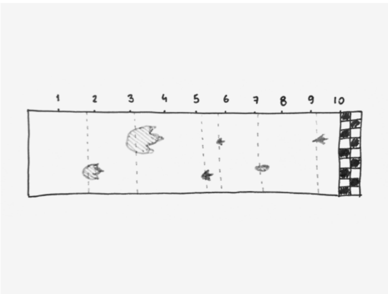

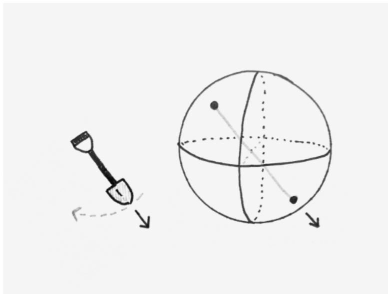

Interactive Data Physicalizations

How natural science museums might engage visitors through tangible and embodied interaction

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Abstract

For thousands of years, physical objects have been used to represent data, in order to support cognition, communication and learning. Such representations, especially newly computer-supported ones, became the focus of an emerging field called data physicalization.

Although most physicalizations are passive (*i.e.,* static), a growing number of active (*i.e.,* dynamic) representations have been recently created. There is still, however, an immense opportunity in exploring interactive data physicalizations.

This thesis proposes a tangible artifact (a shovel equipped with orientation sensors) that could be used by visitors of Earth sciences museums. *SuperTunnel Simulator* calculates a hole through Earth, indicating where in the world visitors would end up if they dug in a certain direction.

Feedback from participants indicate such embodied interaction might influence learning by igniting visitors' curiosity and stimulating hypothesis formulation. Finally, we point to research opportunities in conveying data not through an object's shape, but through our interaction with it.

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1. INTRODUCTION

1.1 Context and motivation

For thousands of years, humans have been using physical objects to represent abstract or quantitative data. This type of representation has been demonstrated to support cognition, communication and learning (Jansen *et al.*, 2015). Such representations, especially newly computer-supported ones, became the focus of the emerging field of data physicalization (Data Physicalization Wiki contributors, 2021; Jansen *et al.*, 2015).

Typically, these physicalizations consist of objects that convey data through their geometry (Dragicevic *et al.*, 2019, p. 1). A simple data physicalization, for instance, would be a set of three-dimensional bar charts made from wood. The length of each bar would be mapped to a numerical value. Please refer to section 2.1 for a more detailed definition.

This kind of static data representation is where most of the research on data physicalization is focused on. This is made apparent by comparing the amount of "passive", "active" and "interactive" physicalizations present on the *List of Physical Visualizations* (Dragicevic & Jansen, 2012), the most prominent online catalogue for this research area.

There are currently 210 passive data physicalizations listed. In contrast, there are 39 active data physicalizations showcased, plus 7 projects labelled as "interactive installations". The comparison, including the sum of the latter, is as follows:

- "Passive" physicalizations:

  210 projects.

- "Active" or "interactive" physicalizations:

  46 projects.

Although most physicalizations are passive, a growing number of dynamic representations have been recently created. Out of the 46 "active" or "interactive" projects (Dragicevic & Jansen, 2012), 33 were created after the year 2010.

Since relatively few studies have been conducted in this field, there is an immense opportunity in exploring the intersection of interaction design and data physicalization. This gap is known – as well as the desire to minimize it –, as researchers have made evident on *Opportunities and Challenges for Data Physicalization*:

> *"[...] Tangible and Human-Computer Interaction researchers can contribute knowledge on how to best design and implement interactions for physical data representations"* (Jansen *et al.*, 2015)

The next section further details the specific subfield of interaction design that the present research is dedicated to addressing.

1.2 Research area

This thesis focuses on the intersection of two research areas: embodied interaction and information visualization. More specifically, the present research aims to explore the emerging field of data physicalization (Dragicevic *et al.*, 2019, p. 1), through the design (Gaver, 2012) of tangible and embodied interactive artifacts.

According to the *Computing Classification System*, elaborated in 2012 by the Association for Computing Machinery (ACM), both aforementioned fields are under the hierarchical umbrella of "Human-Centered Computing". As a consequence, by researching interactive data physicalizations (or "dataphys"), this thesis seeks to bridge two fields that descend from a common ancestor. The simplified diagram below (Figure 1) represents the research areas within the problem domain of this thesis.

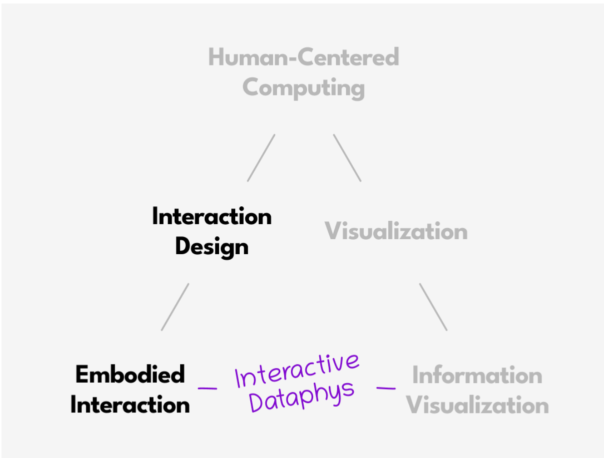

Figure 1. Simplified diagram representing interactive data physicalization at the intersection of embodied interaction and information visualization. Created based on the *Computing Classification System* (Association for Computing Machinery [ACM], 2012) and the definition of data physicalization by Dragicevic *et al.* (2019).

This report also considers "tangible interaction" to be an encompassing term, one that emphasizes the "materiality of the interface", the "physical embodiment of data" and "whole-body interaction" (Hornecker, 2016).

However, this thesis uses "embodied interaction" to refer to "interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with us" (Dourish, 2001, p. 3).

Moreover, the term "embodied" is used throughout this report to emphasize two aspects: how an interaction benefits from being situated in the world, and the concept of "embodiment" – which has a specific meaning in the realm of data physicalization (Dragicevic *et al.*, 2019). Such definition is presented in section 2.1.4 of this report.

1.3 Application area

The present thesis project focused on designing an interactive data physicalization for a specific use situation: in-person visits to an Earth sciences museum. As a way to address real opportunities on such institutions, this research is anchored on the characteristics of a specific venue in Brazil: the Geosciences Museum of University of São Paulo.

Throughout the course of this research, the venue has been **closed due to the Covid-19 pandemic**. However, the project was conducted as if the designed artifact was to be used on-site. Since most museums had also been closed during the same time period, the Geosciences Museum was, in part, chosen because the author had already visited it twice, prior to the pandemic.

Besides casual and independent visitors, schools also benefit from museum visits, in order to elicit more student engagement. Aligned with such practices, the mission pursued by the Geosciences Museum includes bringing Earth sciences and society closer together (Museu de Geociências, 2021). The pursuit of such mission is based on educational actions: welcoming casual or school visitors through guided tours (Figure 2), providing free consulting and even renting samples of minerals, rocks, fossils, and replicas (Museu de Geociências, 2021).

Figure 2. School students visiting the Geosciences Museum of University of São Paulo, Brazil. To begin the guided tour, visitors are encouraged to visually analyze the *Allosaurus fragilis'* skeleton, as well as reflect on its scenic environment (Museu de Geociências, 2011).

The other reason for choosing the Geosciences Museum is related to its attention to making learning into a tangible experience (Figure 3). As an anecdote, at the entrance of the museum, even though mediators invite visitors to visually observe the characteristics of a real-scale dinosaur skeleton replica (where no touching is allowed), inside the museum, a replica of the skull of the same dinosaur species is presented (and visitors are encouraged to explore it through touch). A similar approach happens at the "touch table", where minerals, fossils, and replicas are available for visitors to explore, with tools like magnifiers.

Figure 3. On the left, a tangible replica of an *Allosaurus fragilis'* skull is presented inside the museum, where visitors are encouraged to explore it (Museu de Geociências, 2020). On the right, visitors are encouraged to explore minerals, fossils, and replicas at the "touch table", where tools like magnifiers are provided (photo provided by Museum staff).

From all of the topics addressed by the museum, this research selected three, as a basis for the ideation phase (please refer to section 4.2 for details):

- Dinosaurs.
- Minerals.
- Earth.

1.4 Research question

All of the design openings described in the introduction chapter – related to the fields of embodied interaction and information visualization – have led the research question to be formulated as follows:

How embodied interaction might influence Earth sciences learning for museum visitors through data physicalization?

In the process of seeking answers to the question above, this thesis also aims to explore the intersection of embodied interaction and data physicalization. More specifically, it aims to experiment with new ways to convey data (not through the form of an object, but only through our interaction with it).

1.5 Thesis outline

The present report is organized mostly in chronological order. As expected, the first chapter introduces the theme and states the research question. In order to address such question, chapter 2 presents the theory that would be imperative during the design process. The methods that were employed during such process are presented on chapter 3. However, the process itself is detailed on chapter 4 (and categorized into several iterations). As the last iteration of the design process, the final design is presented on chapter 5, followed by an analysis of the main research results on chapter 6 (including its limitations). A broader opportunity for future research is outlined on the discussion chapter (number 7). Finally, a summary of this research is present on the concluding chapter (number 8).

2. BACKGROUND AND THEORY

2.1 Data physicalization

As an emerging area related to information visualization, the data physicalization field inherits some of its core assumptions: both aim to help humans make sense of information by stimulating our senses into perceiving abstract data (Dragicevic *et al.*, 2019). Commonly, this goal is achieved through vision, mainly by using two-dimensional figures, like bar or line charts. Such purely visual renditions of data are commonly referred to as "data visualizations".

2.1.1 Definition

Data physicalizations, on the other hand, often refer to physical, three-dimensional objects that convey abstract data through their shape. Prominent researchers have defined the term as follows (although signaling the following excerpt consists of a working definition):

> *"A data physicalization [...] is a physical artifact whose geometry or material properties encode data."* (Jansen *et al.*, 2015, p. 2)

External representations of abstract and quantitative information are not something new. For thousands of years, physical objects have been used to represent data, in order to support "cognition, communication, learning, problem solving, and decision making" (Jansen *et al.*, 2015).

2.1.2 Classification

As the potential of such representations largely increases with new technological advancements (*e.g.*, digital fabrication and low-cost embedded sensors and actuators), such artifacts became the focus of this emerging field – to which this report will often refer as "physicalization" or "dataphys" (Data Physicalization Wiki contributors, 2021).

Although data physicalizations might be created manually, advances in digital fabrication have enabled humans to revive ancient forms of external representation (*e.g.*, the Mesopotamian clay tokens from 5500 BC on Figure 4).

