataset containing a comprehensive overview of key figures on district, neighborhood, and municipality level [24]. Included in this dataset are statistics on poverty, type of housing, and general demographic statistics such as age. This data was chosen as it is the most complete dataset covering the Netherlands, with large amounts of variables to be represented for synthesis by the user. Because the dataset is often published incomplete, with certain statistical data not added until it has been processed, the most recent complete dataset is currently from 2019. Additionally, the Dutch Police publishes crime data annually on district and neighborhood level [24].

Based on the substantial number of municipalities in a province and districts in a municipality, neighborhood level was chosen as the most practical scale. The number of neighborhoods in a municipality is often less than 10, which allows a Physicalization to be built that covers every relevant datapoint. Interaction with the data should allow for an interesting overview of the municipality that is represented, providing insights in the determining characteristics of each neighborhood.

4.1.3 Variables

The choice for variables was made based on the available variables in the datasets. The most interesting data from the CBS dataset are related to socio-economic indicators such as the percentage of low-income households, labor participation, average car ownership, and percentage of house ownership. From the Police database on crime, distinct categories of crimes and misdemeanor are given. For the sake of simplicity, the total number of crimes for each neighborhood is taken as variable.

4.2 INITIAL SPECIFICATION WITHIN DESIGN SPACE

4.2.1 Choice of modality

Through literature review and inquiry into the state of the art, a gap was discovered in the research. For many non-visual modalities there is no research into how effective they are at communicating data and the experience of the user when interacting with them. The modalities of friction and resistance were chosen based on initial concepts and consideration. Since the Physicalization will present geographic data to the user, the name of the location will have to be represented in combination with the tangible data where sound, sight, and touch (Braille) were options. Sight was chosen as the most accessible option, as touch present significant challenges for design and sound is a non-persistent representation.

A distinction to make in the choice of modality is the one between representation modality and sensory modality. Representational modality is the format, material or medium in which the data is represented, sensory modality is the sensory channel through which the data is perceived by the user. In some cases, these two are different, for example when data can be touched but is only viewed by the user. For the representation of friction and resistance, the representational and sensory modalities are intended to be the same.

In designing a Physicalization, the materiality of the data can be taken into consideration and used as part of the representation of the data. For friction and resistance, both modalities rely on material properties to translate the data. As mentioned before, shape-changing interfaces have been used to mimic the physical properties of a certain material [13]. In the same way, the counteracting force felt by the user when interacting with resistance can in this same way represent properties of materials. The main property of friction, meaning a user moving their hand or finger over a surface, is the intensity of this friction. Surface roughness or material type can also influence this perceived friction. In these ways the concepts chosen will close the metaphorical distance to the data.

4.2.2 Representational intent

Representational intent covers the motivation for creating the data representation as well as the purpose of interacting with it. This intent can be classified as either Utilitarian or Casual, where a Utilitarian approach attempts to study utilitarian factors and convey information clearly and a Casual approach seeks to invoke an emotional reaction or discussion related to the data.

The intent is to study both the effectiveness and the experience of the Physicalization by the user, meaning a case can be made for the suitability of both sorts representational intent. A good comparison to make is a data Physicalization that was built to show water usage to create a sense of awareness on the topic [19], like the intended concept of this project. A creative, playful design was used but the primary purpose was still to convey a certain set of data and create awareness, meaning it could still be viewed as utilitarian. The intent of this project, to portray data clearly to study accuracy, efficiency, and user experience, is similar to this, so it could be considered most accurately as a utilitarian representational intent.

4.2.3 Human-data relations

The way in which humans interact with the data, and the nature of the data used, need to be considered when designing a Physicalization. The way in which the user interacts with the data representation can be active or passive. A representation is passive if it requires the user to intentionally interact with it to interpret the data and passive if does not (fully) require the user to interact with it. The nature of the data can be either static or dynamic. Static data comes from a fixed data source and is not updated often or at all, while dynamic data is live data that is continually updated.

For the concept, the modalities of friction and resistance need to be actively interacted with through touch to interpret the data. The data itself will be static, coming from a yearly published dataset there is little reason to continuously update the Physicalization as this would practically never influence the experience of the user.

4.3 CONCEPTS

Before the final concept was chosen two other concepts were developed and evaluated.

4.3.1 Concept one

For the first concept some alternative actuators were evaluated for the modalities of force and resistance. In representing both force and resistance, a linear solenoid was considered. Solenoids are commonly employed for locking mechanisms, as when a current is introduced, a magnetic field draws a metal rod in. If a Pulse Width Modulation (PWM) signal is used however, both the speed of this motion and the force can be controlled, allowing it to resist an outside force until a certain extent and apply a certain force to the user. This way both modalities could be embodied by one actuator as shown in figure 6.1. Practically however, this force is hard to control as there is not a linear relation between the current applied and the force applied, meaning it would be a practical uncertainty whether this relation could be derived. Additionally, if the current applied is too high, the rod could extend rapidly and hurt the user. For this reason, the concept was abandoned.

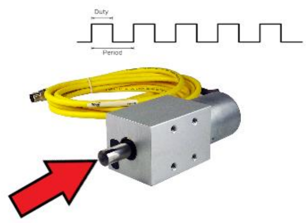

Figure 4: solenoid concept

4.3.2 Concept two

For the second concept the electromagnet was identified as a suitable alternative to the solenoid for resistance. For force, the idea of a lateral or vertical force was abandoned in favor of a rotational force, for this a DC motor can be used. The concept combines both actuators into a single concept, where the user can directly compare both modalities. The DC motor is attached to a wheel which the user can touch, and the electromagnet is interacted with by the user moving a magnet towards it, feeling the resistance of the electromagnetic field. Both the rotational force and the electromagnetic field can be controlled with an Arduino.

4.3.3 Final concept

Concept two was adapted, separating the electromagnet and the DC motor as the electromagnetic force would interfere with the motor, since it operates using magnets. This also allows for both modalities to be more separated in a within-subject study design, which might be clearer. The electromagnets and DC motor constructions will be mounted on a map of the municipality represented, most likely Enschede. In this way there are two Physicalizations, one for resistance and one for force. The final concept is illustrated in figure 6.2

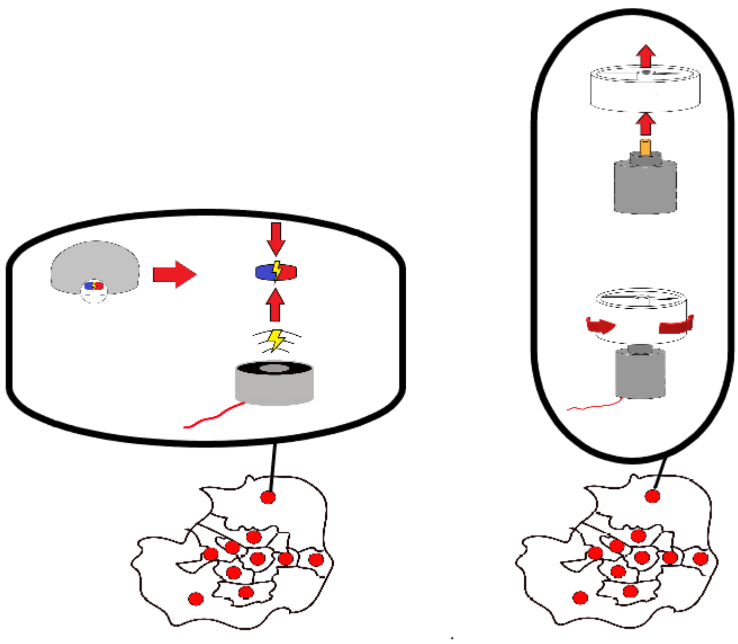

Figure 5: final concept

4.4 Conclusion

The different processes of ideation were described, from the initial selection of data to represent to the final concept.

Data on neighborhoods within a municipality was chosen based on the availability of a large, comprehensive database and the number of projects already using maps in Physicalizations, showing the potential it can have for this type of data. This also allows for a manageable quantity of datapoints for representation. Socio-economic indicators and criminality were chosen as variables based on the comparisons; they allow on neighborhood level as well as the availability of these variables within the datasets.

To further specify the Physicalization, taking the essence of the data into consideration, requirements were discovered by considering the choice of modality, representational intent, and human-data relations.

In the end, three concepts were developed and discussed with supervisors. The final concept that was chosen consists of two Physicalizations; one using an electromagnet to create resistance, and one that uses a DC motor to create a rotational force with which the users interact. These systems will be placed on a map of the municipality of Enschede and will allow users to compare neighborhoods across certain socio-economic variables.

5 SPECIFICATION

Specification builds upon the ideation chapter by considering functional and non-functional requirements in more detail based on the initial final concept(s). The main way that these requirements are set up is by prototyping. Because prototyping is an iterative process, adjustments can be made and quickly tested based on the requirements. At the same time, new requirements can be discovered. In this case, one prototype was built and improved upon until a final design was reached. This improved final design is covered in detail.

5.1 FORMULATION OF REQUIREMENTS

Based on initial plans for evaluation and the final concept from the ideation phase, initial requirements become apparent. A user test that could be performed in a reasonable timespan (~1 hour) necessitate an intuitive and uncluttered installation for the user to interact with. For this reason, and because the magnets were found not to interfere with each other, both modalities would preferably be included in the same Physicalization and should be easily switched between. For comparing the Physicalization two types of data are compared, numerical and categorical with tasksets for both. Two datasets are therefore necessary for the experiment. Before the experiment, the user would first need to become familiar with the Physicalization. Another dataset is used for this familiarization, so the installation would have to include three datasets that the user could choose from.

During the initial stages of prototyping more requirements were discovered. The size of the Physicalization would have to accommodate for the relatively large amount of data points, also taking into consideration the size of the hardware required and wiring.

Further requirements were discovered based on user-centric scenarios developed by taking envisioned interaction as a starting point. Using the final concept from the ideation phase, requirements were found such as that the Physicalization should be easy to understand for a variety of users and that it should allow the user to get familiar with interaction before the start of the experiment. The installation should also allow for quick switching between modalities, datasets and datapoints, as otherwise some users might take a lot of time during the experiment.

5.1.1 Scenario's

Scenarios were constructed in order to consider the requirements that might arise in interacting with the prototype before it is built. These scenarios allow for a better understanding of different motivations and needs that users might have and apply them to the design.

Scenario 1: HCI student interacting with final concept

Name	Kim
Age	21
Gender	female
Occupation	student Creative Technology
Experience with technology	High, has interacted with a data Physicalization before

Kim is a third-year student of Creative Technology. With lots of experience interacting with interactive installations and having designed a data Physicalization in her second year, she is familiar with prototypes similar to the final design. Before, she has also conducted HCI research with human participants, meaning she is aware of how a user test is conducted.

To Kim, the Physicalization is intuitively easy to use, taking only a little while to get used to its functions. Kim is able to switch between neighborhoods while having the right modality and dataset selected and understands what is asked of her during the experiment.

Scenario 2: non-technical student interacting with final concept

Name	Jules
Age	24
Gender	male
Occupation	student Psychology
Experience with technology	medium, has never interacted with a data Physicalization

Jules is quite skilled at using the latest technology but does not have much technical knowledge beyond that. His knowledge of data Physicalization is non-existent, but he is able to quickly understand the concept. His background in Psychology extends to his ability to grasp the contents and procedures of the study quite quickly.

Still, Jules struggles initially with interacting with the Physicalization, as reading data from a magnet and a motor is vastly different to his usual interactions with technology. As soon as he understands how to use the installation, he is able to read the data, yet still might struggle with having the right dataset and modality selected.

Scenario 3: middle aged car mechanic

Name	Martin
Age	52
Gender	male
Occupation	car mechanic
Experience with technology	low, has never interacted with a data Physicalization

Martin has limited understanding of modern technology. He uses a computer for work but often struggles beyond the tasks he does on a daily basis. Beyond this he does work in a technical field but does not know the inner workings of many of the machines that he uses. The concept of data Physicalization is hard for him to grasp. When it is explained to him using the installation, he understands the basic concept.

Interaction with the installation is a complicated process for Martin. At first, he uses the magnets and motors in ways that they are not intended to be used. He often pushes buttons he has already pushed and takes a long time to read the data from both modalities. He often forgets the data he has just read and has to go back to re-evaluate.

5.1.2 Non-functional requirements

The Physicalization should:

- Users should be able to interpret and understand data encoded in Physicalization
- be large enough to fit for the required electronics and wiring
- display a map of Enschede containing all ten neighborhoods
- Not be physically demanding to use
- Not be mentally demanding to use
- Be interesting and enjoyable
- Be easy to use and non-obstructive for studying the modalities of friction and resistance

5.1.3 Functional requirements

The Physicalization should:

- Be suited to study the efficiency of friction and resistance in conveying data
- Be suited to study the accuracy of friction and resistance in conveying data
- Allow users to switch between datasets
- Allow users to switch between modalities
- Allow users to switch between neighborhoods
- be able to show three datasets

5.2 Interaction functions

Interaction with the installation consists of the user completing tasks by reading data from the Physicalization. Users should be able to switch between datasets and modalities and select the neighborhood in Enschede from which they want to read out the data. The interaction flow of the interaction can be seen in figure 4. The interface with the dataset and modality selection can be seen in figure 5.