Today, however, computation makes it possible to produce tangible objects that encode data in their form with a high level of automation and precision (*e.g.*, the data-driven topographic map on Figure 7).

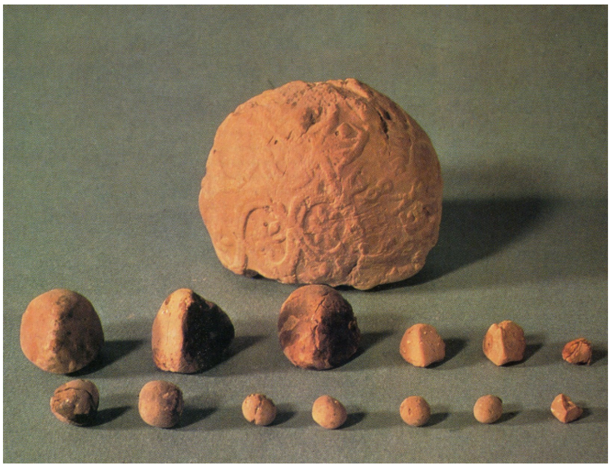

Figure 4. Mesopotamian clay tokens from around 5500 BC, from the ancient city of Susa (modern-day Shush, Iran). Such artifacts were likely used as an external representation of quantitative information, before writing even existed (Schmandt-Besserat, 1979).

Regardless of how physicalizations are produced (either manually or automatically), it is possible to classify such artifacts in several categories. This report is specially interested in organizing physicalizations in three categories: passive, active, and interactive data physicalizations. The following sections will further detail such categories and illustrate each one of them with emblematic examples.

2.1.2.1 Passive data physicalizations

This report uses the term "passive" to refer to three-dimensional, physical artifacts that encode data, but that are typically static and immutable, analogous to a sculpture that was carved in stone. This definition is based on the terminology section of the most prominent resource for this emerging research field (Data Physicalization Wiki contributors, 2021).

Figure 5. Photo of the Worry Beads artwork, as it was displayed on Lake Tahoe Community College's Gallery (South Lake Tahoe, CA, USA). The volume of each bead represents the number of people killed by terrorists that year, since 1945 (Madsen, 2018).

When a passive data physicalization has a strong artistic component (Figure 5), that is, when it seeks to "elicit emotions and convey meaning beyond mere data" (Jansen *et al.*, 2015), it is also commonly called a data sculpture. This report, however, uses the encompassing term "passive" to refer to any type of static artifact that represents data.

2.1.2.2 Active data physicalizations

This report uses the term "active" to refer to three-dimensional, physical artifacts that encode data, but that are typically dynamic and mutable, analogous to a kinetic sculpture (*e.g.*, one that has actuated parts, controlled digitally through electronic components). This definition is also based on the terminology section of the most prominent resource for this emerging research field (Data Physicalization Wiki contributors, 2021).

An emblematic example of "active" physicalization is the Tidal Memory (Figure 6) installation. Even though this data physicalization uses real-time data, sensors, and actuators, it is not interactive – as museum visitors have no agency over how the installation behaves. Researchers also call this type of data physicalization a "kinetic data sculpture" (Data Physicalization Wiki contributors, 2021). This report, however, uses the encompassing term "active" to refer to any type of dynamic (but not interactive) artifact that represents data.

Figure 6. Tidal Memory is an installation at the Exploratorium, a science museum in San Francisco, CA, USA. By automatically increasing or decreasing the water level inside each tube, the installation represents the hourly tide variation at a specific location, at a 1:1 scale (Sowers, 2013).

2.1.2.3 Interactive data physicalizations

This report uses the term "interactive data physicalizations" to refer to three-dimensional, physical artifacts that convey data, but that are constantly changing according to user's actions. Such definition, however, is not present in the aforementioned terminology literature (Physicalization Wiki contributors, 2021).

It is worth emphasizing that this research does not aim to provide or propose any sort of definition for interactive data physicalizations. Instead, this thesis draws upon the definitions of tangible (Hornecker, 2016) and embodied interaction (Dourish, 2001, p. 3) and applies them to a data physicalization context, as defined by Jansen *et al.* (2015).

To further detail how interactivity might apply to data physicalizations, this section will present two data-driven projects. Both of them utilize electronic components and behave according to user input, but with different levels of interactivity.

Data physicalization researchers often state their interest into making physicalizations as dynamic and interactive as their on-screen counterparts (Taher *et al.*, 2017, p. 451). By interacting with a virtual chart on a screen, one could easily sort, filter or dynamically update the underlying data. Such procedures are naturally more challenging to perform on physicalizations (Jansen *et al.*, 2013, p. 2593).

Today, recent advances in technology have made it easier and cheaper to embed data objects with sensors and actuators (Dragicevic *et al.*, 2019, p. 39; Jansen *et al.*, 2013), thus helping humans bring some of these interactions to the physical space. This is the case of Wage Islands (Figure 7), a data physicalization that allows users to dynamically filter the data that is being represented.

Figure 7. Wage Islands is an interactive artifact commissioned by Storefront for Art and Architecture. By submerging a topographic map of New York City, the installation shows areas which are affordable by low-wage workers (Ijeoma, 2015).

By pressing a physical button (Figure 8, on the left), users are able to select the numerical value to be represented. As a consequence, motors are used to change the level of the water (colored with black tint) in a container (Figure 8, on the right) – thus revealing more or less parts of a topographic map.

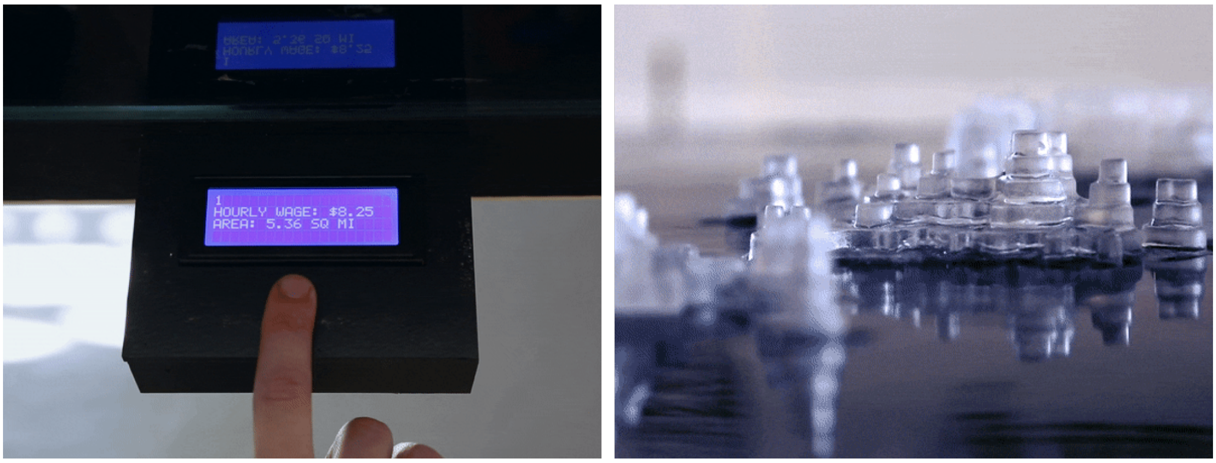

Figure 8. On the left, a close-up of the interactive device that is attached to the physical map. By pressing a button, users change the hourly wage to be visualized. The screen also displays how many square miles of the city workers would be able to pay for. On the right, a close-up of the data-driven topographic map, which was digitally fabricated to represent areas affordable by different wage ranges (Ijeoma, 2015).

Even though interactivity is present, the Wage Islands project perfectly fits the definition of data physicalization (Jansen *et al.*, 2015, p.2) presented in section 2.1.1 of this report. It does so because the data-driven topographic map **encodes data as part of its shape**. Even if there were no interaction, the map could still be considered a passive data physicalization.

In comparison, one other data-driven artifact is exceptionally interesting as inspiration for this thesis. The Solar Radiation Dowsing Rod (Figure 9) is a device created for a space observatory that allows visitors to point it towards the sky and feel, through light, vibration, and sound, the level of radiation coming from that direction (Hogan, 2017).

Figure 9. The Solar Radiation Dowsing Rod being used inside the Blackrock Castle Observatory, located in Cork, Ireland (Hogan & Hornecker, 2013).

This project is also equipped with sensors and actuators. Besides, it also allows users to interact with it. However, it radically differs from the Wage Islands example. The Solar Radiation Dowsing Rod, instead, **enables people to perceive data only during interaction** – as data is not encoded in the shape of the artifact, but rather experienced through it.

This characteristic makes this project drift away from the definition of data physicalization proposed by Jansen *et al*. (2015, p. 2). On the other hand, such embodied approach is deeply connected to the one of Dourish's (2001, p. 183) design principles: "embodied interaction turns action into meaning".

2.1.3 Opportunities

As an implication of the comparison presented in the previous section, this thesis project focused on designing an artifact that conveys data not through its shape, but through our interaction with it.

This opportunity is made apparent by the following excerpt, from a seminal work in data physicalization (this quote consists of an expanded version of the one cited in the introduction of this report, section 1.1.):

> *"[...] Tangible and Human-Computer Interaction researchers can contribute knowledge on how to best design and implement interactions for physical data representations. [...] Data Physicalization research is truly at its beginning and researchers now have the great opportunity to shape and influence it."*
> (Jansen *et al*., 2015)

Furthermore, Jansen *et al*. (2015), when proposing a definition for "data physicalization", emphasized the provisional aspect of it, by labelling it as a "working definition". The present work considers this to be an opening – an opportunity – to experiment with new ways to bridge embodied interaction and data physicalization, even though the designed artifact may not perfectly fit the proposed definition of Jansen *et al*. (2015).

2.1.4 Embodiment

It is relevant to mention that the field of data physicalization employs the term "embodiment" to refer to a specific quality of data-driven artifacts:

> *"[...] the concept of 'embodiment' was proposed to capture how a physicalization typically conveys data to its audience via the use of a metaphor that is linked to the meaning of the data it depicts [...]"* (Dragicevic *et al*., 2019)

In other words, this report also considers a representation to be "embodied" if it consists of an analogy to the bound data. The present research not only utilizes the term "embodiment" to address such metaphors, but also assigns great importance to this characteristic during the design process (presented in chapter 4) – as metaphors might harness known concepts in order to facilitate the introduction of new ones.

2.2 Tangible and embodied interaction

2.2.1 Tangible interaction

This report considers “tangible interaction” to be an encompassing term, that emphasizes the “materiality of the interface”, the “physical embodiment of data” and “whole-body interaction”, as described by Hornecker (2016), as well the how users interact “in real spaces and contexts”.

2.2.2 Embodied interaction

This report uses “embodied interaction” to refer to an “interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with us” (Dourish, 2001, p. 3).

In summary (while building on top of the definition presented in section 2.1.4), the term “embodied” is used throughout this report to emphasize two aspects: 1) how an interaction benefits from being situated in the world, and 2) how data might be conveyed through metaphors.

2.2 Active learning

Traditional classrooms – when students are just listening to a lecture – are closely related to the concept of passive learning. There is evidence, however, that an active learning situation might bring educational benefits. According to Prince (2013), actively learning is generally defined as an approach that “requires students to do meaningful learning activities and think about what they are doing” (p. 223). His research indicates that even brief activities introduced to lectures will help students remember more content (p. 229).

Active learning moments, however, are not confined to classrooms. There are several informal learning situations in which institutions try to benefit from the active learning approach. The Science Museum Group, for instance, claims to harness the “richness of object-based” learning (Science Museum Group, 2020).

As it was just mentioned, such active learning activities usually involve physical objects, whether from natural origin (*e.g.*, minerals samples brought to class) or produced by humans (*e.g.*, colored polystyrene spheres to represent planets in the Solar System). These artifacts could also be used to represent abstract and quantitative data – thus becoming more closely associated with the definition of dataphys.

Moreover, recent studies on interactive data physicalizations (*e.g.*, actuated bar charts) indicate their benefits for learning, especially for non-experts:

> *“[...] physicalizations encourage people to engage in data exploration, [...] and have the potential to support thinking about data in ways that are different from non-physical visualizations.”* (Taher *et al.*, 2017, p. 458)

As a way to support active learning, data physicalizations have also been demonstrated to improve “users’ efficiency on retrieving information” (Jansen *et al.*, 2013, p. 2593). Furthermore, researchers have been trying to understand how physicalizations can make STEM (Science, Technology, Engineering, and Math) learning more engaging and easier to understand (Hayes, 2018).

3. METHODS

In order to address the research question (as stated in section 1.4), the present study has deployed two methods, which are briefly explained in the following sections:

3.1 Research through design

The present research is focused on manifesting its results as an artifact that is aspirational and conceptually rich — not on proposing a definite solution or a framework (Gaver, 2012). In other words, the final design (presented in chapter 5) is to be considered not only a work in progress, but mainly as a basis for future work that explores the intersection between embodied interaction and data physicalization.

3.2 Qualitative interviews

This research relies strongly on qualitative, semi-structured interviews (please refer to appendix 1, 2, and 3 to read the guiding questions). These interviews were used both as a way to open up possibilities in early stages of the design process (having a generative role), as well as to validate and source user feedback regarding a specific iteration on the design process (having an evaluative role).

Due to the status of Covid-19 pandemic in Brazil throughout the development of this research, all interviews have been conducted remotely. Participants (interviewees) consist of three experts (research and practitioners in related areas), as well as three anonymized potential users, who provided feedback after testing the final prototype (*i.e.*, interacting with the website through their own smartphones – and recording their screen while doing so).

Findings from these interviews are not to be generalized, as participants were chosen by convenience (and in small number). Regardless, all interviews conducted have provided relevant and actionable insights for the development of this thesis project.

4. DESIGN PROCESS

This chapter narrates the development of the project, beginning with the initial interviews, moving into the ideation phase, and concluding with functional prototypes. The development process of the chosen idea (selected from ideation phase) is categorized into four iterations. The fourth (and last) iteration is presented as the final design in chapter 5.

4.1 Interviews

4.1.1 Researchers and practitioners

Since this thesis project requires a moderate level of familiarity with related areas, qualitative interviews were conducted with people experienced in three different activities. Arielly Tomazia Costa is experienced in mediating visits at the Geosciences Museum; Júlia Giannella, Ph.D., is experienced in lecturing information visualization and conducting data physicalization workshops; and Fernanda Silva is experienced in teaching primary school students, with a solid pedagogical approach. Each one of the three participants was invited to join a one-hour session of semi-structured interview.

Figure 10. The diagram represents qualitative interviews (conducted through the Zoom application) with experts in geography, information visualization and teaching. The circles containing the letters "A", "J" and "F" will be used as a way refer back to each individual interviewee in following sections.

All three interviews followed a similar set of guideline questions, but each one was tailored to that specific interviewee. Even though all interviews have been conducted in Brazilian Portuguese, the guideline questions for each interview are present in the appendix of this report (items 1, 2 and 3, respectively) in English. The results of this initial set of interviews are presented in the following section.

4.1.2 Pedagogic principles

After the three interviews with researchers and practitioners were concluded, their responses were clustered by similarity. As a next step, responses that strayed too far away from the themes related to the research question (*i.e.*, embodied interaction, Earth sciences, learning, museums, and data physicalization) were filtered out.

As a consequence, the author composed a list (in no particular order) of five pedagogic principles, which should provide guidance in the design of the interactive data physicalizations. The first four principles are general and could be applied to any science-related topic. However, the fifth (and last) principle is specific to Earth sciences. The letters below each list item represent the initial of the interviewee who brought that topic up.

1. Ignite children's curiosity through exploration.
   A J F
2. Associate new concept with day-to-day (or personal) reference.
   A J F
3. Encourage social interaction (experience exchange, discussion).
   A J F
4. Stimulate hypothesis formulation (not just answer questions).
   A F
5. Guide children into locating themselves geographically.
   A F

4.2 Generating and evaluating ideas

Assuming the pedagogic principles listed on the previous section as a guiding direction, the present research selected three topics covered by the Geosciences Museum as a starting point for the ideation phase. The three topics were: dinosaurs (*e.g.*, data could be related to their size or speed), minerals (*e.g.*, data could be related to their geometry or material properties), and Earth (*e.g.*, data could be related to its inner structure or dimensions).

The next three sections describe three design visions (*i.e.*, possible paths to be further developed). These early ideas are accompanied by a hand-drawn sketch, to better illustrate how each one of them could work. After evaluating all three possible paths, one of those ideas was chosen to be further developed.

4.2.1 Dinosaur Race Track

This idea was inspired by an information visualization workshop conducted by Júlia Giannella, Ph.D. (one of the interviewees). In this workshop, children were prompted to perform long jumps, which were measured (turned into quantitative data) and visualized. This type of physical activity, combined with the generation and comparison of personal data, was highly engaging for the participants.

In a similar way, the Dinosaur Race Track idea was devised. It consists of a sprint track, where real-scale dinosaur footprints would be marked on the floor. Such footprints would be placed at specific distances, calculated based on the estimated running speed and acceleration of each species.

Visitors would be invited to run through the track, in an attempt to answer the question "how far can you get in 2 seconds?". After this short period of time had elapsed, a sound would signal the runner to freeze in their current position. Visitors would, then, be able to compare their current position with the footprints on the ground. Surprisingly, recent studies suggest humans could have easily outrun a *Tyrannosaurus rex* (Montanari, 2017).

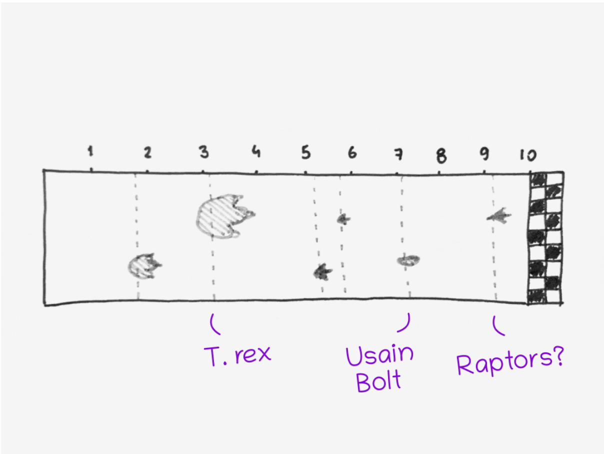

Figure 11. Sketch representing the Dinosaur Race Track idea. Participation from visitors could be prompted by questions such as "How far can you get in 2 seconds?" or "Could you outrun a *T. rex*?"

Even though this idea addresses the pedagogical principles numbers 1, 2, and 3, the author decided not to pursue this path. Although users might benefit from having a digital timer for "go" and "stop" signals, such interaction would be trivial – as most effort would be spent on data collection and information visualization, not on interaction design.

4.2.2 Mag(ma)nifier

This idea was inspired by an activity conducted at the Geosciences Museum. Arielly Tomazia (one of the interviewees) mentioned visitors are encouraged to grab and experiment with certain minerals at the "touch table" (please refer to Figure 3), where tools like magnifiers are provided. Building on top of such activity, the Mag(ma)nifier idea is about exploring crystals with a magnifier that turns colors into sound.

The name consists of a pun, which joins the words "magma", the source of all minerals and rocks, and "magnifier", a tool commonly used to visually inspect such materials. The idea, however, would be to equip certain magnifiers with electronic color sensors, so visitors could explore the material properties of crystals and turn the readings from these sensors into sounds, creating a shared sonic experience for the museum.

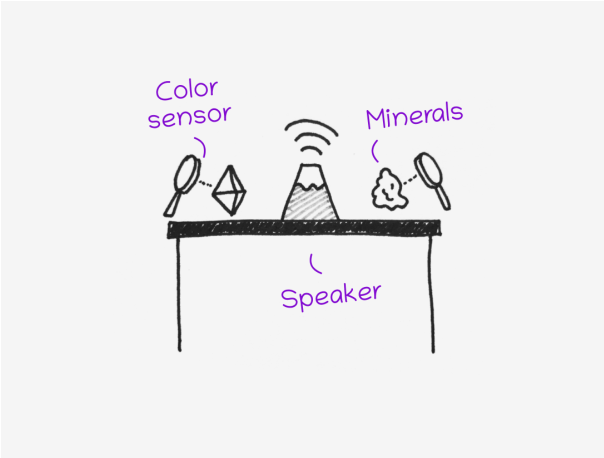

Figure 12. Sketch representing the Mag(ma)nifier idea. The shape and colors of the speaker could go as far as to resemble a volcano – an element that is deeply connected to the origin of rocks.

Even though this idea addresses the pedagogical principles numbers 1 and 3, the author decided not to pursue this path. Although users might benefit from creatively exploring the material properties of minerals through auditory feedback (an unconventional sense in doing so), the author is not familiar with electronic audio manipulation. Therefore, it could be too risky to further develop this idea without external help.

4.2.3 Magic Shovel

This idea was also inspired by an activity conducted at the Geosciences Museum. Having a background in geography, Arielly Tomazia (one of the interviewees) mentioned she often begins her guided tours by encouraging visitors to reflect on their current position on the globe – as a way to help visitors situate themselves in the vast geological space.