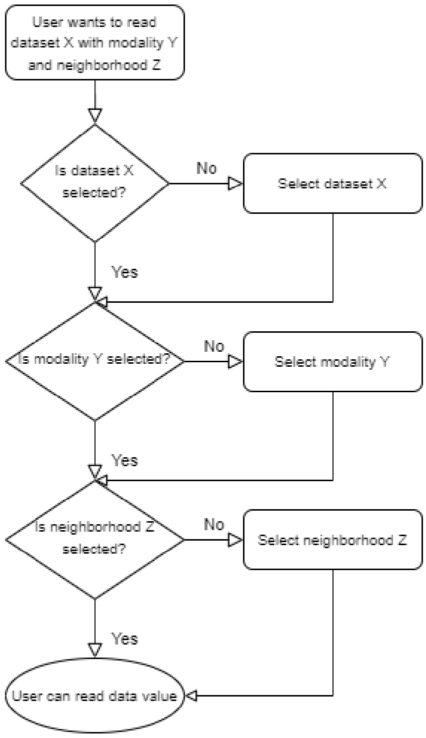

Figure 6: envisioned interaction flowchart

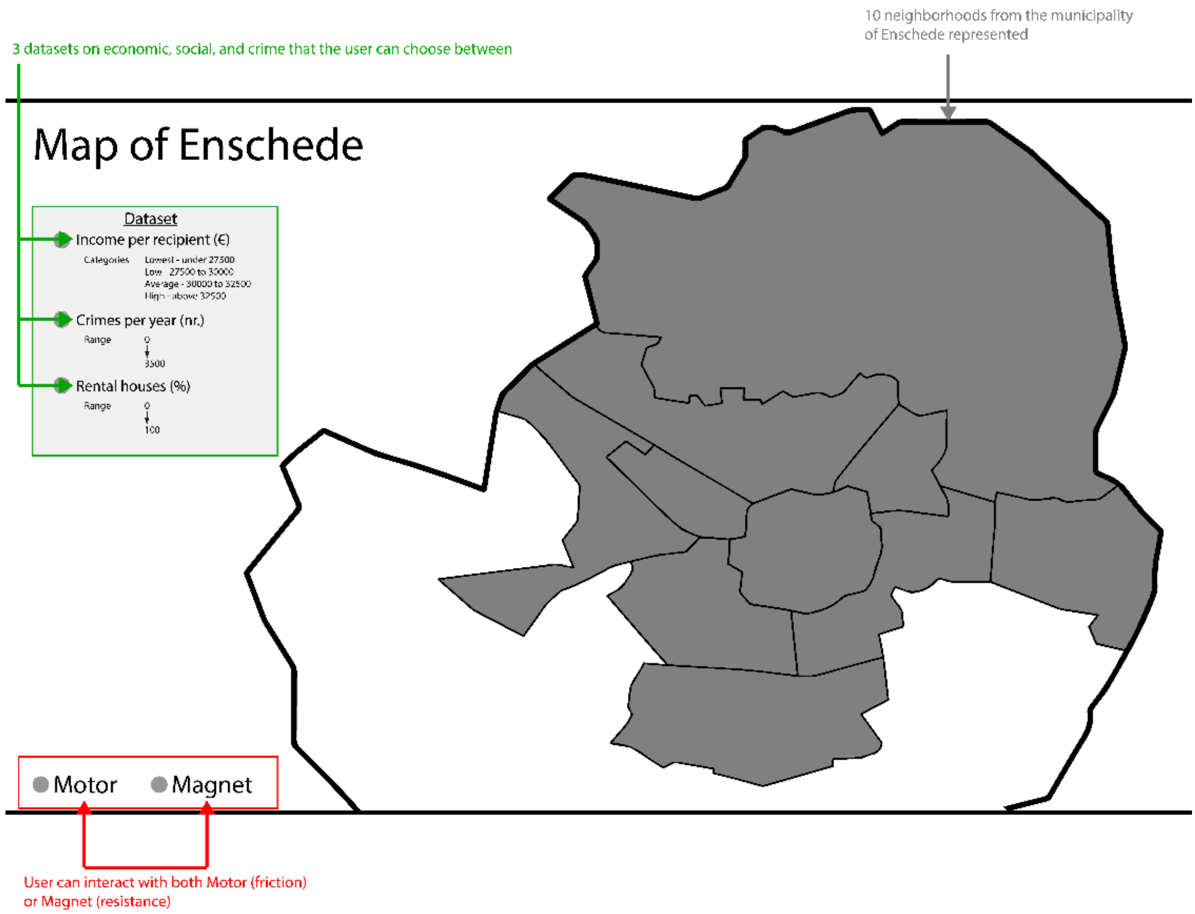

Figure 7: diagram of dataset and modality selection

Interaction with the modalities is discussed in section 5.3.1 (resistance) and section 5.3.2 (friction).

5.2.1 Resistance

The Physicalization aims at studying how the resistance a user feels when enacting a force can be used to convey data. For this project, electromagnets were chosen for this purpose as they present an intuitive way to create a force with which the user can interact. Data represented by the magnet can be scaled according to the strength of magnet, where the range of force that the user has to apply is pleasant. This range needs to be large enough for the user to be able to detect the differences between data values, and the lowest value communicated to the magnet also needs to be observable by the user. Because the magnetic field generated attracts flat metal objects best, there will have to be metal plate that is easy for the user to hold and large enough for the magnet to attract. Figure 6 shows the magnet in the context of the whole installation.

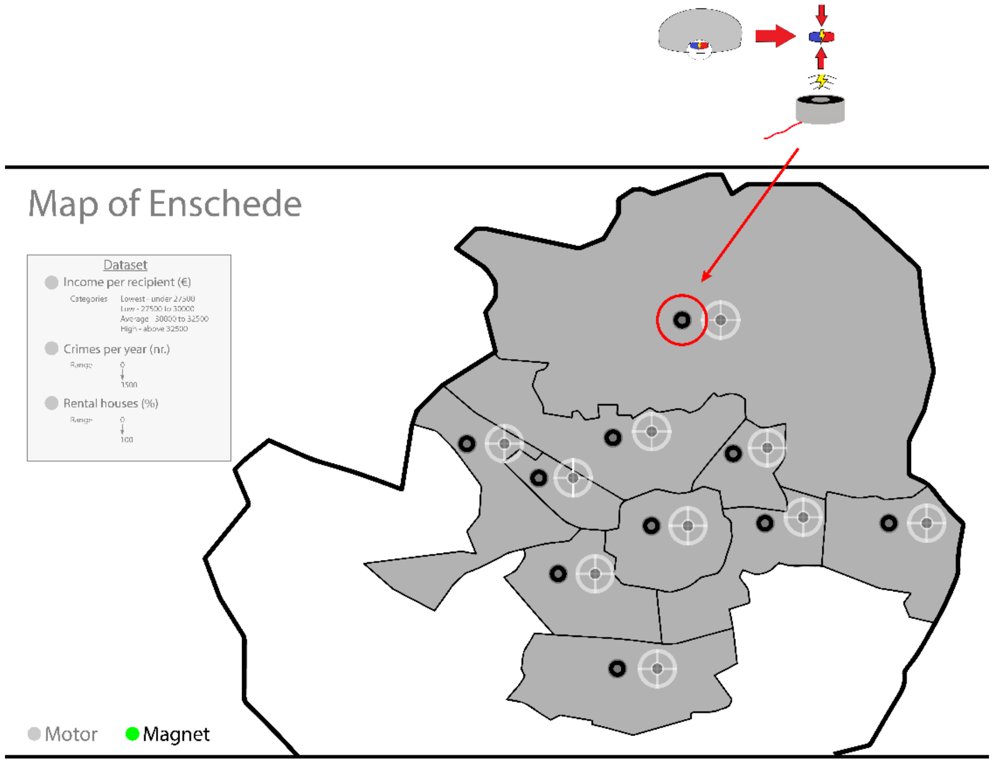

Figure 8: interaction with magnet

5.2.2 Friction

For studying how friction can communicate data, a motor is used with a 3D-printed wheel which the user can touch. The interaction of the motor with wheel can be seen in figure 7. Here the same principles can be applied as for the magnet, as the range of force that the motor creates needs to be pleasant to the user. It must also accurately convey data values, where differences between data values are observable by the user. Here the data is linked to the speed of the motor, where a higher speed is experienced as more friction, which translates to a higher data value.

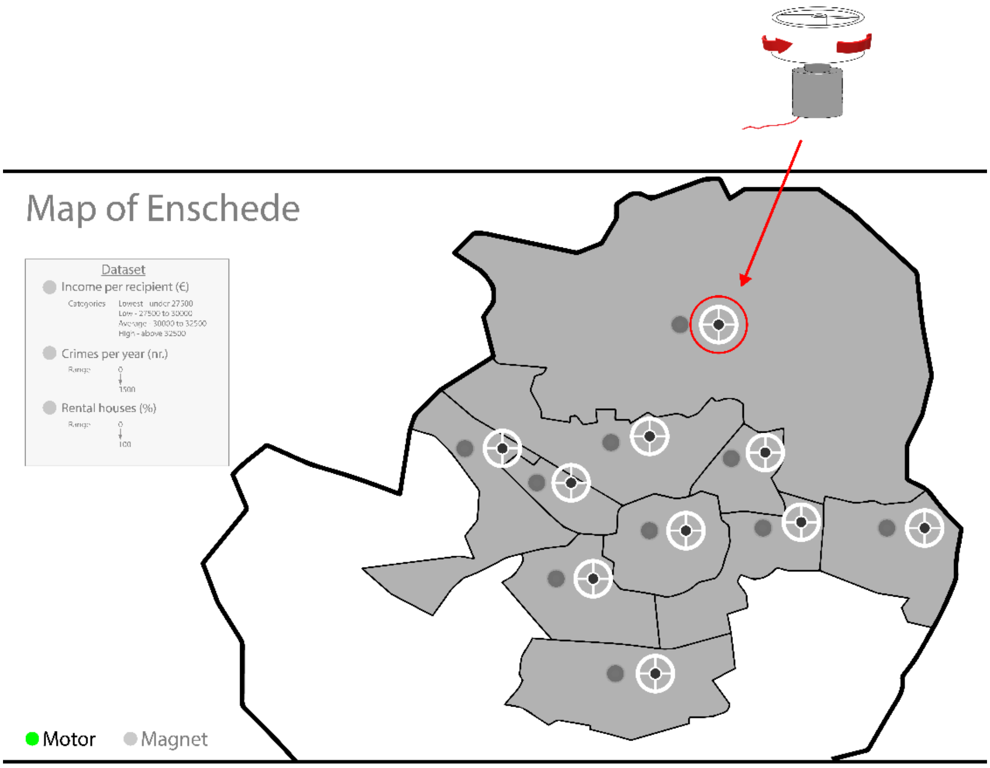

Figure 9: interaction with motor and wheel

6 REALIZATION

For the testing prototype, some adjustments were made based on practical considerations, most importantly the use of motor shields for controlling both the motors and the electromagnets. Components were selected and ordered based on the requirements from section 5 and a Physicalization was constructed that would allow for the evaluation of friction and resistance for conveying data.

6.1 ELECTRONICS: SELECTION OF COMPONENTS AND CONNECTIONS

6.1.1 Microcontroller

The Arduino platform of microcontrollers is accessible and suitable for rapid prototyping. In addition, many components have libraries available due to the platform's popularity. Arduino's have Input/Output (I/O) pins that can easily be configured, with useful features such as internal pull-down resistors and Pulse Width Modulation (PWM). For these reasons, and the researcher's affinity with the platform, an Arduino was chosen for the project.

Due to the large amount of wiring required for ten motor shields, fifteen buttons and 5V and ground lines, the choice was made for an Arduino Mega. Compared to the standard Arduino Uno, the Arduino Mega has an expanded I/O input array of fifty-four digital pins, fifteen of which can provide PWM output. For all buttons and motor shields, thirty-five conventional digital pins are required. The ten motor drivers also require an additional 20 PWM pins. Because this exceeds the amount of available PWM pins, the wiring for PWM is separate for the five motor drivers used for the familiarization phase of the experiments and the five motor drivers used for the experimental phase. The wiring is then switched in between these phases.

The Arduino Mega is powered by the external 5V power supply.

6.1.2 Motor drivers

Because both the motor and the electromagnet work on the same principles of electromagnetism, a Pulse Width Modulation (PWM) signal can be used to control both speed and magnetic field strength, respectively. When a lower PWM signal is sent, less voltage flows to the motor or magnet, resulting in a lower speed or a weaker magnetic field. Motor drivers are designed for driving motors and allow this PWM signal to control the speed of a motor. Drivers can also be used to reverse the motors.

For the installation, a 4-channel L293D motor driver was chosen based on the power it can supply and its ability to drive two motors. For each neighborhood, a motor driver is connected to the motor and the magnet. All motor drivers are connected to the Arduino through two wires for logic on/off and two wires for PWM, allowing both the magnet and the motor to be turned on/off and controlled based on a PWM signal. The motor driver also has a 5V and ground for power from the external supply. The connections of the motor driver can be seen in figure 8.

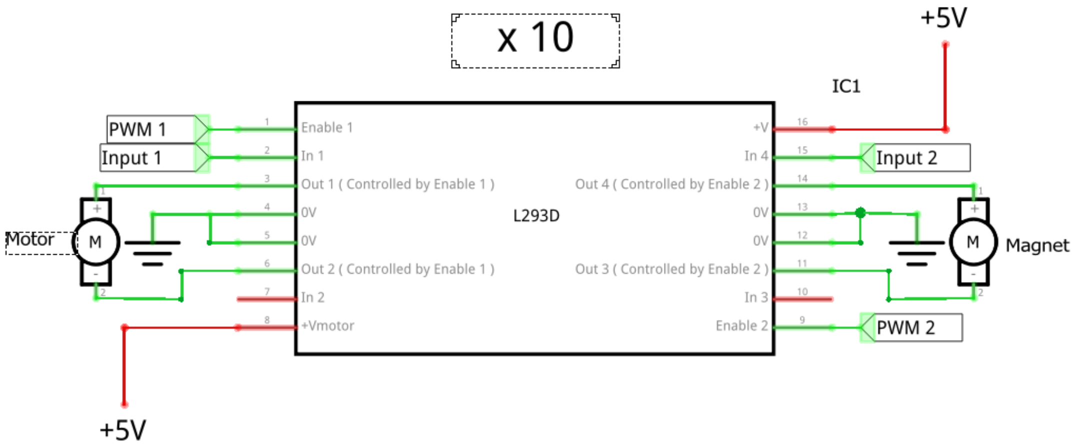

Figure 10: L293D Motor Driver connection

6.1.3 DC motors

To ensure that the installation was not uncomfortable to use, relatively weak DC motors were chosen. A generic micro-DC motor was selected based on this requirement, which operates at 3V to 6V at 0.35A to 0.4A. Holes which are the approximate size of the motor were laser cut into the wood plate, in which the motors are hot-glued. The placement of these motors can be seen in figure **XX**.

To facilitate the interaction, a wheel is attached to the motor's shaft through a press fit. Figure 9 shows a number of variations of the wheel that were printed, along with the final design chosen on the right. In the end, a small wheel was chosen as it requires less power to start turning and clutters the installation less. The downside of the weak motors is that the motors can stop if the user presses too hard on the wheel, to prevent this the user is specifically instructed to lightly touch the wheel.

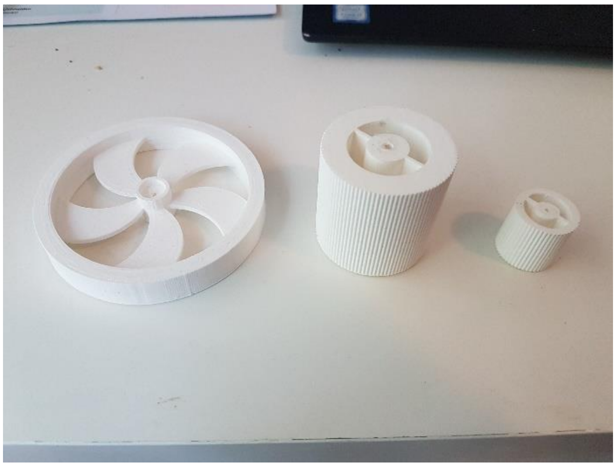

Figure 11: evolution of wheel attached to motor

6.1.4 Electromagnets

Electromagnets work similarly to DC motors, using a magnetic field to generate force. In the electromagnet, this field creates a holding force which attracts metal objects. Again, a fairly weak component was chosen for the prototype, so no discomfort or unnecessarily high forces are present. The DFRobot0794 operates at the required 5V, can hold 3kg and does not require much power. The magnetic force is felt most prominently when a flat metal object larger than the magnet is placed in front of it. The top of a common bicycle bell (see figure 10) was found to be suitable, while being a pleasant size and weight for tangible interaction by the user.

Figure 12: metal plate used for interaction with magnet

The magnets are fixed to the installation user using the included bolts and washers, meaning they are securely fixed to the wooden plate. This connection can be seen in figure **XX**. 5V and ground are connected to the L293D motor shield.

6.1.5 Buttons

The selection of the neighborhoods, datasets and modalities is possible through pushbuttons. These buttons are connected to ground and a digital pin on the Arduino. The internal pull-up resistors in the Arduino are used, meaning no resistors are connected. The familiarization and test datasets and neighborhoods are color-coded, blue for familiarization and green for testing. The connection of the buttons can be seen in figure 11 and the placements of buttons in figure **XX**. When a user presses a button, its state is communicated to the Arduino. The last button pressed for dataset, modality, and neighborhood is stored in the Arduino, meaning the user only has to select these once.

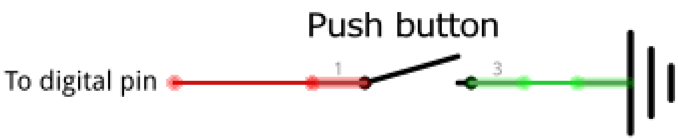

Figure 13: connection of buttons to Arduino

6.2 SOFTWARE

All coding for the installation was done for the Arduino and written in C++. A basic overview for the functions is the reading of the buttons, processing the logic of which dataset, modality, or neighborhood is pressed, and outputting the right PWM signal value to the right actuator. This sequence can be seen in figure 12.

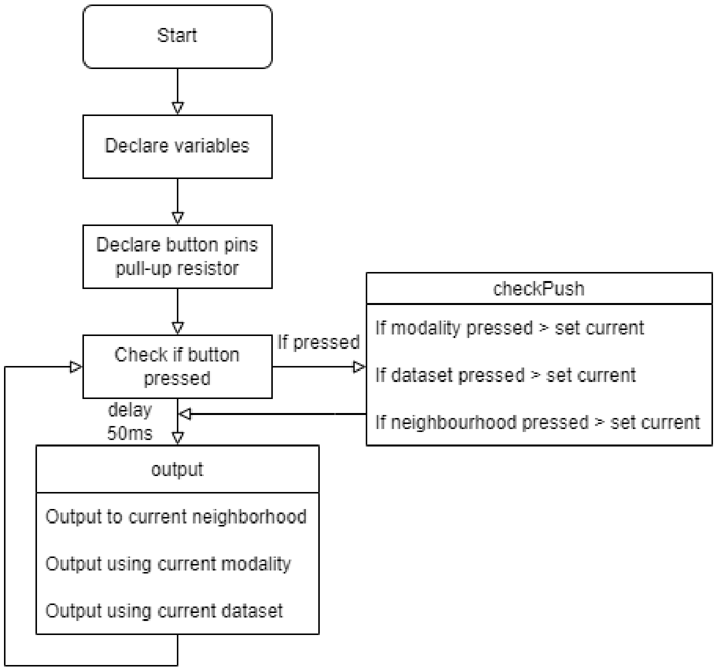

Figure 14: flowchart of the Arduino code

6.2.1 Reading buttons

Every time the code runs, which is about twenty times per second, the Arduino checks if a button is pressed. Before the program starts, all buttons are pulled to a “high” state to avoid the buttons from “bouncing”, meaning an incorrect button state is read because of noise. When a button is pressed, the Arduino therefore reads a “low” state. The function “checkPush” checks the buttons, but also translates the selected digital pin number into the right values for further processing, such as the neighborhood code, modality, or dataset selected.

6.2.2 Mapping & Data encoding

To translate the values from the dataset into a PWM signal that can be interpreted by the motor driver, a mapping had to be made. This PWM signal can range from 0 to 255, where the voltage drops from a 100% at 255 to 0% at 0. For all datasets, the data was mapped to the range of PWM values where 0 is mapped to the lowest PWM value felt by the user and the highest value in the dataset to 255.

Separate mappings were made to linearly distribute the data over the range of PWM values for both modalities. In initial tests of the motor, a value of 60 was discovered to be the lowest value at which the motor starts spinning. The mapping for the motor for a given data value:

$$60 + (\left(\frac{value}{maxValue}\right) * 195)$$

For the electromagnet, a value of 100 was found to be necessary in order to produce a magnetic field strong enough to be observed by the user. This mapping for a given data value is then:

$$100 + (\left(\frac{value}{maxValue}\right) * 155)$$

Values are linearly distributed over the PWM signal ranges with the exception of the income dataset set, which is categorized. A categorization was created based on the tasks for the experiment, which would require a minimum value, a maximum value, and two values in the same category. Because of the five neighborhoods represented by the installation, four categories could then be made. The mapping for this can be found in table 1.

Income category	Range	Neighborhood (# code)
1	< €27.500	00 & 03
2	€27.500 - €30.000	04
3	€30.000 - €32.500	05
4	€32.500 <	09

Table 1: categorization of income data

Because the data is static for this experiment, values are hard coded into arrays for processing by the Arduino. Because there are three datasets and separate mappings for both modalities, six different arrays are encoded. The Arduino takes the last dataset, modality, and neighborhood pressed and chooses the right value from the right array. This value is then sent to the appropriate motor driver through the PWM pin, which the driver translates into a signal that controls the magnet or the motor.

The full mapping of the data along with the original values can be found in appendix D.

6.3 TESTING SETUP

6.3.1 Wood plate

The electrical components were fit to a laser cut wooden plate representing the municipality of Enschede and its neighborhoods. This plate was scaled to the maximum size of the laser cutter, 100 cm wide and 60 cm high. The map was created in Adobe Illustrator, with cutting lines in hairline red and engraving possible through a greyscale. Neighborhoods and relevant information about the datasets are engraved into the plate. Holes were cut for the DC motors and the pushbuttons, with a small margin for the glue to allow for a secure fit.

A small counterbored hole was drilled to allow for the electromagnets to be screwed into place. Because the initial textbox containing the datasets did not cut out correctly due to formatting, an additional plate was laser cut containing only this section. The plate was glued over the original plate, meaning larger holes had to be cut for the buttons to fit through. The plate that was cut can be seen in figure 13, where the cut lines can be seen in red. Photos of the final result can be seen in figure 14.

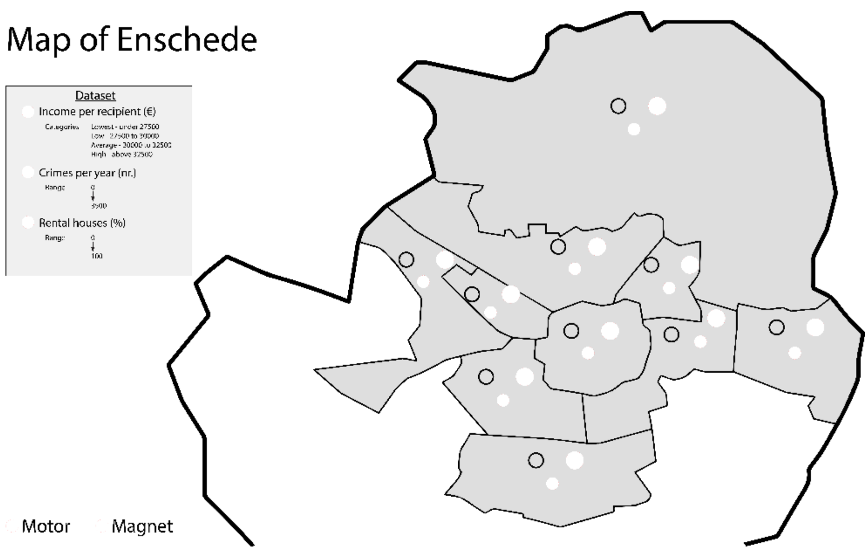

Figure 15: flowchart of the Arduino code

Figure 16: front of plate

For the datasets, the range and type of data are presented to the user. This was done to give an additional indication of the exact values that the user is exploring with the Physicalization, which is not possible using resistance or friction. This type of information also aids the experiment, as it requires the user to be aware of the categorical or numerical nature of the data. For the modalities, the user can select “motor” or “magnet”. It is not relevant for the user to know which corresponds to resistance or friction. The plate containing the datasets can be seen in figure 15.