The Magic Shovel idea was conceived as a way to potentialize such reflective process, with the help of technology. Building on top of the "old children's tale of digging to the other side of the world" (Zimmerman, 2015), this idea aims to answer a simple question:

Where in the world would you end up if you were to dig in a certain direction?

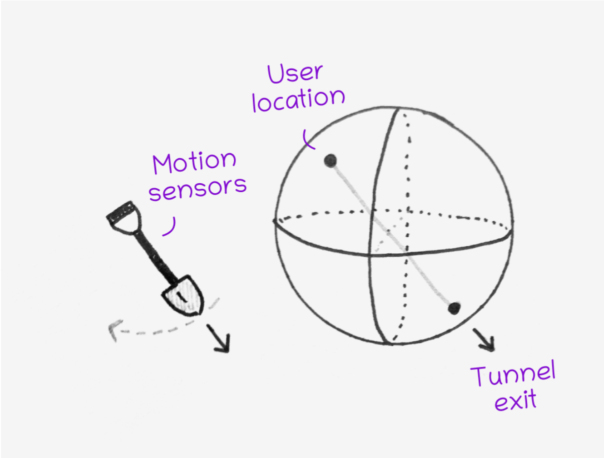

Figure 13. Sketch representing the Magic Shovel idea.

The idea consists of a real shovel equipped with orientation sensors. Visitors would be invited to point the shovel to the ground at varying angles – and a calculation would be made taking into account the visitors' position on the globe. As a result, the shovel would simulate a hole through the Earth, indicating where in the world visitors would end up if they were to dig in that direction (*e.g.*, towards a specific country).

Even though this idea might address all listed pedagogic principles, it seems to more strongly impact principles number 1, 4, and 5.

Since this shovel might help users situate themselves geographically, get a sense of Earth's magnitude and formulate hypothesis while discussing the tunnel's feasibility, this idea was selected by the author to be further developed.

As the first iteration, the sketch below represents three potential use situations of the shovel. While one visitor would be manipulating the tangible artifact and experimenting with different angles, a real-time representation of the simulated tunnel would be available for all visitors to see.

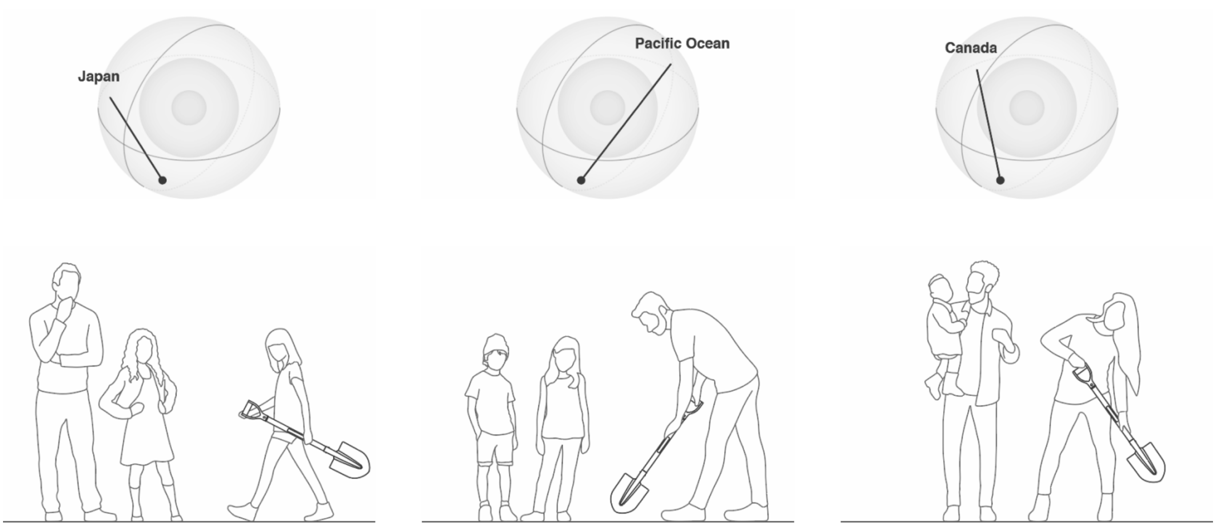

Figure 14. Sketch representing three potential use situations of the magic shovel.
Attribution: human figures adapted from dimensions.com.

In order to get early feedback from this idea, the sketch above (iteration number one) was presented to the three interviewees. All three participants demonstrated enthusiasm and provided relevant feedback.

The two most relevant insights from each participant are featured on the image below (Figure 5). Circled in purple, one insight about the project (from each participant) was highlighted. Namely: how the interactive shovel might provide an embodied sense of scale regarding Earth's magnitude; how subtle angle changes could be an issue; and how the project might also engage adults.

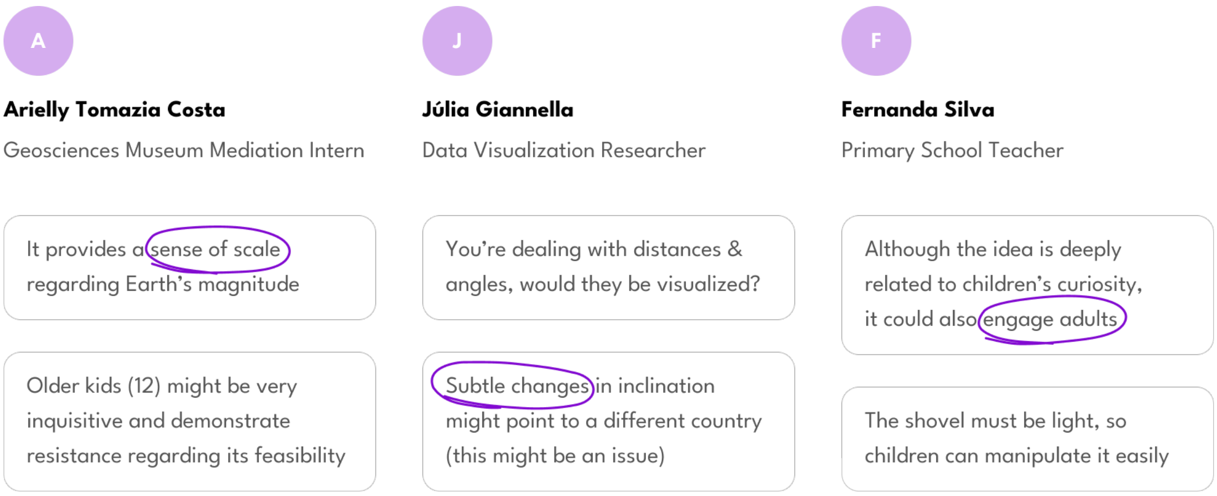

Figure 15. This diagram represents important feedback from participants (who were the same researchers and practitioners initially interviewed). The sentences showed here are not direct quotes – they been translated from Brazilian Portuguese and adapted by the author.

After positive feedback on the shovel idea, it was imperative to conduct a more in-depth analysis of related work – which spans from tangible interfaces for controlling data to web-based interactive maps in the browser. This analysis is briefly presented in the next section.

4.3 Related work

This chapter briefly analyzes projects that are related to the chosen design vision (the shovel that simulates a hole through Earth). For each analyzed project, this report provides a short description, highlights its relevance for the design vision, and concludes by stating how that project has influenced the final design of the artifact produced by the present research.

4.3.1 Tangible interface for interactive visualization

Most projects that aim to bridge tangible interaction and information visualization seem to be focused on analytical tasks. This is the case of the tangible interface project featured below (Figure 16), where physical objects are used to manipulate (*e.g.*, filter or combine) data. As users move a set of cylinders and cubes on the table, the on-screen data visualization is updated accordingly in real time (Jofre, Szigeti, Keller, *et al.*, 2015).

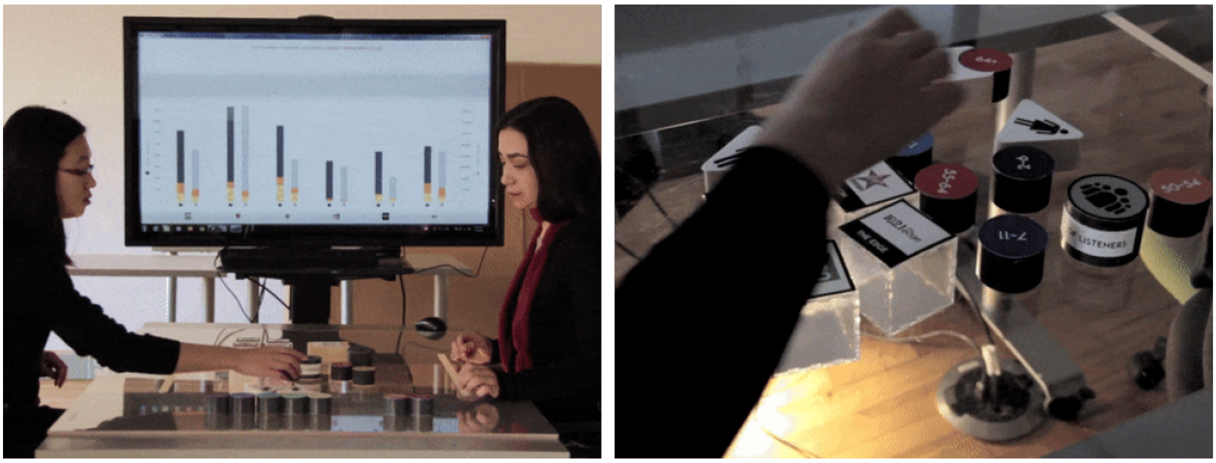

Figure 16. In this tangible interface for interactive visualization, physical objects are used to manipulate an on-screen data visualization (Jofre, Szigeti, Keller, *et al.*, 2015).

It is worth pointing that, even though the controls are tangible (*i.e.*, users can move them in the real world with their hands), they are not embodied, as they are not metaphorically related to the bound data (*i.e.*, they consist of generic shapes that are disconnected from the nature of the data they represent). This statement draws upon the definition of embodiment used in the data physicalization field, as detailed on section 2.1.4.

As future wok, authors of that project (Jofre, Szigeti, Keller, *et al.*, 2015) point to opportunities in exploring the use of metaphors for tangible interaction. This has strongly influenced the present research into emphasizing the use of a metaphor (the analogy of digging a hole through Earth, embodied by the shovel itself).