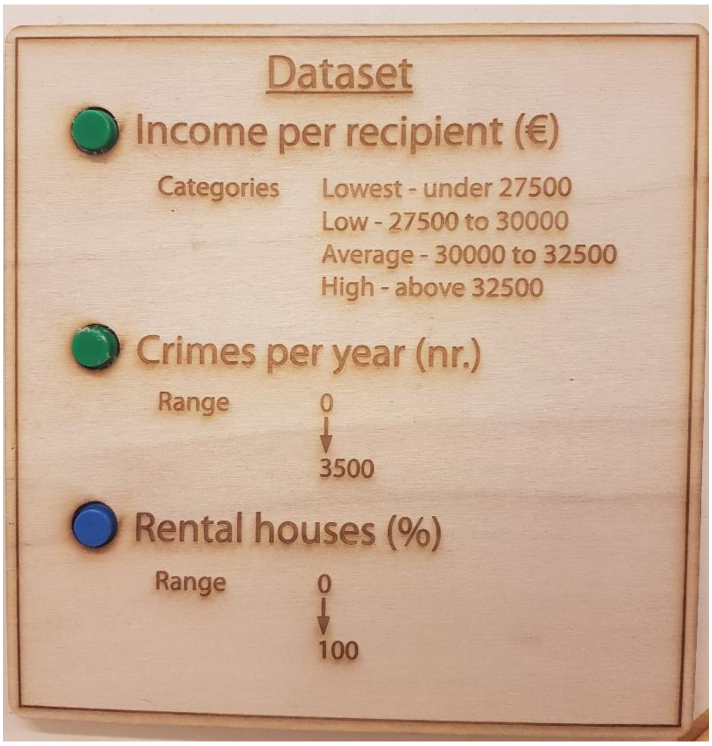

Figure 17: plate containing the datasets

6.3.2 Wiring and layout of electronics

On the back of the wooden plate all electronics can be seen. Every neighborhood with motor driver, magnet, button, and motor requires five wires to go to the Arduino. On top of this, there are 5V and ground wires, meaning an extensive network of wiring is present. Jumper wires are used to allow for easy attachment and detachment when necessary. Because the Arduino Mega does not have enough digital PWM inputs to accommodate all ten motor drivers, there is a group of PWM wires for both the neighborhoods used for familiarization and the neighborhoods used for the experiment, which are swapped out in between these phases of the user study. Wiring is color-coded per neighborhood for easier bug-fixing.

The Arduino Mega is fixed near the bottom of the plate and can be easily accessed for debugging and changing the code. All components, including the Arduino, are powered by a single 5V 0.5A switching power supply. A rail of 5V and Ground attaches to all component with red wires for 5V and black for ground. Glue was used to hold most components, with exception of the electromagnets, into place. This glue provides a sturdy connection to the wood plate while being relatively easy to remove. Attachments of these components can be seen in figure 16.

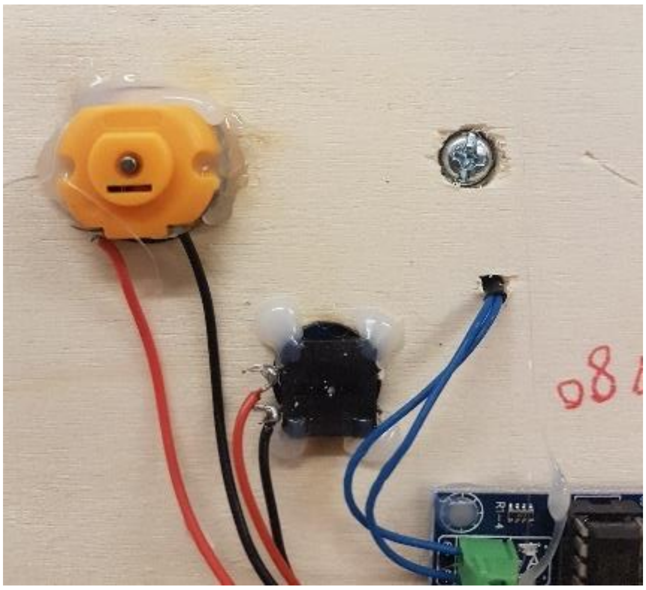

Figure 18: attachment of DC motor (left top), electromagnet (screw at right top) and button (middle bottom)

7 EVALUATION

7.1 EVALUATION PLAN

7.1.1 Goal, hypothesis, and variables

The evaluation of the installation was aimed at answering the question which of the modalities of friction and resistance leads to a better user experience when conveying geographical data. Based on the lack of previous research and existing knowledge, the hypothesis for the experiment was formulated.

H0: "There will not be a significant difference in user experience between the modalities of friction and resistance"

Independent variables are variables that are changed in the experiment in order to study their effect. The independent variables are the type of modality which the data is observed, and the type of task performed. Dependent variables are that which is measured during the experiment. For this experiment, the dependent variables are the time which the user takes per tasks, the correctness of the answers, the subjective experience of the user, and task load/fatigue.

7.1.2 Study design

A within group study design is possible where all subjects experience both modalities. The Physicalizations and data that the participants interact with are kept as similar as possible. To avoid confounding variables counterbalancing will be used, exposing different subjects to a different order of tasks and modalities. As there are two sets of tasks and two modalities, there are four different orders. As the interaction is quite novel and lack of familiarity could influence the time taken and accuracy when performing the tasks, a familiarization period precedes the experiments. A separate dataset is used for this phase, where both the magnet and the motor can be used. The full design of the study is illustrated in figure 17.

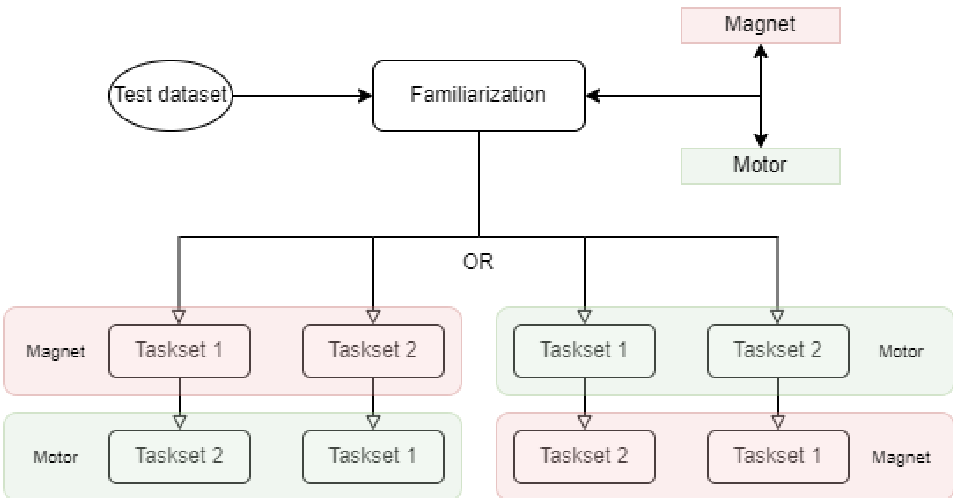

Figure 19: study design

Taking a general guideline for HCI research of 15-20 participants required [28], a minimum of sixteen participants was chosen such that the different orders of tasks and modalities are all represented equally. There are no specific requirements for age and experience, no prerequisite knowledge is needed besides proficiency in the English language. Participants are recruited through word of mouth, flyers, and social media.

7.1.3 Tasks

The participants are subject to three types of tasks while interacting with the Physicalizations: finding the minimum/maximum values [25] and finding the value most similar to a certain point (cluster). For these tasks, the accuracy will be measured by the number of correct answers given by the users. Questions will be provided to user in two sets, each using a different modality and dataset but the same task types. The two datasets are either numerical or categorical data, with the differences between the datapoints being, on average, higher in the categorical dataset. An overview of the values presented to the user can be seen in appendix D. An overview of these tasks can be seen in tables 2 and 3. As described in section 7.1.2, these tasksets and the modalities are counterbalanced. The efficiency will be measured through the time spent using the modalities before completing the stated objective, a camera is used so that the time taken can be determined after the experiment. Tasks and modalities will be counterbalanced, meaning there are four possible combinations if the participant is subject to all different types of tasks twice, once for both modalities.

Minimum	Which neighborhood has the lowest amount of crimes?	05 has the lowest amount of crimes
Maximum	Which neighborhood has the highest amount of crimes?	00 has the highest amount of crimes
Cluster	Which neighborhood has a similar amount of crimes to neighborhood 03?	09 and 03 are most similar

Table 2: taskset 1

Minimum	Which neighborhood(s) are in the “lowest” income category?	00 and 03 are in the lowest income category
Maximum	Which neighborhood(s) are in the “high” income category?	09 is in the highest income category
Cluster	Which neighborhood(s) are in the same income category as neighborhood 00?	00 and 03 are in the same income category

Table 3: taskset 2

7.1.4 Procedure

At the start of study, the participant is shortly introduced to the objective of the study and the approximate time spent, which will be around 1 hour. To supplement this introduction, an information brochure is provided with more in-depth information about the purpose of the research, the procedure, risks, and usage of data. This information brochure can be found in appendix B. The participant is then asked to document their consent using an informed consent form, which is consistent with the provided information. This form can be found in appendix C. For 5 minutes before the experiment is conducted, the participant will be able to interact with the Physicalization to get familiar with the interaction and can ask questions to the researcher. The participant can interact with the data points that will not be used for the tasks, this way no learning effect occurs with regard to the data. Each participant will be subjected to the Physicalization with the modalities of friction or friction, the participant performs tasks for both. The experiment will be recorded to be able to measure the time spent in perceiving the data.

After the tasks, the participant is asked to fill out a survey questionnaire which consists of sixteen questions with scales, questions in the questionnaire are taken from the short version of the User

Experience Questionnaire, the NASA Task Load Index, and the Device Assessment Questionnaire. These questionnaires were chosen as they could give a complete overview of the user's experience in interacting with the installation, as well as validate the concept in evaluating friction and resistance as modalities. The short User Experience Questionnaire contains questions about the subjective impression of user towards the user experience of a product [26]. Questions are formulated in a way that users can express subjective feelings, impressions, and attitudes in a quite straightforward way. The Nasa Task Load Index consists of a rating scale with which the user's perceived cognitive workload can be studied, with questions relating to mental/physical demand, performance, and more general subjective experience [27]. This index was chosen so the workload relating to the chosen testing apparatus could be evaluated. Lastly, questions on fatigue relevant for the installation were taken from the Device Assessment Questionnaire [29]. These consist of finger and wrist fatigue rated from none to very high, adapted to the same seven-point scale as the User Experience Questionnaire.

At the end, the participant will be asked a number of questions by the researcher on the subjective experience and the differences between both modalities. What they liked about both modalities and what they disliked, which of the two they liked best. The full questionnaire can be found in appendix E. An overview of the full procedure that the users go through can be found in figure 18.

Figure 20: experiment procedure

7.2 Data processing

Data collected during the experiment is the answers given by the participants by completing the tasks, time taken to complete the tasks, and answers given by the participants in the questionnaire. Answers given for the tasks are compared to the correct answers and stored in an excel file for analysis and visualization. The same is done for the results of the questionnaire.

Time taken to complete the tasks is determined by analysis of the recorded footage, where the moment between selecting a neighborhood and writing down the answer is timed. This method is mostly reliable, with the exception of participants going back to change an answer or skip ahead, which could still be accounted for.

7.3 Results

7.3.1 Experiment results

The experiment was conducted on eighteen participants over a span of 9 days, the setting was the same for each participant. Of the eighteen participants, nine were male and nine female. Eleven participants came from a HCI background and ten had interacted with a Physicalization before. The processed results of the experiment can be found in appendix G.

7.3.1.1 Efficiency

The efficiency, as expressed by the time taken to complete the task, was mostly dependent on the order of the task. Each user was asked to perform the tasks in the order minima, followed by maxima and then cluster. As can be seen in figure 19 and figure 20, this was the case for both motor and magnet, with time taken significantly higher during the minima tasks. The type of dataset, categorical or numerical, was found not to be a significant influencing factor for efficiency.