4.3.2 Dig Deep

In contrast with the previous project, the Dig Deep prototype made use of a metaphor: digging a hole through Earth. The project consisted of a sandbox equipped with a screen under the sand, which played a live video from another sandbox. People could see (and hear) each other through a hole in the sand, when they were both digging at the same time.

This project was a prototype conducted at the MIT by researcher Edwina Portocarrero, as part of a larger research project called Networked Playscapes (Zimmerman, 2015). Unfortunately, this prototype has never been documented directly. One excerpt from a related work, however, describes the project as follows:

> *"Dig Deep (Portocarrero, to be published in 2016) [...] brings the old children's tale of digging to the other side of the world to life. A live feed looking up from the bottom of a networked sandbox is played on a screen under the sand. If people are digging in both sandboxes at the same time, they can see each other through the hole in the sand. The visual feed is accompanied by audio; the sound of someone digging from the other side can be heard at a distance, enticing people to come over and interact."* (Zimmerman, 2015)

The influence the Dig Deep project had on the final design of this thesis is twofold: it demonstrated both the relevance of the “digging to the other side of the world” metaphor, as well as the role interactive artifacts might play into supporting interaction also between people (not just focusing on people-to-computer interaction).

4.3.3 Illuminating Light

Since one of the interviewees (Júlia Giannella, Ph.D.) mentioned it could be interesting to visualize the varying angles and calculated distances, the present research sought inspiration from a seminal work in tangible interfaces.

Illuminating Light (Underkoffler *et al.*, 1999) is a seminal work by the Tangible Media Group, at the MIT Media Laboratory. As a tangible prototyping tool for optical engineers, it fosters an embodied sense of how laser beams behave, at varying angles, by using tangible artifacts that are analogous to mirrors. Due to this metaphor, the present research also considers this project to be embodied, regarding the definition mentioned in section 2.1.4).

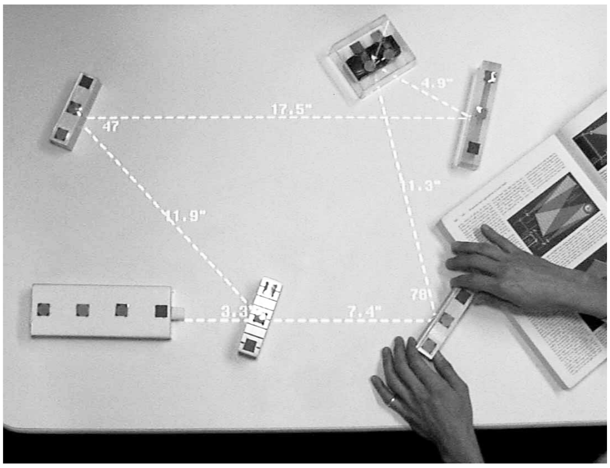

Figure 17. Illuminating Light, a tangible prototyping tool for optical engineers. This prototype mimics the behavior of laser beams by projecting computer-generated lines and numbers onto a table – which are updated constantly, as users manipulate mirror-like objects (Underkoffler *et al.*, 1999).

This interactive workbench has inspired the final design to include numerical values onto a visual representation of a globe (*e.g.*, as a label anchored to the center of the virtual tunnel, whose value would be constantly updated to match the length of the simulated tunnel, in thousands of kilometers).

4.3.4 Globus IMP instrument

An early idea that emerged, while developing the first iteration of the present project, was to create a physical globe: one that would be actuated to match the direction and angle that the shovel would be pointing to.

For instance, one could imagine a globe made from translucent material. Attached to this globe, there would be a laser beam emitter, positioned on the surface of the globe, at a location equivalent to the geographic coordinates of the user. As the visitor moved the shovel, the laser emitter would be automatically angulated to match the shovel direction and, as a consequence, the laser beam would hit a specific location on the other side of the globe, revealing the destination of a hypothetical tunnel towards that angle.

However, taking into account that this would require a lot of effort into creating such physical model, as well as that actuated globes are not something entirely new (please refer to Figure 18), this idea was abandoned for the scope of this research. Instead, the present thesis focused on creating a tangible artifact, but that would convey data through virtual means (and not through a physical model).

Figure 18. Photo of a Globus IMP instrument, in which a rotating (actuated) globe indicates the position of Russian spacecrafts (*i.e.*, the location they are currently flying over). The device was initially used during the world's first manned spaceflight, by Yuri Gagarin, on April 12, 1961 (Dragicevic & Jansen, 2012).

4.3.5 Web-based projects

This section briefly presents five websites that are strictly related to a hypothetical tunnel through Earth.

The first two projects (Figures 19 and 20) are interactive web-based tools. To use them, users either type in their addresses (Figure 20) or rotate the globe to match their locations (Figure 19). In return, users visualize, in a map or a virtual globe, the coordinates of the antipode (*i.e.*, the exact opposite side of that point on the globe) of that location.

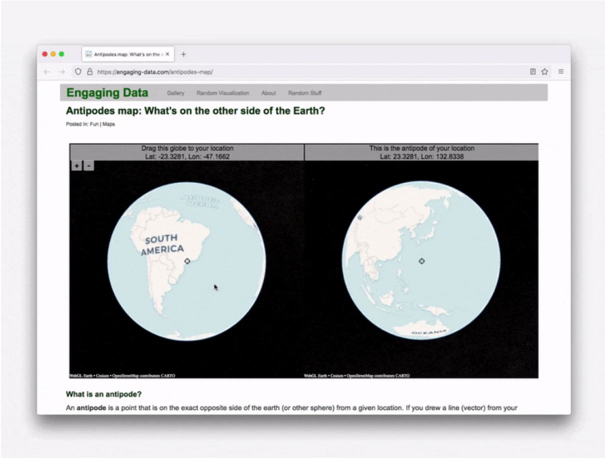

Figure 19. Screen capture of “Antipodes map: What’s on the other side of the Earth?”. It consists of interactive 3D graphics. By rotating a virtual globe, uses are able to see the matching antipode (the exact opposite point) of that location, as a second globe is inversely rotated in real time. A crosshair indicates both the user’s location, as well as the calculated antipode (Engaging Data, 2019).

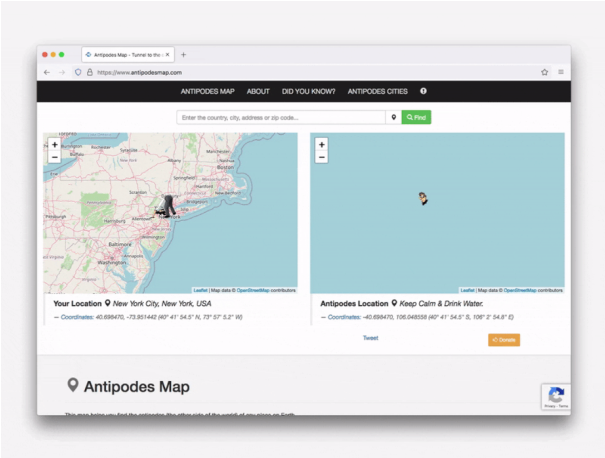

Figure 20. Screen capture of “Antipodes Map” (Antipodes Map, 2014). It combines two interactive 2D maps. The first one displays the location of the user (as defined by the address that was typed in), and the second displays the exact antipode of that location (most antipodes are in the middle of the ocean).

Those two interactive maps influenced the present research into creating a different representation of the tunnel through Earth. Instead of just indicating the “entrance” and the “exit” of the tunnel on the map, the final design should, in fact, represent the whole path of such tunnel, through the interior layers of Earth.

The last three projects are also related to making a trip through the center of the Earth. However, they are not interactive. These three projects offer, on the other hand, an interesting perspective into the potential users of the proposed interactive artifact.

Even though the initial idea of this research was to focus on children (just like the video showcased on Figure 21 does), it seems that a lot of interest in this topic (and its real-life limitations) arise from adults.

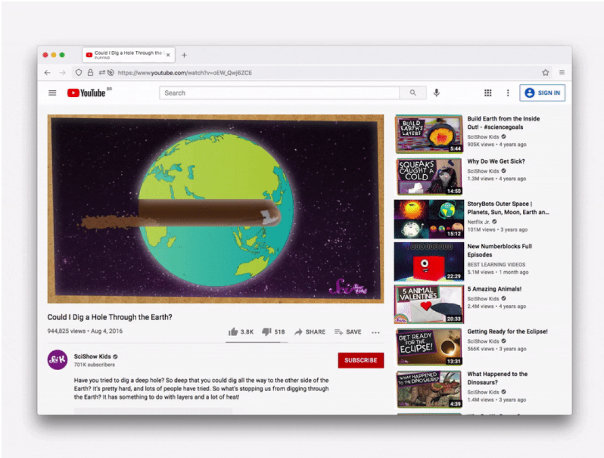

Figure 21. Screen capture of the “Could I Dig a Hole Through the Earth?” video on the YouTube platform. The content is targeted at children and both the shovel and digging metaphors are present (SciShow Kids, 2016).

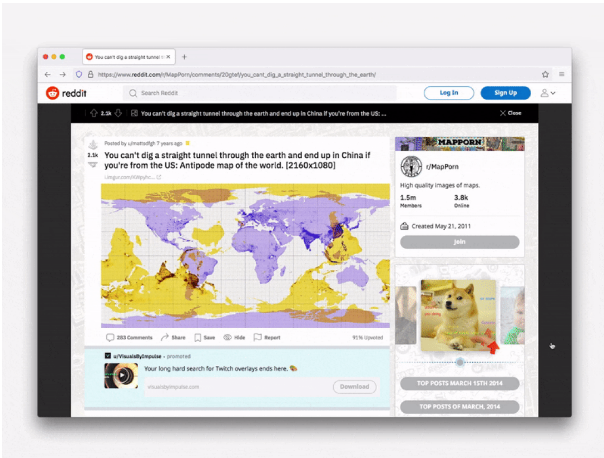

Figure 22. Screen capture of a map titled “You can't dig a straight tunnel through the Earth and end up in China if you're from the US: Antipode map of the world”, posted on the Reddit platform. The content is targeted at non-specialists. On the comments section, discussion around an angled tunnel also exists ([mattsdfgh], 2014).