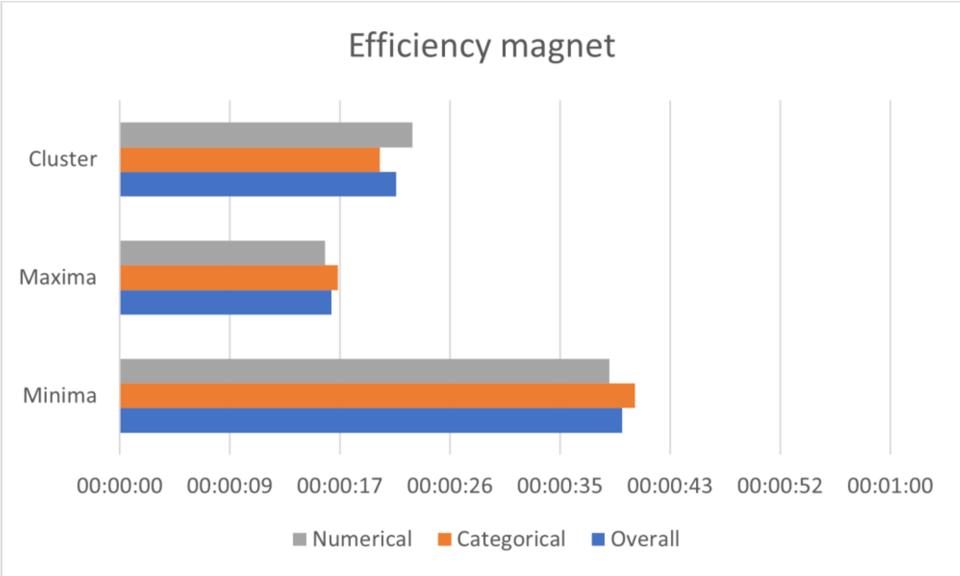

Figure 21: efficiency of task types and datasets for magnet

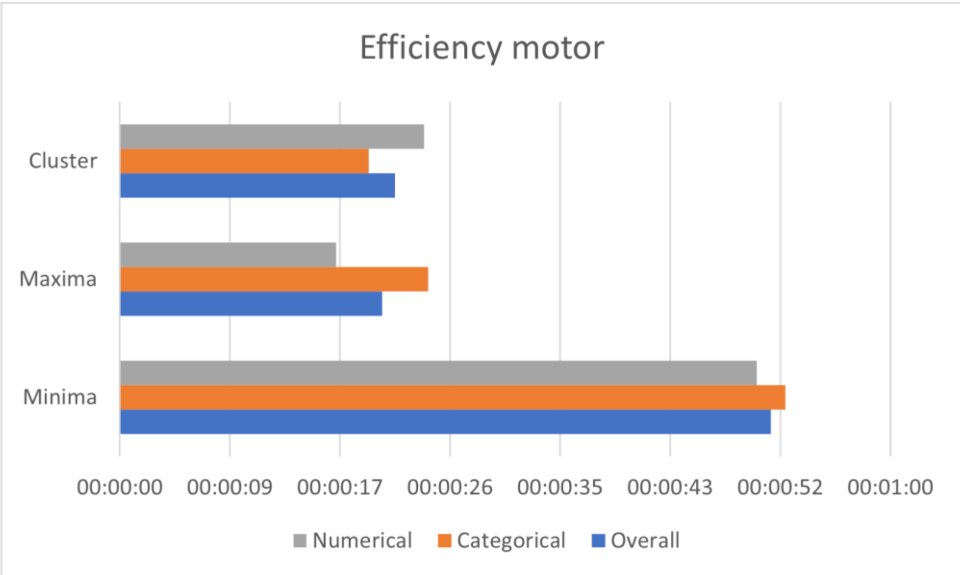

Figure 22: efficiency of task types and datasets for motor

In figure 21**,** the mean efficiency of both modalities can be compared. Using the magnet, the average time spent on a task was 1 minute and 17 seconds. For the motor, the average duration of a task was 1 minute and 32 seconds. A difference can be observed of 15,22 second in favor of the magnet, meaning participants spent this amount of time less to complete the tasks. Both modalities had large standard deviations, as some participants spent considerably more time on tasks than others.

	Modality	N	Mean	Std. Deviation	Std. Error Mean
Speed	Magnet	18	0:01:16,89	0:00:25,167	0:00:05,932
	Motor	18	0:01:32,11	0:00:32,276	0:00:07,608

Figure 23: group statistics for efficiency of both modalities

An independent samples t-test was performed to compare the means of the modalities, the results of which can be seen in figure 22. Given the significance of Levene's Test, equal variances could be assumed. For the Two-Sided p significance, a value can be observed of 0,124, meaning no significant difference is present between the means of the efficiency.

		Levene's Test for Equality of Variances		t-test for Equality of Means					
						Significance			
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference
Speed	Equal variances assumed	.003	.958	-1.578	34	.062	.124	-0:00:15,22	0:00:09,647
	Equal variances not assumed			-1.578	32.093	.062	.124	-0:00:15,22	0:00:09,647

Figure 24: independent samples test for efficiency of both modalities

7.3.1.2 Accuracy

Figure 23 and figure 24 show the accuracy of both modalities for the different variable types. The accuracy was determined by the number of correct answers given for the tasks. This accuracy was found to be vastly different depending on the variable type, with the accuracy for numerical tasks being considerably lower than categorical with the exception of the maxima task, which was similar.

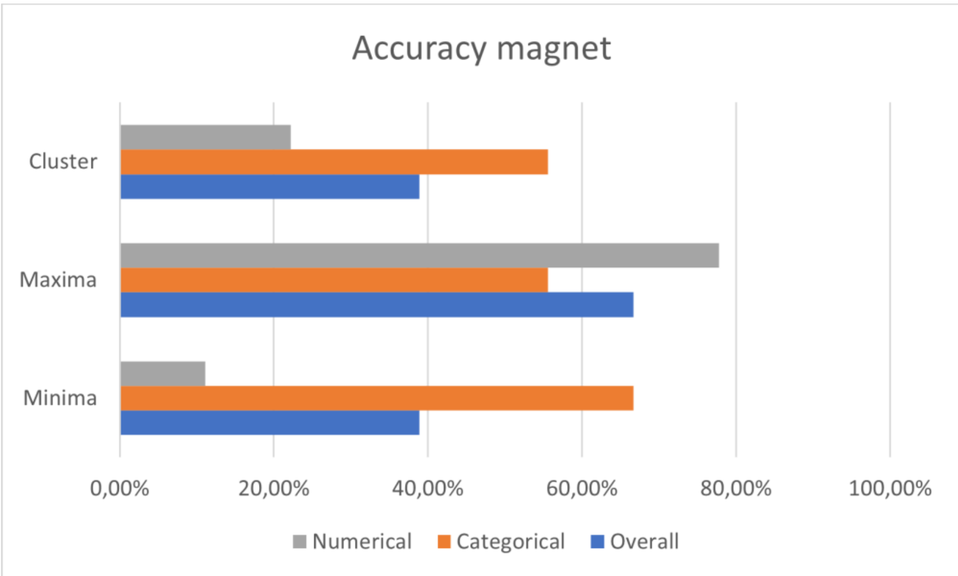

Figure 25: accuracy of task types and datasets for magnet

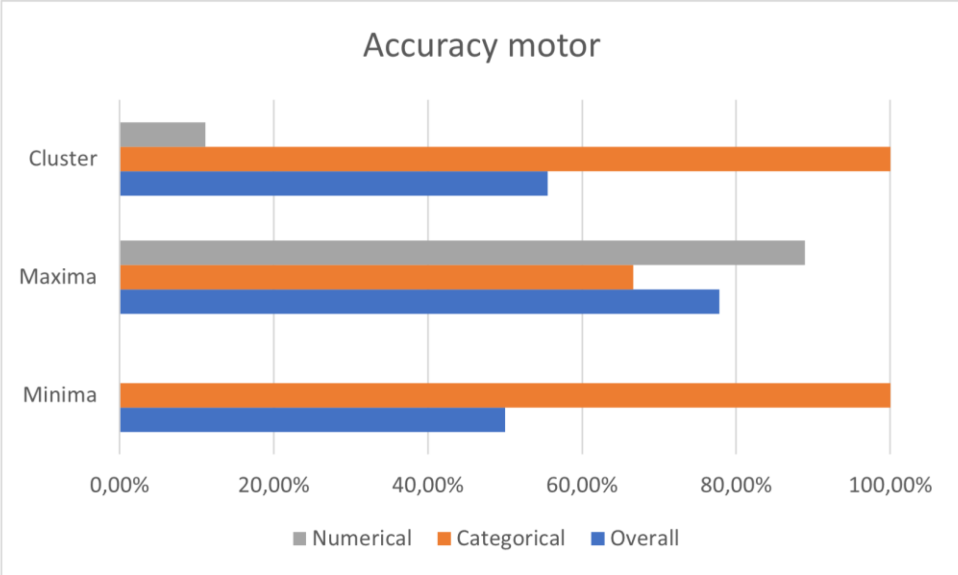

Figure 26: accuracy of task types and datasets for motor

The overall accuracy of the modalities can be seen in figure 25. The motor was found to be 61,11% accurate, while the magnet was only 48,15% accurate. Both had large standard deviations of 32% procent, as accuracy varied quite a lot between participants and variable type.

	Modality	N	Mean	Std. Deviation	Std. Error Mean
Percentage correct	Magnet	18	48.148148148	32.784146939	7.7272975385
	Motor	18	61.111111111	32.839478871	7.7403394002

Figure 27: group statistics for efficiency of both modalities

An independent samples t-test was also performed to compare the means of the modalities for accuracy, the results of which can be seen in figure 26. Given the significance of Levene's Test, equal variances could be assumed. For the Two-Sided p significance, a value can be observed of 0,244 , meaning no significant difference is present between the means of the accuracy.

		Levene's Test for Equality of Variances		t-test for Equality of Means					
						Significance			
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference
Percentage correct	Equal variances assumed	.025	.876	-1.185	34	.122	.244	-12.96296296	10.937274856
	Equal variances not assumed			-1.185	34.000	.122	.244	-12.96296296	10.937274856

Figure 28: independent samples test for efficiency of both modalities

7.3.2 Subjective results

All eighteen participants filled in the questionnaire, followed by the question which of the two modalities had their preference. The participants were also asked to provide general comments and feedback on the installation. In appendix F, the results of the questionnaire as well as the transcribed responses to the general comments question can be found.

7.3.2.1 Questionnaire results

The User Experience Questionnaire can be evaluated based on the distance from the neutral value, which in this case is 4. On average the user experience of the installation was observed as excellent according to the benchmark provided for the questionnaire. The distinction between pragmatic quality and hedonic quality can be made with the benchmark [31]. Here pragmatic quality denotes factors influencing the user's perceived ability to reach their goal. Hedonic quality includes the aspects that are not task-oriented, such as psychological and emotional characteristics of the Physicalization. As can be seen in figure 27, pragmatic quality was found to be above average and hedonic quality to be excellent. An overview can also be observed in figure 28, where hedonic quality aspects leading edge, inventive, interesting, and exciting score on average higher that pragmatic quality aspects clear, efficient, easy, supportive.

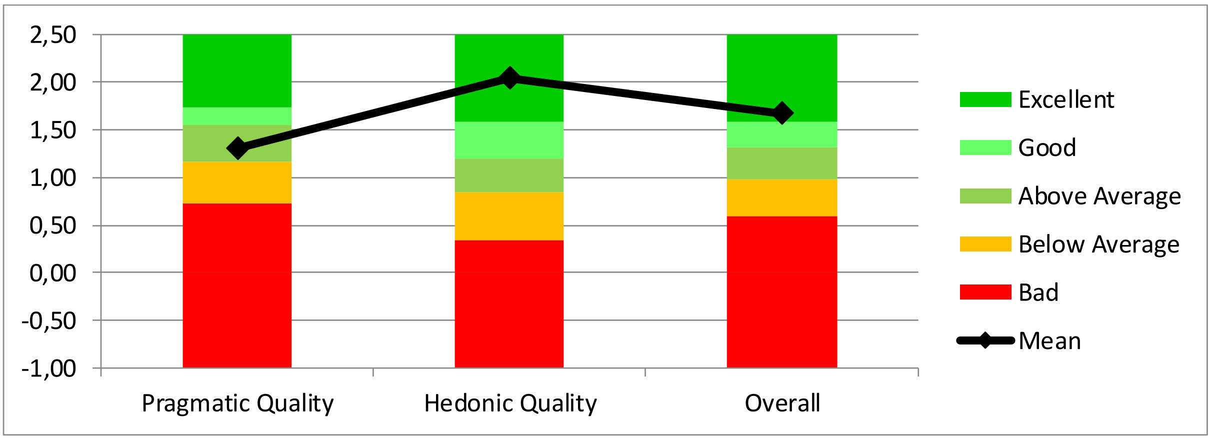

Figure 29: benchmark results UEQ

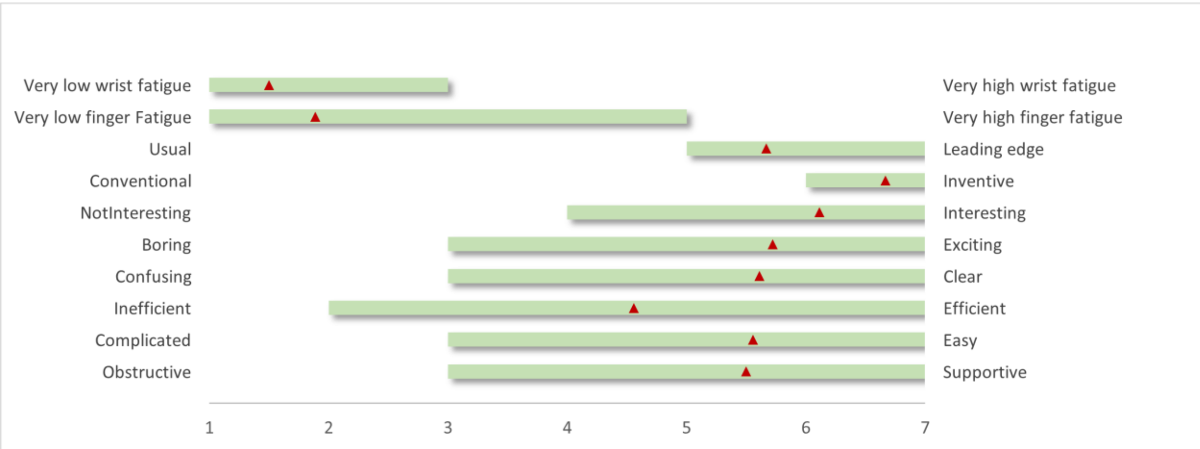

Figure 30: questionnaire results UEQ & DAQ

Finger and wrist fatigue were found to be very low, with the majority of answers being the lowest possible. These results can also be seen in figure 28.