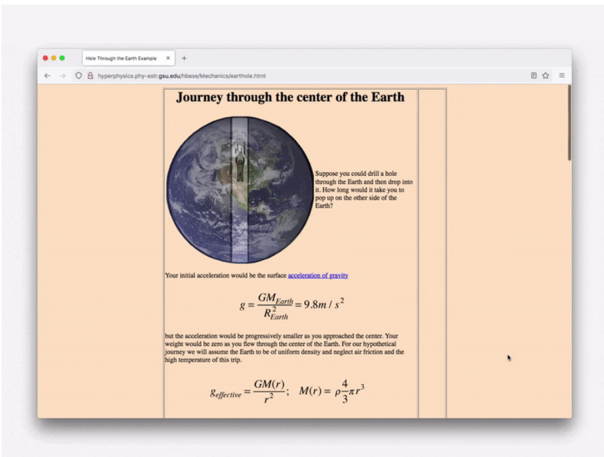

Figure 23. Screen capture of the “Journey through the center of the Earth” article, posted on the decades-old HyperPhysics website, hosted by Georgia State University. Targeted at specialists, it is dedicated to advanced estimates, like the trip’s duration in minutes or how gravity would vary inside the tunnel (Nave, 2002).

The interest from adults is made apparent by analyzing the kind of discussion present on forums (even by non-specialists), as hundreds of comments were posted regarding an antipodes map (Figure 22). Debate regarding its feasibility and its geophysical limitations is constantly present, as well as the discussion about an angled tunnel (*i.e.*, not through the exact center of the Earth). These varying angles became the focus of the present project.

Groups of specialists also recurrently debate estimates and simulations (please refer to Figure 23 for an anecdote, as it consists of an article for physicists, dedicated to advanced estimates, like the hypothetical trip's duration in minutes or how gravity would vary inside the tunnel).

Taking into account that this hypothetical tunnel through Earth is a common – and highly discussed – topic among groups of both specialists and non-specialists, the present research chose to shift its focus – from children visitors, to adult visitors.

4.4 Target users

Building on top of the insights from section 4.3.5, as well as from the feedback by the primary school teacher Fernanda Silva (one of the interviewees), who mentioned that the shovel idea could easily engage adults as well (please refer to Figure 15), this research chose to shift its focus. One factor that was also weighted-in for this decision was the convenience of access to participants. That being the case, the three anonymized participants who tested the prototypes were all adults, whose age range is between 20 and 60 years old.

Figure 24. This sketch represents three potential use situations of the shovel, however, all four adults represented are highlighted, indicating they were the chosen target age group for this project. Attribution: human figures adapted from dimensions.com.

4.5 Prototyping

The second and third iterations of the project are described on this chapter. By taking into consideration the feedback from the first iteration (Figure 14) and the insights from the related work section (chapter 4.3), the present research sought to create a functional prototype.

Such prototype should factor in both the visitors' location and the direction that they would be pointing the shovel to. In return, as the result of a computer-supported simulation, the prototype should indicate the calculated destination (*e.g.*, a specific country or an ocean) to the visitor, as well as the length of the hypothetical tunnel to reach that location.

A simplified diagram of such data exchange (*i.e.*, data inputs and outputs between the shovel and an external computer) is represented below (Figure 25).

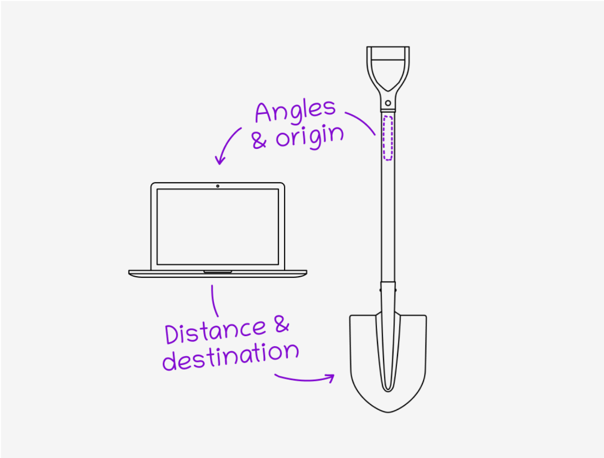

Figure 25. This diagram represents a simplified version of data exchange. There would be two types of data input (from user to computer): North-based readings from the orientation sensor and the geographic coordinates of user's position. There would also be two types of data output (from computer to user): the country of destination (if any) and the tunnel length until that place. The initial idea was to use Bluetooth Low Energy (BLE) for data transfer between shovel and computer.

An external computer was initially chosen to process the data for two reasons:

1. The first one is that, since visual representation of the tunnel simulation was desirable (as suggested by interviewees and described in section 4.3.3), it would be best to process calculations in a virtual 3D space, rather than just calculate using pure trigonometry. In other words, if the project was to present two different types of feedback (the country of destination, as calculated using pure math; and a visual representation of the globe and tunnel, as created in a virtual 3D scene) the results could be different from each other, due to slight imprecisions in the data (more details in section 6.2, item 2). Therefore, it would be more consistent and efficient to employ a single way of calculating – and the comprehensive way (*i.e.*, that could produce both types of feedback) was using a 3D virtual scene.

2. The second reason for utilizing an external computer is related to the author's familiarity with programming languages that are browser-based (*i.e.*, HTML, CSS and, mainly, JavaScript). Furthermore, these languages (that are the backbone of every website) enable immense freedom when creating visual representations.

As a consequence, it was decided that electronic components attached to the shovel would send data to a website, that would simulate the tunnel and output the results to the user (as illustrated on Figure 25).

The second iteration of the project was based on Arduino, the open-source electronics platform, as detailed below.

4.5.1 Arduino-based

In order to create a working prototype, the Arduino platform was initially chosen as a way to capture and communicate data with an external computer. Both the Arduino Uno and Arduino Nano 33 BLE boards were used for prototyping (separately). The idea was to group a board, a battery and some external electronics (*e.g.*, orientation sensors and a GPS module) and attach these to the shovel, as illustrated below (Figure 26).

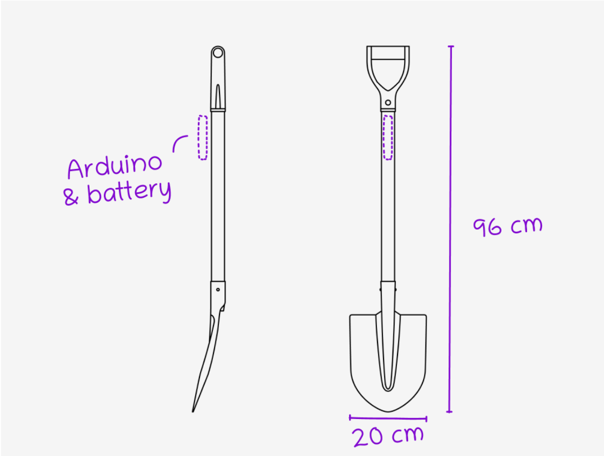

Figure 26. This diagram represents the position on the shovel where electronics would be attached to. The idea was to miniaturize the hardware (using Arduino Nano 33 BLE), a GPS module and a 9V battery. The electronics should not take much of the handle area, as this would make handling the shovel more difficult for users.

In parallel to the setup of the hardware and the programming of the board (to retrieve sensor data), some experiments with browser-based technologies (mainly JavaScript) were made. Those experiments tested different ways of creating a virtual 3D globe. After exploring different representations (Figure 27), the present research settled on a globe that would, as the final design (chapter 5), render three main elements (which would convey relevant information, with minimized visual clutter):

- Earth's crust (as the wireframe of a sphere, so you users can see through it)
- Countries' geometries (as elements that could be individually highlighted)
- Simulated tunnel (as a rotating cylinder, anchored at the user's location)

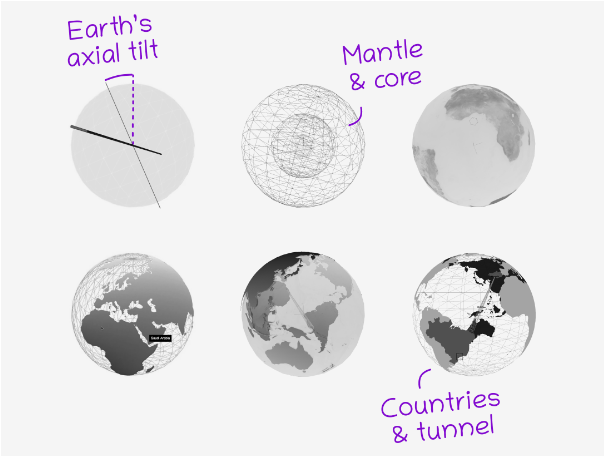

Figure 27. This composition features six screen captures of virtual 3D globes and tunnels during prototype development. Experiments were made with in-browser JavaScript, using the 3D capabilities of the libraries p5.js (first globe on the upper-left corner) and three.js (all others).

Back to the hardware, some experiments were also conducted to explore ways of providing feedback to users directly from the shovel. In the sequence of images below (Figure 28), an Arduino Uno board, a battery and a LED display were (temporarily) attached to the handle of the shovel using a few elastic bands. The goal of this setup was to provide visual feedback for users – as they would be pointing the shovel at different directions – representing whether they would be hitting water (*i.e.*, an ocean) or land (*i.e.*, a country) on the other side of Earth.

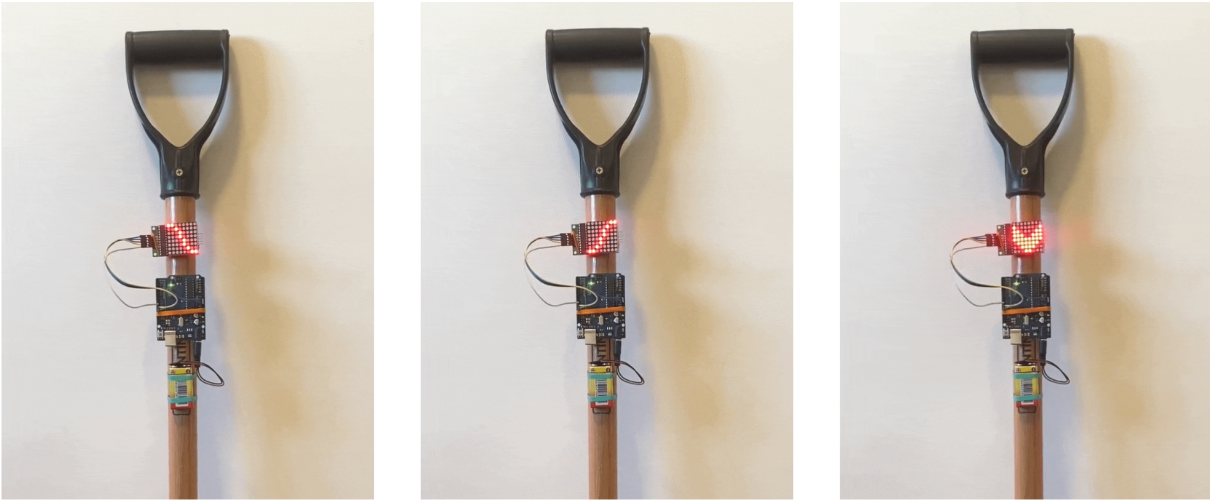

Figure 28. Sequence of photos of the Arduino-based prototype (using an Uno board, a 9V battery and an 8x8 red LED display). The first two images display an animated wave pattern, that would indicate the user was pointing to an ocean. The third image displays an animated down-arrow pattern, that would indicate the user was pointing to land (a specific country) on the other side of Earth.

As another experiment, the visual feedback of the LED display was accompanied by auditory feedback, coming from a buzzer connected to the Arduino. The buzzer constantly emitted a low synthetic "wavy" sound, that resembled computer static. This noise was paused whenever the user was pointing to land on the other side of Earth. Then, the sound was replaced by two short beeps, followed by some moments of silence. Even though the author had not much experience with sound manipulation, this auditory feedback made the experience feel, somehow, more complete (according to the perception of the author while playing with it).

Another option for auditory feedback would be if the artifact mimicked users could hear the other side of the world, using pre-recorded sounds. Whenever users were pointing to water on the other side of Earth, ocean waves would be heard. Then, these wave sounds would fade into people chattering in different languages as users moved the shovel (and were pointing to a specific country). However, there was a limited amount of effort to be employed during this thesis and the author decided not to pursue this path.

Although this type of feedback really made it felt like the shovel was acting like a real "land detector" (again, according to the author's on perception), there was no way to communicate which country the user was pointing to. One idea to address this would be to use a synthetic voice to speak aloud the name of each country. However, as mentioned on section 4.2.2, the author is not familiar with audio manipulation and decided to focus on visual feedback for this thesis.

Meanwhile, advancements had been made in both the virtual 3D globe (running in the browser) and the code to read the angles from the orientation sensor (running in the Arduino board). The sequence of photos below (Figure 29) highlights how, by moving the electronic components, a virtual 3D tunnel (in red on the screen) could also be moved accordingly.

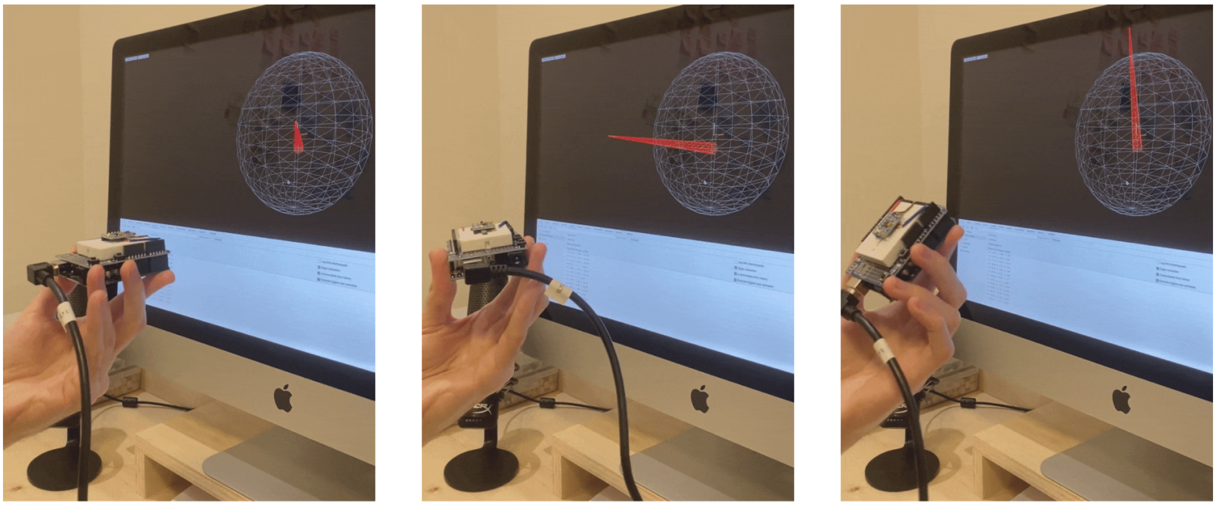

Figure 29. Sequence of photos of the Arduino-based protype, connected to a web browser on the computer through USB cable, using the experimental Web Serial API. An Inertial Measurement Unit (IMU) module was used to send raw orientation data from the handheld device to the website, controlling the rotation of a virtual tunnel in a 3D globe, created using the three.js library.

Even though the Arduino-controlled website worked, it presented several technical limitations that the author could not overcome:

1. The readings from the orientation sensors were oscillating considerably. The author attempted to smooth the readings using a Madgwick filter (*i.e.*, combining readings from both the accelerometer and the gyroscope to calculate orientation), but without success.

2. The orientation readings also appeared to be relative to the position of the Arduino board when it was turned on. That is, the readings were not absolute (*e.g.*, always relative to Earth's North), which is a requirement for simulating the tunnel through Earth. This could be compensated (*i.e.*, readings could be converted into North-based angles) by employing extra effort and factoring in the values from a magnetometer (a digital compass).

3. The Arduino had to be connected through cable with the computer, as the author could not get the Bluetooth connection established with the browser (currently, it consists of experimental technology). Attempts were made using a Bluetooth 4.0 module (HM-10), as well as the built-in Bluetooth offered by the Arduino Nano 33 BLE board. Although the author was, in fact, able to communicate data between the boards and external applications, no connections were established between the boards and the browser (which would be running the virtual 3D scene).

In order to move forward with a working prototype, the author decided to employ a smartphone instead of an Arduino board. Such phase is detailed in the following section.

4.5.2 Phone-based

As the third iteration of the design, this step is based on the idea of attaching a smartphone to the shovel (Figure 30). The phone would be responsible for providing orientation readings (as well as an easier way to calculate North-based angles) and geolocation information (the current latitude and longitude of the user). Besides, the external computer (previously described on Figure 25) would no longer be necessary. Instead, the website (that would simulate the tunnel in a 3D virtual scene) would be running directly on the phone – with direct access to the device's sensors.

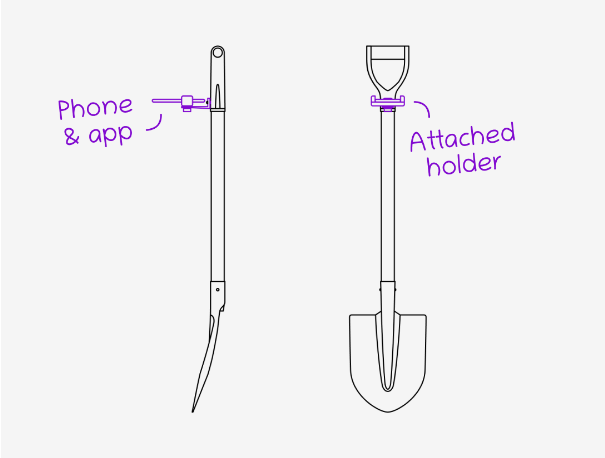

Figure 30. This diagram displays the desired position on the shovel to attach a phone holder to. In this position, the "resting" orientation of the phone (when shovel points straight down) would be parallel to the ground. The device screen would also be in a suitable position to convey visual information to the user (the country of destination and tunnel length), without users having to look away from the shovel.

In order to assess the potential of a smartphone to perform the functions detailed on the previous paragraph, a prototype was developed (Figure 31).

It consisted of an experiment with the phone's built-in digital compass (magnetometer), orientation readings (a combination of both accelerometer and gyroscope readings) and automatic geolocation features (mainly due to its GPS capabilities).

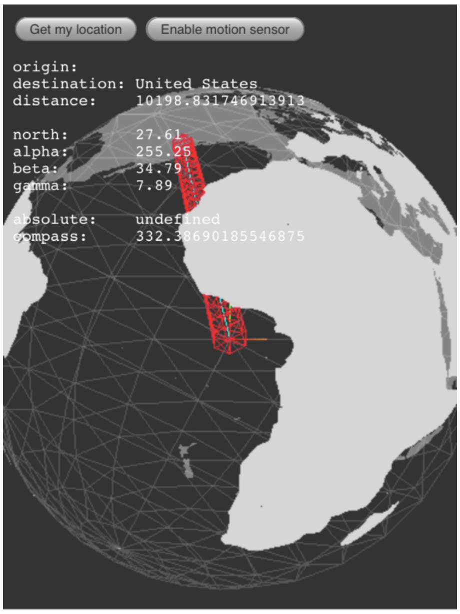

Figure 31. Screen capture of a mobile device (iPhone 7) running a website as a prototype. This should not be considered as a proposed interface – but rather as an easy way to debug and assess the values provided by the sensors.

Although the North indication was not always pointing at the exact same direction (as tested on an iPhone 7), the orientation data seemed more reliable (*i.e.*, it better resembled the actual movements of the device) than the Arduino readings described on section 4.5.1.

Similar to what was required with the Arduino board, the orientation readings on the iPhone are not absolute. Instead, they appear to be relative to the position of the device when the website was loaded. However, the North direction was easier to obtain (when compared to its Arduino-based counterpart), so the compensation – the calculation of absolute orientation values – was easier to perform. As a sidenote, the orientation values currently provided by Android devices seem to be already North based, so that compensation would not be necessary.

The automatic geolocation feature was also much easier to perform on the smartphone – as the GPS, along with other similar geolocation techniques, was already built-in.

As the benefits offered by the phone-based approach seemed promising, the website prototype (Figure 31) was visually refined. Even though it presents the same three elements described in section 4.5.1, the new design of the 3D virtual globe aimed to reduce visual clutter (Figure 32).

The tunnel is now thinner and represented with a solid red color. The sphere wireframe was replaced by a set of arcs representing latitude and longitude lines, at 10 degrees intervals. Thousands of tiny stars were placed on the 3D scene to increase user's perception of camera rotation. Finally, markers were anchored at the globe (*i.e.*, the outlined white square at the origin position and the white dot on the destination), as well as a text label, that displays the name of the country of destination.

Figure 32. Screen capture of the virtual 3D globe, designed for easy visualization of the tunnel direction, origin location (the user's position) and destination (the country they would end up in). The 3D scene, created using in-browser three.js, calculates the tunnel length and country of destination using ray casting and collision detection.

As an overview, the phone-based approach has three main drawbacks:

1. The first one is that websites running in the browser of a smartphone will frequently prompt users to allow access to the device's sensors.

2. The second one is that a smartphone is more expensive than an Arduino board (even when the price of the board is combined with other required electronic components).

3. Finally, the third drawback is that the smartphone is not easy to hide or to miniaturize, in order to create an artifact with embedded (*i.e.*, invisible) technology.

Taking those factors into account, the smartphone solution presented in this chapter should be considered as a provisional way of putting a prototype together – not as the desired way for it to be implemented in museums.