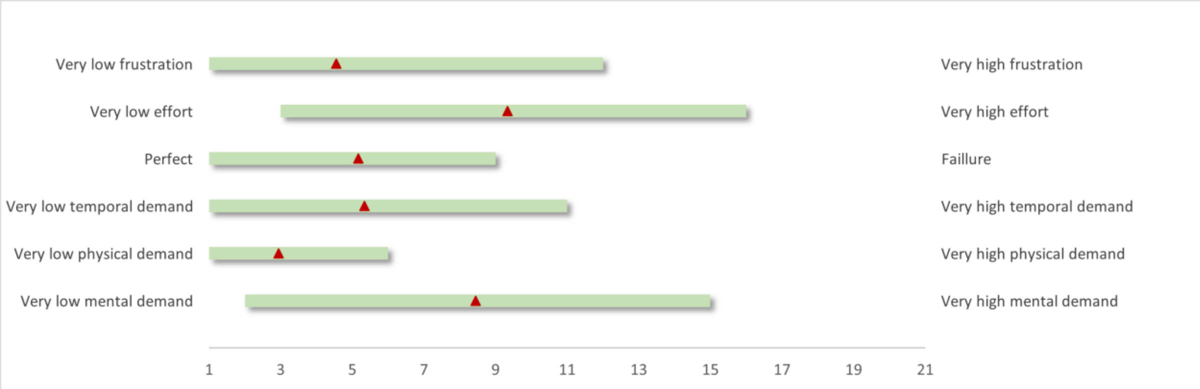

Figure 31: questionnaire results NASA-TLX

Results from the NASA Task Load Index (TLX) indicate that the perceived cognitive workload when performing the tasks was low. The installation was found not to be frustrating to use and participants rated their performance to be high. Temporal demand, meaning the pace of the task, and physical demand were perceived as low as well. Mental demand and effort, while still relatively low, indicate to be more present than the other factors. An overview of the questionnaire results of the Nasa-TLX can be seen in figure 29.

7.3.2.2 *Preference and general feedback*

Each participant, with the exception of one, was asked to indicate if the motor of the magnet had their preference for reading the data. The overwhelming majority of the participants chose the magnet, with fifteen out of seventeen participants, or 88,23%, choosing this option.

Reasons for choosing the magnet were in part due to the novelty of reading data in this way. For example, participant seventeen noted: “I have a slight preference for the magnet because it felt intuitive and easier”. Most also indicated that they perceived slight differences in the data better with the magnet, participant eleven stated that: “I perceived the magnet tasks to be easier because the delta in resistance was better to differentiate”. A downside of the magnet was that the force felt by the user was dependent on which angle the metal plate was applied. Participant seven noted that “Magnet would be better if it did not have to be interacted with exactly perpendicular”. Another point, brought up by participant nine, was that the magnets made a noise that could be distracting during interaction: “The thing I noticed was that the noise, especially from the magnets could tell me something as well, so that it draws more attention that the magnets itself. This could be fixed with more accurate and higher frequency drivers?”.

The two users that preferred the motor gave different reasons for choosing this option. Participant two noticed the sound that motor made when spinning, and identified the data through hearing rather than touching, meaning the motor was found to be easier to use. Participant twelve preferred the motor, because “The motor gave a clearer view whether a variable was high or low. Also liked that you could use your finger to 'feel' the data”. Reasons for disliking the motor were mainly centered around the motor spinning slower or stopping when touched, meaning only the initial contact gave an accurate indication of the data value. Some also disliked the motor for the sound that it made, serving as a distraction when trying to focus on the data. Participant thirteen stated that “(the) sound of motor was distracting and (I) paid attention to the sound instead of the force”.

General feedback on the installation was positive, in line with the answer gathered from the user experience questionnaire. Some general comments on the Physicalization can be found below.

“It is a very fun, unusual, and interactive way to deal with datasets about a city. Cool to have in a council building on display. I doubt the accuracy a bit, and you need a bit of explanation before you really get it, but when I understood it is really cool and it kept my attention.” – Participant nine.

“Good legend so the mental demand was low in addition with the good explanation beforehand. Touching the motors or using the magnet was fun and not really physically demanding. Insecurity about the data biggest factor of distraction” – Participant 14.

“Sometimes it was hard to feel the differences, which could be frustrating” – Participant 15.

8 DISCUSSION

8.1 LIMITATIONS

The study was limited in a number of ways, in part due to the scope of the graduation project and the lack of existing research on evaluating physical modalities for data Physicalization. Because of this, chosen concepts and methods are potentially not the most effective for studying the modalities of friction and resistance.

Because of the limited scope of the graduation project, with a large part of the conceptualization and execution of the project restricted to a 9-week period, much of the concept was not evaluated with users before the study. At various stages in the project, the concepts used for representing the modalities could have been validated with users, which could have led to discovering limitations earlier and adapting the installation. The scope also limited the amount and type of participants involved in the experiment and introduced sampling bias, with many being students with a Human-Computer Interaction background that had interacted with a Physicalization before. Being from a very narrow user group, the results from these participants cannot be generalizable to other user groups.

As data Physicalization is a very novel field of research, no clear guidelines exist for studying physical modalities. Therefore, most of the study had to be designed in accordance with assumptions on which factors influence the effectiveness of the modalities being evaluated. While a fairly thorough study design was constructed in the timespan of the project, a more intensive evaluation method is necessary to make conclusion on the modalities as opposed to a single way of conveying those modalities.

The data processing method for efficiency, using recorded footage to extrapolate the time spent performing tasks, was time consuming and not the most accurate. While the participant was asked to perform the tasks in order, this was disregarded on several occasions. On other occasions, the participant already identified an overview of the datapoints, leading to the answers being written down consecutively instead of interacting with the Physicalization for each task.

8.1.1 Motor

A fairly weak motor was chosen in order to prevent discomfort and fatigue, which resulted in the motor stopping when the user applied a moderate force. Consequently, many users were frustrated with the motor stopping and only being able to poll the data through initial contact.

Another point of feedback was on the sound of the motor, which was found to be distracting. While the sound it made was not directly proportional to the data it represented, many tried to read the data this way regardless.

Overall, the motor was found to be slightly more accurate that the magnet, but numerical data was found to be harder to differentiate, with smaller differences between data points.

8.1.2 Magnet

Most of the feedback around the magnet was centered around the interaction being fairly unintuitive for some participants. This was mostly due to the metal plate having to be precisely applied perpendicular to the magnet. After short familiarization however, all no participants struggled with the interaction, with the vast majority preferring the magnet over the motor.

The magnet was also found to be slightly less accurate than the motor overall, while being more accurate in conveying numerical data.

8.2 Recommendations

The motors could still be an effective way of conveying data with friction, with accuracy being slightly higher than the magnets. With the main limiting factor as indicated by the participants being the strength of the motor, a calibration could be done to improve the user experience. A balance will need to be found between the strength of the motor and the discomfort experienced, which would ideally be evaluated during the specification stages of developing the concept. A higher torque motor operating at the same speed or slightly faster could potentially be more accurate and efficient.

For the magnets, some users struggled during the familiarization phase with getting used to the interaction, with the metal needing to be applied directly perpendicular to the magnet. The core functioning of the electromagnet makes it difficult to create a field that could be interacted with from different angles. Potentially, multiple magnets could be combined to emulate this effect.

Another factor to be evaluated is whether a repulsive force could be more effective than the attractive force used in the project. To do this, two magnets with unequal poles will have to be used. This could possibly solve the issue of needing to apply a metal object perpendicularly and could be a more enjoyable method of interaction.

8.3 Future work

As a whole the Physicalization built for evaluating the modalities was experienced very well. An easy to use, non-fatiguing installation was essential for the experiment as users were able to comprehend the selection of neighborhoods, dataset, and modalities quickly. No problems arose during the experiments relating to the Physicalization itself, and many commented on its intuitive layout. Similar Physicalizations could potentially be used to accommodate and study other physical modalities, with needed adjustments specific to the context and variables.

To aid future studies, a framework for evaluating modalities will need to be constructed. Here the use of objective scales, including the measures of accuracy and efficiency, and subjective scales, such as user experience and perceived task load and fatigue, can be included. This framework could also include methods for conceptualizing data Physicalizations meant for studying physical modalities and evaluating them.

More comprehensive studies are needed also including the evaluation of different methods of actuation for representing modalities. The magnet and motor, chosen for representing resistance and friction respectively, are not by any means the only ways of doings so. Comparing different actuators can prove useful as part of a similar study, or as a separate study. Future studies with more experimental technologies for imitating material properties and kinesthetic variables could prove as more intuitive techniques for physicalizing data.

Based future research, complete guidelines will need to be constructed on the use of physical/haptic variables for conveying data. Such guidelines for data visualization already exist, and take into account the different types of data, such as ordinal or nominal. For data Physicalization however, only assumptions exist, as can be seen in figure 30.

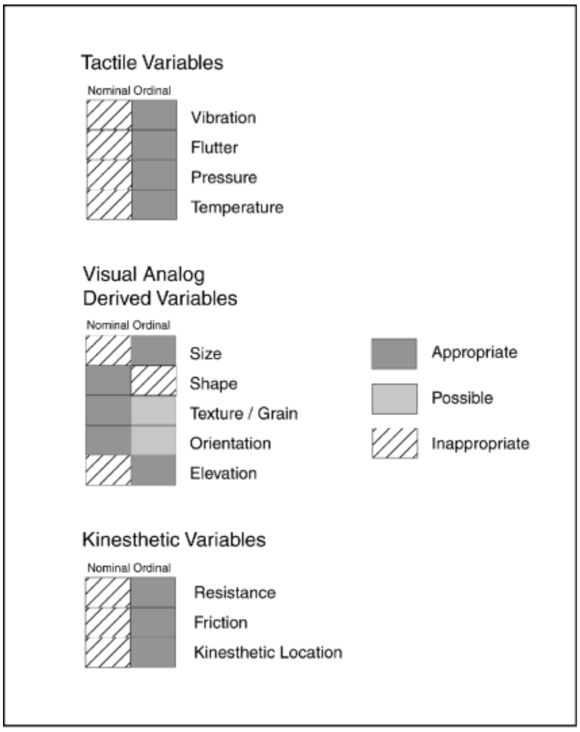

Figure 32: proposed haptic variable syntax [10]

Research should, include a wider range of users, as opposed to the fairly homogenous group of students that participated in this study. With data Physicalization showing potential to increase the accessibility of data, research involving physical data representation will preferably include users for which conventional data visualizations are inaccessible. Examples of these specific user groups are the visually impaired, low literate, and younger users, many of whom could benefit from understanding certain data.

While this study provides an overview of how friction and resistance could be used to convey data, and how effective they are at doing so, more study will be necessary to draw conclusions about whether they can be appropriately used. More types of data can be evaluated on a larger set of users, allowing for more reliable results. As discussed, other methods used for representing resistance and friction can be more effective and should be explored.

9 CONCLUSION

Based on the experiment and questionnaire, conclusions can be made based on the research question and sub questions that were formulated.

The research question was:

> *"Which of the modalities of friction and resistance is more effective when conveying data?"*

But first the sub-questions must be answered.

For the sub-question "*Which of the modalities of friction and resistance is more accurate when conveying data?"*, the answer was obtained by asking the participants of a user study to perform tasks. The answers of these tasks were analyzed and compared between modalities. With a sample size of eighteen participants, resistance, as represented by an electromagnet, was found to be 48,15% accurate in conveying data, while the motor, represented by a motor, was found the be 61,11% accurate. This difference was determined not be be significant. Tasks for a numerical dataset were found to be difficult for the user to perform, though categorical data was more accurately interpreted by the majority of participants.

For the sub-question "*Which of the modalities of friction and resistance is more efficient when conveying data"*, the efficiency was determined by observing the time spent on the various tasks on the recorded footage of the experiment. While this method was fairly time consuming and not perfectly accurate, it allowed for this data to be extrapolated in the majority of cases. For resistance, the average time spent on tasks was 1 minute and 17 seconds, while for the motor this was 1 minute and 32 seconds. This difference was not found to be significant, meaning neither modality is likely to be more efficient.

For the sub-question *"Which modality do users prefer when interacting with data?"*, the preference was noted at the end of the questionnaire which participants were asked to fill out. 88,23% of users preferred resistance as represented by the magnet. Reason for this were mostly centered around the perceived ability to observe smaller differences in the data while using the magnet, and the motor being fairly weak, often stopping when touched.

The entire installation was experienced as excellent, with pragmatic, task-oriented, quality being above average and hedonic, non-task-oriented, quality excellent. The installation was not found to be physically fatiguing and task-load was indicated as low to very low. As a whole this serves as a validation of the Physicalization built around the modalities, giving indication that it could potentially serve as a platform for further research into physical modalities.

Of resistance and friction, neither were found to be significantly better in both accuracy and efficiency when conveying data. Observations based on the available data could serve as a starting point for further research however, with smaller differences being perceived better when using the magnet. Subjective preference also shows a large user preference for the magnet, meaning resistance could be the preferable modality for interaction. Overall, the whole Physicalization was found to be excellent in non-task-oriented qualities and above average in task-oriented qualities, which indicates that the installation built was, as a whole, a good testing environment for physical modalities.

10 APPENDIX

APPENDIX A: ARDUINO CODE

```
/* Installation code by Sander Dullaert for the Creative Technology
Graduation Project

   This program reads a large amount of buttons on an interactive
installation and assigns them to variables needed for interpretation
   The installation has motors/magnets that the user can switch between,
these are referred to as modalities
   There are 3 datasets with separate data mappings for both modalities,
meaning 6 total arrays with data, each value for a separate neighborhood
   Values in the data arrays are PWM signal values that are output to motor
shields for the right modality and neighborhood
*/

int inMin = 22; // Lowest input pin
int inMax = 31; // Highest input pin
//Pin variables for motor driver
int pinout1;
int pinout2;
int pwm1;
int pwm2;

//Last pressed buttons
int lastPressed;
int lastPressedDataset;
int lastPressedModality;

//Arrays for pins used
int mainSet[] = {0, 3, 4, 5, 9};
static int testSet[] = {1, 2, 6, 7, 8};
static const uint8_t analog_pins[] = {A11, A12, A13, A14, A15};

//Arrays with datasets
static int ink_mag[] = {100, 152, 100, 100, 152, 203, 100, 100, 152, 255};
static int huurw_mag[] = {202, 165, 185, 190, 190, 160, 178, 167, 156,
134};
static int misdr_mag[] = {255, 131, 152, 125, 138, 113, 156, 113, 131,
121};
static int ink_mot[] = {60, 125, 60, 60, 125, 190, 60, 60, 125, 255};
static int huurw_mot[] = {189, 142, 167, 173, 173, 136, 158, 144, 130,
103};
static int misdr_mot[] = {255, 99, 126, 91, 108, 76, 130, 76, 98, 86};



void setup() {
  //Initialize pull-up resistor for button pins
  for (int i = inMin; i <= inMax; i++)
  {
    pinMode(i, INPUT_PULLUP);
  }
  for (int i = 0; i < 5; i++) { //or i <= 4
    pinMode(analog_pins[i], INPUT_PULLUP);
  }
  Serial.begin(9600);
}
```

```
void loop() {
  checkPush();
  delay(50); // quick and dirty debounce filter
  output (lastPressed);
}


void checkPush()
{
  //checkPush() checks whether a button is pressed, if any button is
pressed it assigns its value to the last pressed variables for
neighborhood, modality, and dataset.

  //Check pins used for neighborhood buttons
  for (int i = inMin; i <= inMax; i++)
  {
    int pushed = digitalRead(i);  // read input value

    if (pushed == LOW) {
      lastPressed = i - 22;
    }

  }
  //Check pins used for modality buttons
  for (int i = 0; i < 2; i++) {
    int pushed = digitalRead(analog_pins[i]);
    if (pushed == LOW) {
      lastPressedModality = analog_pins[i] - 65;
      Serial.println(lastPressedModality);
    }
  }
  //Check pins used for dataset
  for (int i = 2; i < 5; i++) {
    int pushed = digitalRead(analog_pins[i]);
    if (pushed == LOW) {
      lastPressedDataset = analog_pins[i] - 67;

    }
  }

  //Serial.println(lastPressed);

  //Translate lastpressed dataset & neighborhood to right motor driver
output pins
  if (lastPressedDataset == 0) {
    for (int i = 0; i < 5; i++) {
      if (lastPressed == testSet[i]) {
        pwm1 = 2 + i * 2;
        pwm2 = 3 + i * 2;
        pinout1 = 32 + lastPressed * 2;
        pinout2 = 33 + lastPressed * 2;
        break;
      } else {
        pwm1 = 0;
        pwm2 = 0;
        pinout1 = 0;
        pinout2 = 0;
      }
    }
```

```
  } else  if (lastPressedDataset == 1 || lastPressedDataset == 2) {
    for (int i = 0; i < 5; i++) {
      if (lastPressed == mainSet[i]) {
        pwm1 = 2 + i * 2;
        pwm2 = 3 + i * 2;
        pinout1 = 32 + lastPressed * 2;
        pinout2 = 33 + lastPressed * 2;
        break;
      } else {
        pwm1 = 0;
        pwm2 = 0;
        pinout1 = 0;
        pinout2 = 0;
      }
    }
  }

}


void output(int buttonPressed) {
  //output() takes the last pressed neigborhood, dataset, & modality and
writes to the motor driver

  //Set all logic outputs to LOW
  for (int i = 32; i < 60; i++) {
    digitalWrite(i, LOW);
  }
  //For the chosen modality, set output HIGH
  if (lastPressedModality == 0) {
    digitalWrite(pinout1, HIGH);
    digitalWrite(pinout2, LOW);
  } else if (lastPressedModality == 1) {
    digitalWrite(pinout1, LOW);
    digitalWrite(pinout2, HIGH);
  }

  //Set all PWM signals to LOW
  for (int i = 0; i < 13; i++) {
    analogWrite(i, 0);
  }

  //For the right dataset for the right modality, output the PWM signal
from the dataset
  if (lastPressedDataset == 0) {
    if (lastPressedModality == 0) {
      analogWrite(pwm1, huurw_mag[buttonPressed]);
    } else if (lastPressedModality == 1) {
      analogWrite(pwm2, huurw_mot[buttonPressed]);
    }
  } else  if (lastPressedDataset == 1) {
    if (lastPressedModality == 0) {
      analogWrite(pwm1, misdr_mag[buttonPressed]);
      Serial.println(misdr_mot[buttonPressed]);
      Serial.println(pwm1);
    } else if (lastPressedModality == 1) {
      analogWrite(pwm2, misdr_mag[buttonPressed]);
      Serial.println(misdr_mot[buttonPressed]);
      Serial.println(pwm2);
    }
```

```
  } else  if (lastPressedDataset == 2) {
    if (lastPressedModality == 0) {
      analogWrite(pwm1, ink_mag[buttonPressed]);
    } else if (lastPressedModality == 1) {
      analogWrite(pwm2, ink_mot[buttonPressed]);
    }
  }
}
```

APPENDIX B: INFORMATION BROCHURE

Information Brochure

Dear reader,

This letter will inform you about the research you have applied to participate in. The purpose of the research is to test how effective interaction with haptic resistance and friction is in communicating a set of data to a user. Data will be physically represented using a physical data visualization, referred to as a Physicalization, with which a user can interact with both resistance and friction. First you will be allowed to familiarize yourself with the dataset and the Physicalization itself. The interaction will be shortly explained by the researcher. After this you will be asked to perform a number of tasks that require you to interact with both resistance and friction in the Physicalization to gather data. Following the tasks, a survey will be conducted on your experience in interacting with the Physicalization. Participating in the experiment poses no significant risk and the project has been reviewed by the Ethics Committee Information and Computer Science. It is possible that during the interaction with the Physicalization discomfort or fatigue occur, in this case the experiment can be paused or stopped. As participant you are able to withdraw from the study. This possible both during and after the session for any reason. Interaction with the Physicalization will be recorded for analysis. An anonymous participant ID noted on the consent form will be linked to the footage that is recorded. The purpose of this is to identify the footage of you interacting with the Physicalization and link it to the answers provided by you on the survey and when performing the tasks. Recorded footage will be stored securely and according to General Data Protection Regulation (GDPR), it will only be accessible to the researcher and, upon request, to the participant. You have the right to access, rectify or erase your personal data, please contact the researcher if you wish to do so. Data collected during the study will be kept by the researcher and processed for statistical analysis and data coding. The data is presented in the discussion of the research and results, it will be anonymized for publication, data itself will not be separately published. The retention period of the collected data will be up until the bachelor thesis is completed and published, which will be the 1st of September 2022 at the latest.

For questions on the study, if you want to withdraw your participation from the research, or if you want to erase the collected data, you can contact the researcher. The contact information of the researcher is:

S.A. Dullaert

s.a.dullaert@student.utwente.nl

+31 637094701

For other complaints regarding the research, the Ethics Committee Computer and Information Science can be contacted at:

drs. P. de Willigen

ethicscommittee-cis@utwente.nl

+31 534892085

Alternatively, the supervisor of the Graduation Project can be contacted:

dr. C. Epa Ranasinghe

c.m.eparanasinghe@utwente.nl

+31 534899189

APPENDIX C: INFORMED CONSENT FORM

Consent Form for “studying the effect of friction and resistance in the interaction with a regional dataset”

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
- I have read and understood the study information dated 09/05/2022, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
- I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
- I understand that taking part in the study involves a video-recorded experiment consisting of me interacting with a physical installation and completing task, of which the recording will be destroyed after the completion of the bachelor’s assignment. I understand that afterwards I will complete a survey questionnaire relating to this interaction.	○	○
Risks associated with participating in the study		
- I understand that taking part in the study involves the following risks: possibility of mild physical discomfort and mild fatigue	○	○
Use of the information in the study		
- I understand that information I provide will be anonymized and used for scientific publication or made public in any other manner.	○	○
- I understand that personal information collected about me that can identify me, such as recorded footage and identification code, will not be shared beyond the study team.	○	○
- I agree to be audio/video recorded. Yes/no	○	○

Signatures

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Sander Dullaert

Researcher name Signature Date

Study contact details for further information:

Researcher:

Sander Dullaert - s.a.dullaert@student.utwente.nl - +31 637094701

Ethics Committee Computer and Information Science:

DRS. P. de Willigen - ethicscommittee-cis@utwente.nl - +31 534892085

Graduation project supervisor:

dr. C. Epa Ranasinghe - c.m.eparanasinghe@utwente.nl - +31 534899189

APPENDIX D: DATA WITH MAPPING

Raw Data

Neighborhood	average income	Income category	percentage rental	crimes

Wijk 00 Binnensingel	**27**	**66**	**3201**		**0**	**60**	**60**	**202,3**	**202**	**155,0484375**	**255**
Wijk 01 Hogeland - Velve	**29,2**	**42**	**639,00**		**1**	**125**	**125**	**165,1**	**165**	**30,9515625**	**131**
Wijk 02 Boswinkel - Stadsveld	**26,1**	**55**	**1081,00**		**0**	**60**	**60**	**185,25**	**185**	**52,3609375**	**152**
Wijk 03 Twekkelerveld - T.H.T.	**25,2**	**58**	**514,00**		**0**	**60**	**60**	**189,9**	**190**	**24,896875**	**125**
Wijk 04 Enschede-Noord	**28**	**58**	**789,00**		**1**	**125**	**125**	**189,9**	**190**	**38,2171875**	**138**
Wijk 05 Ribbelt - Stokhorst	**30,7**	**39**	**268,00**		**2**	**190**	**190**	**160,45**	**160**	**12,98125**	**113**
Wijk 06 Enschede-Zuid	**26,3**	**50**	**1153,00**		**0**	**60**	**60**	**177,5**	**178**	**55,8484375**	**156**
Wijk 07 Bedrijfsterreinen Enschede-West	**27,40**	**43**	**270,00**		**0**	**60**	**60**	**166,65**	**167**	**13,078125**	**113**
Wijk 08 Glanerbrug en omgeving	**28,5**	**36**	**631,00**		**1**	**125**	**125**	**155,8**	**156**	**30,5640625**	**131**
Wijk 09 Landelijk gebied en kernen	**35,4**	**22**	**430,00**		**3**	**255**	**255**	**134,1**	**134**	**20,828125**	**121**

Neighborhood 00 Binnensingelgebied	27	1	66	3201
Neighborhood 03 Twekkelerveld - T.H.T.	25,2	1	58	514
Neighborhood 04 Enschede-Noord	28	2	58	789
Neighborhood 05 Ribbelt - Stokhorst	30,7	3	39	268
Neighborhood 09 Landelijk gebied en kernen	35,4	4	22	430

Motor data mapping

Lowest PWM value for operation is 60. PWM value is therefore given by:

$$60 + (\left(\frac{value}{maxValue}\right) * 195)$$

Rounded to nearest integer

Neighborhood	PWM value income	PWM value rental	PWM value crimes
Neighborhood 00 Binnensingelgebied	60	189	255
Neighborhood 03 Twekkelerveld - T.H.T.	60	173	91
Neighborhood 04 Enschede-Noord	125	173	108
Neighborhood 05 Ribbelt - Stokhorst	190	136	76
Neighborhood 09 Landelijk gebied en kernen	255	103	86

Magnet data mapping

Lowest PWM value for operation is 100. PWM value is therefore given by:

$$100 + (\left(\frac{value}{maxValue}\right) * 155)$$

Rounded to nearest integer

Neighborhood	PWM value income	PWM value rental	PWM value crimes
Neighborhood 00 Binnensingelgebied	100	202	255
Neighborhood 03 Twekkelerveld - T.H.T.	100	190	125
Neighborhood 04 Enschede-Noord	152	190	138
Neighborhood 05 Ribbelt - Stokhorst	203	160	113
Neighborhood 09 Landelijk gebied en kernen	255	134	121

APPENDIX E: QUESTIONNAIRE FOR EVALUATION

GP Questionnaire

Date: Participant nr.:

Subjective experience

Obstructive	o o o o o o o	Supportive
Complicated	o o o o o o o	Easy
Inefficient	o o o o o o o	Efficient
Confusing	o o o o o o o	Clear
Boring	o o o o o o o	Exciting
Not interesting	o o o o o o o	Interesting
Conventional	o o o o o o o	Inventive
Usual	o o o o o o o	Leading edge

Finger fatigue

None	o o o o o o o	Very high

Wrist fatigue

None	o o o o o o o	Very high

Mental Demand: How mentally demanding was the task?

Very Low Very High

Physical Demand: How physically demanding was the task?

Very Low Very High

Temporal Demand: How hurried or rushed was the task?

Very Low Very High

Performance: How successful were you in accomplishing what you were asked to do?

Perfect | Failure

Effort: How hard did you have to work to accomplish your level of performance?

Very Low | Very High

Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low | Very High

Did you prefer the magnet or the motor?

Why?

General comments on the installation/feedback:

Appendix F: Questionnaire results

Appendix F.1: Preference & general comments

Participant nr.	Preference	Why/general comments
1	/	/
2	Motor	Easier because of the sound it makes, otherwise magnet
3	Magnet	Difference was more noticeable
4	Magnet	Was easier to 'feel' the difference. Motor stops spinning, hard to measure friction
5	Magnet	I preferred the magnet as I feel you can feel the difference better as the force on your hand is continuous. As opposed to the motor which is kind of stopped when touched. Also I paid more attention to the sound of the motor rather that the feel of the rotation
6	Magnet	The difference in strength between the magnets was in my opinion more easily noticeable that with the motors. With the magnet I was more sure about my answer
7	Magnet	Magnet was better, with the motor it was difficult to feel the difference. Magnet would be better if it did not have to be interacted with exactly perpendicular
8	Magnet	Motors were a bit hard to distinguish, maybe less pronounced ribs? Magnets were clear
9	Magnet	Magnet, as it is really interesting and cool. It is a very fun, unusual and interactive way to deal with datasets about a city. Cool to have in a council building on display. I doubt the accuracy a bit, and you need a bit of explanation before you really get it, but when i understood it is really cool and it kept my attention. The thing i noticed was that the noise, especially from the magnets could tell me something as well, so that it draws more attention that the magnets it self. This could be fixed with more accurate and higher frequency drivers? Overall though, really cool and interesting Physicalization.
10	Magnet	The difference was easier to feel than the motor. The motor stops when touched so it is hard to estimate the speed. Maybe a slower spinning motor would be more clear
11	Magnet	I perceived the magnet tasks to be easier because the delta in resistance was better to differentiate. With the motor there was the extra factor of my own finger pressure which controlled my ??? a little bit
12	Motor	The motor gave a more clearer view whether a variable was high or low. Also liked that you could use your finger to 'feel' the data
13	Magnet	Values were easier to differentiate. Sound of motor was distracting and paid attention to the sound instead of the force
14	Magnet	The motors was hard to feel small differences, the magnets was better to feel the small differences. Good legend so the mental demand was low in addition with the good explanation beforehand. Touching the motors or using the magnet was fun and not really physically demanding. Insecurity about the data biggest factor of distraction
15	Magnet	I liked the magnet the best because for me it felt easier to uncover the differences, I was able to feel them better. Sometimes it was hard to feel the differences, which could be frustrating
16	Magnet	Magnet was easier to recognize (the differences), and less discomforting to my finger
17	Magnet	Both the motor and the magnet can be equally effective. Both were original ways to physicalize data. I have a slight preference for the magnet because it felt intuitive and easier to compare than pushing my finger against a spinning lid
18	Magnet	Easier to read and easier to differentiate

Appendix F.2: UEQ results

Participant nr.	Obstructive - Supportive	Complicated - Easy	Inefficient - Efficient	Confusing - Clear	Boring - Exciting	Not Interesting - Interesting	Conventional - Inventive	Usual – Leading Edge
1	6	6	5	6	6	6	6	6
2	3	5	2	6	3	4	6	5
3	6	5	7	5	7	7	7	6
4	5	5	4	6	6	6	7	5
5	5	7	6	5	6	7	6	5
6	6	6	4	7	7	7	7	6
7	6	6	6	6	4	5	6	5
8	5	6	3	6	5	6	7	5
9	7	5	6	5	7	7	7	6
10	6	5	4	4	6	6	7	6
11	6	7	4	7	6	7	7	7
12	5	5	6	4	6	7	7	6
13	6	6	6	7	5	5	7	5
14	6	7	4	7	6	6	6	6
15	6	4	3	5	6	6	7	6
16	5	6	3	6	6	6	7	5
17	5	6	5	6	5	6	7	6
18	5	3	4	3	6	6	6	6

Appendix F.3: DAQ results

Participant nr.	Finger Fatigue	Wrist Fatigue
1	1	1
2	2	2
3	1	1
4	1	1
5	1	2
6	1	1
7	5	1
8	1	1
9	2	3
10	4	3
11	1	2

12	2	1
13	1	1
14	1	1
15	1	1
16	4	1
17	2	2
18	3	2

Appendix F.4: NASA TLI results

Participant nr.	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
1	14	3	2	6	16	4
2	7	2	3	5	12	12
3	7	1	1	4	8	1
4	14	3	11	5	13	1
5	13	1	6	5	7	5
6	4	1	11	5	7	1
7	11	1	9	6	12	11
8	4	2	1	4	3	3
9	8	4	5	7	12	2
10	7	3	8	3	11	2
11	3	4	11	5	8	1
12	15	4	3	3	13	3
13	2	2	2	7	3	1
14	4	6	2	7	4	6
15	9	2	2	9	7	11
16	4	4	5	1	13	7
17	13	6	10	4	6	6
18	13	4	4	7	13	5

APPENDIX G: EXPERIMENT RESULTS

Appendix G.1: Answers

Participant nr.	magnet_dataset	magnet_min	magnet_max	magnet_cluster	motor_dataset	motor_min	motor_max	motor_cluster
1	crimes	0	1	0	income	1	1	1
2	income	0	1	0	crimes	0	1	0
3	income	1	1	1	crimes	0	1	0
4	crimes	0	1	0	income	1	1	1
5	crimes	1	0	0	income	1	1	1
6	income	1	1	1	crimes	0	1	0
7	income	1	0	1	crimes	0	1	0
8	crimes	0	1	0	income	1	1	1
9	crimes	0	1	0	income	1	1	1
10	income	1	1	1	crimes	0	1	0
11	income	0	0	0	crimes	0	1	0
12	crimes	0	1	1	income	1	0	1
13	crimes	0	1	1	income	1	0	1
14	income	1	0	1	crimes	0	1	0
15	income	1	1	0	crimes	0	0	0
16	crimes	0	0	0	income	1	1	1
17	crimes	0	1	0	income	1	0	1
18	income	0	0	0	crimes	0	1	1

Explanation: 1 is correct, 0 is incorrect or partially correct

Appendix G.2: Overview of accuracy for variable types

Task type	Minima	Maxima	Cluster	Column2	Minima3	Maxima4	Cluster5
Overall	38,89%	66,67%	38,89%	Overall	50,00%	77,78%	55,56%
Continuous	11,11%	77,78%	22,22%	Categorical	100,00%	66,67%	100,00%
Categorical	66,67%	55,56%	55,56%	Continuous	0,00%	88,89%	11,11%

11 REFERENCES

[1] Y. Jansen, P. Dragicevic, P. Isenberg, J. Alexander, A. Karnik, J. Kildal, S. Subramanian, and K. Hornbæk, “Opportunities and challenges for data physicalization,” *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 2015.

[2] K. Danyluk, T. Ulusoy, W. Wei, and W. Willett, “Touch and beyond: Comparing physical and virtual reality visualizations,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 28, no. 4, pp. 1930–1940, 2022.

[3] I. López García and E. Hornecker, “Scaling data physicalization – how does size influence experience?,” *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*, 2021.

[4] L. M. Brown, S. A. Brewster, and H. C. Purchase, “Multidimensional Tactons for non-visual information presentation in mobile devices,” *Proceedings of the 8th conference on Human-computer interaction with mobile devices and services - MobileHCI '06*, 2006.

[5] E. Hoggan and S. Brewster, “New parameters for Tacton Design,” *CHI '07 Extended Abstracts on Human Factors in Computing Systems*, 2007.

[6] T. Hogan and E. Hornecker, “How does representation modality affect user-experience of data artifacts?,” *Haptic and Audio Interaction Design*, pp. 141–151, 2012.

[7] A. Boem and H. Iwata, “‘it’s like holding a human heart’: The design of Vital + morph, a shape-changing interface for remote monitoring,” *AI & SOCIETY*, vol. 33, no. 4, pp. 599–619, 2017.

[8] Y. Jansen and P. Dragicevic, “An interaction model for visualizations beyond the desktop,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 12, pp. 2396–2405, 2013.

[9] W. S. Cleveland and R. McGill, “Graphical perception: Theory, experimentation, and application to the development of graphical methods,” *Journal of the American Statistical Association*, vol. 79, no. 387, pp. 531–554, 1984.

[10] A. L. Griffin, “Feeling it out: The use of haptic visualization for exploratory geographic analysis,” *Cartographic Perspectives*, no. 39, pp. 12–29, 2001.

[11] M. K. Rasmussen, E. W. Pedersen, M. G. Petersen, and K. Hornbæk, “Shape-changing interfaces,” *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2012.

[12] S. Follmer, D. Leithinger, A. Olwal, N. Cheng, and H. Ishii, “Jamming user interfaces,” *Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST '12*, 2012.

[13] K. Nakagaki, L. Vink, J. Counts, D. Windham, D. Leithinger, S. Follmer, and H. Ishii, “Materiable,” *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 2016.

[14] S. Follmer, D. Leithinger, A. Olwal, A. Hogge, and H. Ishii, “Inform,” *Proceedings of the 26th annual ACM symposium on User interface software and technology*, 2013.

[15] L. Yao, R. Niiyama, J. Ou, S. Follmer, C. Della Silva, and H. Ishii, “PneUI,” *Proceedings of the 26th annual ACM symposium on User interface software and technology*, 2013.

[16] M. Weiss, F. Schwarz, S. Jakubowski, and J. Borchers, “Madgets,” *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, 2010.

[17] A. H. Mader and W. Eggink, “A Design Process for Creative Technology,” *Proceedings of the 16th International conference on Engineering and Product Design, E&PDE 2014*, Sep. 2014.

[18] T. Hogan and E. Hornecker, “Towards a design space for multisensory data representation,” *Interacting with Computers*, 2016.

[19] N. Haidary, “In-formed,” *Nadeem Haidary*, 2010. [Online]. Available: http://www.nadeemhaidary.com/informed. [Accessed: 11-Apr-2022].

[20] T. White, “Symbolization and the visual variables,” *Geographic Information Science & Technology Body of Knowledge*, vol. 2017, no. Q2, 2017.

[21] L. J. Perovich, S. A. Wylie, and R. Bongiovanni, “Chemicals in the creek: Designing a situated data physicalization of open government data with the Community,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 27, no. 2, pp. 913–923, 2021.

[22] Tang, S. K., Sekikawa, Y., Leithinger, D., Follmer, S., and Ishii, H. Tangible cityscape, 2013. tinyurl.com/tcityscape.

[23] D. Offenhuber, “The Invisible Display–Design Strategies for Ambient Media in the Urban Context,” International Workshop on Ambient Information Systems, Colocated with Ubicomp, p. 152, 2008.

[24] Data Politie, “Registered crimes; type of crime, district, neighbourhood, annual figures.” 15-Mar-2022.

[25] Albers, D., Correll, M., & Gleicher, M. (2014). Task-driven evaluation of aggregation in time series visualization. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/2556288.2557200

[26] Schrepp, M., Hinderks, A., & Thomaschewski Jörg. (2017). Design and evaluation of a short version of the User Experience Questionnaire (UEQ-S). *International Journal of Interactive Multimedia and Artificial Intelligence*, *4*(6), 103. https://doi.org/10.9781/ijimai.2017.09.001

[27] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology*, 139–183. https://doi.org/10.1016/s0166-4115(08)62386-9

[28] Hochheiser, H., Feng, J., & Lazar, J. (2017). 15.2.2: how many subjects? In *Research methods in human computer interaction (second edition)* (pp. 454–455). essay, Morgan Kaufmann Publishers.

[29] Douglas, S. A., Kirkpatrick, A. E., & MacKenzie, I. S. (1999). Testing pointing device performance and user assessment with the ISO 9241, part 9 standard. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems the CHI Is the Limit - CHI '99*. https://doi.org/10.1145/302979.303042

[30] Jansen, Y., Dragicevic, P., & Fekete, J. D. (2013). Evaluating the efficiency of physical visualizations. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/2470654.2481359

[31] Schrepp, M. (2018). User Experience Questionnaire Handbook. Hockenheim, Germany; User Experience Questionnaire.