5. FINAL DESIGN

This chapter presents the fourth (and last) iteration of the project. To summarize what has being detailed in previous chapters, this thesis proposes a tangible artifact (a shovel equipped with orientation sensors) that could be used by visitors of Earth sciences museums. A web-based application has been developed for this research, under the title of *SuperTunnel Simulator*. By running this application, the shovel calculates a hole through Earth, indicating where in the world visitors would end up if they were to dig in a certain direction.

For the final version of the design (even though it should be considered as a work in progress, as described in the end the previous chapter), an off-the-shelf phone holder was attached to the shovel. This holder needs to support a smartphone running the *SuperTunnel Simulator* website. This common holder for mobile devices was screwed into the shovel, taking advantage of a previous hole on the handle (Figure 33). Apart from the attached phone holder, the shovel was subject to no modifications. In this sense, the project has the potential be of low-cost implementation.

Figure 33. Photo of the attached phone holder (with an iPhone 7 – the device used for prototyping – on top of it). A common support for mobile devices was screwed into the shovel, taking advantage of a previous hole on the handle.

It is worth noticing that, although the shovel was also an off-the-shelf item, it has been chosen due to specific characteristics. It is composed of a wooden handle, a plastic grip, and a non-cutting metal blade. More importantly, however, are the dimensions of the shovel (Figure 29) and its light weight (around 1,2 kilograms). These properties make it suitable to be handled by both adults and children (around 8 years old or older).

Characteristics such as the shovel's light weight and its reduced size were suggested by Fernanda Silva (the primary school teacher), during a feedback session (Figure 34). To illustrate how both children and adults could manipulate this model of shovel, the human figures present on the first iteration (Figure 14) are represented to scale, while manipulating the chosen the shovel model (which is also to scale).

Regarding the *SuperTunnel Simulator* application – that would be running on the smartphone attached to the shovel –, it consists of two modes of representation: the first-person and the third-person modes. Both of which are detailed in the following sections.

5.1 First-person perspective

The first-person perspective consists in a visual representation of the globe as if the tunnel's origin was anchored to the user's location. As an imagination exercise, one could try to picture themselves as if they were in a standing-up position, while looking straight down into the ground. Below their feet, a giant tube – represented by the red cylinder (Figure 34) – would connect their current location to the other side of the Earth. In addition, one could imagine the Earth to be completely transparent (as if the floor – and everything else – was made out of glass). As a consequence, the only visible element would be the red tunnel below their feet.

This is what the first-person perspective of the app aims to simulate (Figure 34). In addition, as the person in this analogy points the shovel at the ground (at varying angles), the red tunnel below them would move accordingly. Whenever this tunnel was to encounter a country (not an ocean) on the other side of Earth, the geometry of such country would suddenly become visible.

On the bottom of the screen (Figure 34), the user is also presented with a digital compass that – as expected – indicates the North direction, even while users are spinning around their own axes. The length of the simulated tunnel is also present as a numerical representation (a rounded value, in thousands of kilometers).

A textual label for the country of destination is also present. The label's position is fixed at the center of the screen, so users could keep their eyes focused on a single area of the screen while moving the shovel. Otherwise, they would have to follow a moving label across the screen, if the label were anchored to the other end of the virtual tunnel.

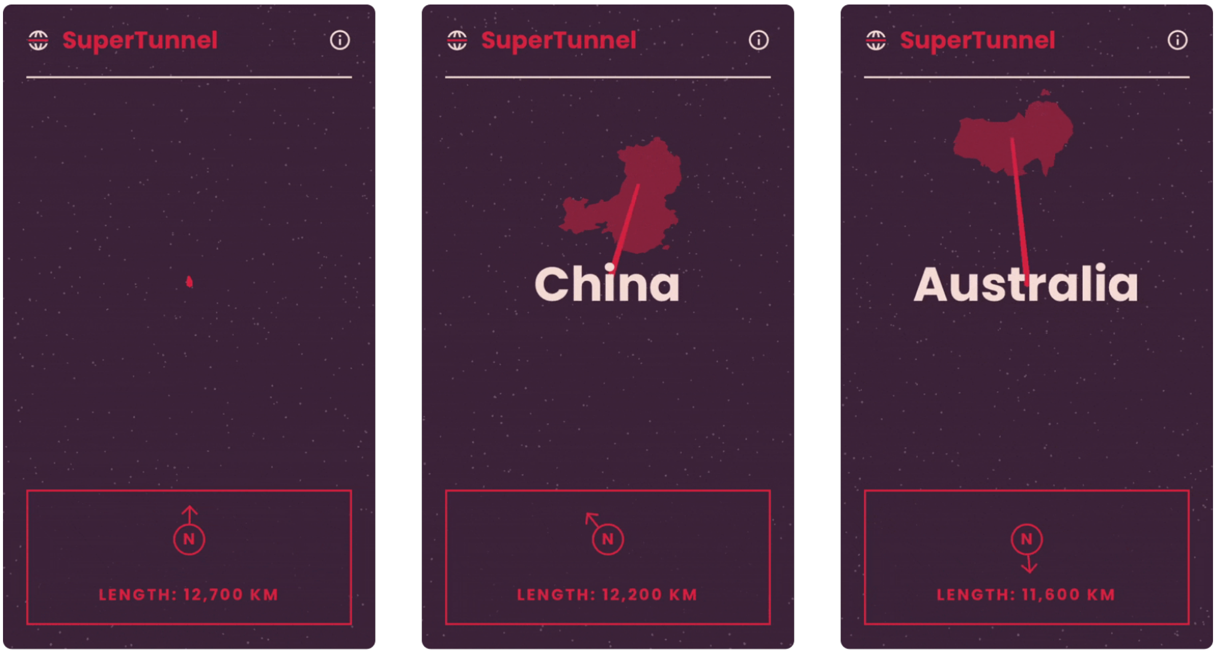

Figure 35. Sequence of screen captures on the mobile device running the final prototype. This website was created to render motion data into a 3D globe. Here, the globe is hidden (to avoid visual clutter), except for the country of destination and the tunnel (the thin red cylinder). On the bottom, a simple compass indicates the North direction (it changes as the user spins) and a numerical representation of the tunnel length. A tunnel straight down (first image) reaches the antipode of the user location – and is approximately 12,700 km long.

The following sequence of photographs (Figure 35) aim to represent the experience of interacting with the shovel, by moving it around. It is possible to notice that, even with slight changes in angulation, users might find themselves pointing to a whole different country. On the first image (starting from the left), the user would reach Japan – if a tunnel was to be dug in that direction. On the second and third photos, the user would reach South Korea and Russia, respectively.

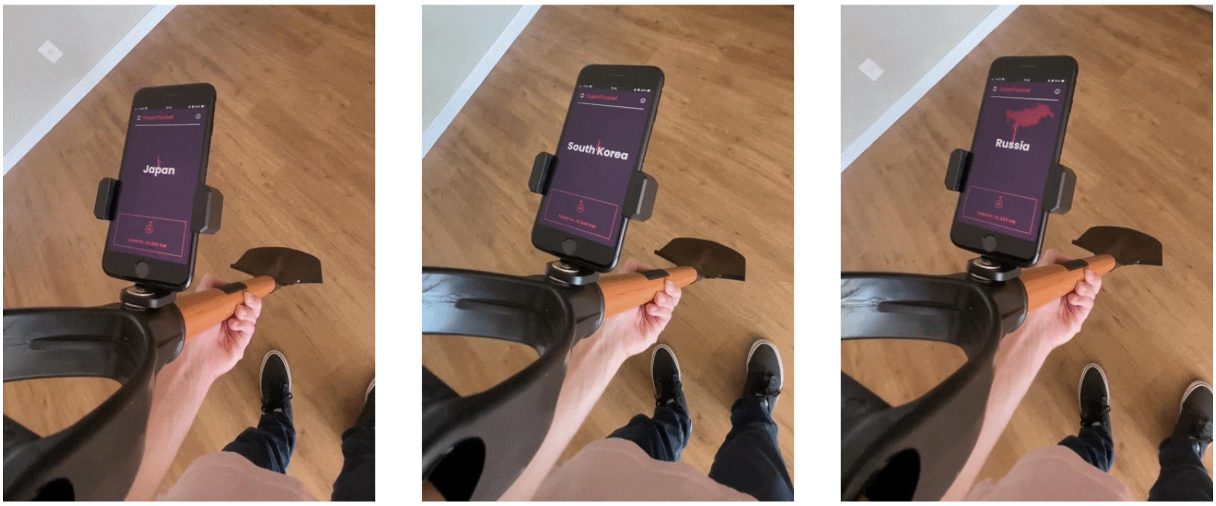

Figure 36. Sequence of photos that aim to represent the user's point of view while interacting with the shovel. The website renders the destination's name, as well as a red cylinder as the tunnel– which provides visual feedback on the shovel's motion (so users feel it is working). With subtle changes in the angle at which the shovel points to the ground, a different country might be virtually reached.

5.2 Third-person perspective

In contrast with the point of view described in the previous chapter, the third-person perspective consists of a visual representation of the globe as if the user was an external observer. In other words, one could imagine a spectator floating in space, orbiting the Earth and observing it from afar.

Within the context of museums, this point of view could be employed as part of an installation. While one visitor would be interacting with the shovel (and experiencing the first-person perspective), bystanders would be able to see the results of such interaction in real time. These results could be manifested as a projection of the virtual 3D globe, in which the simulated tunnel would be directly coupled with the movements of the shovel. The point of view of a bystander is illustrated below (Figure 36).

Figure 37. This sequence of photos aims to represent what a spectator experiences while observing someone interacting with the shovel. These images were digitally overlayed with a 3D globe. On the first image, the user would reach China after crossing a tunnel that is 12,000 km long. On the second image, the user would reach Australia, after crossing a tunnel that is 11,600 km long. Within the museum, there could be a projection of the 3D globe, animated in real time according to the shovel's movement.

The color scheme of the *SuperTunnel Simulator* application was chosen with that situation (projecting the virtual globe) in mind. With small tweaks to the color palette (*e.g.*, adding more contrast and making the background into pure black), the projection could be integrated into the museum environment in a seamless way (*i.e.*, without any apparent rectangular boundaries).

The same version of the *SuperTunnel Simulator* application that was employed in the prototype featured in this chapter (Figures 34, 35, and 36) was also subject to testing and feedback from potential users. Furthermore, the prototype is open-source and available on GitHub (Sueiro, 2021).

For the reasons previously described in section 3.2, no in-person testing sessions with users were conducted (apart from the author's own testing sessions). However, relevant insights arose from remote interviews and feedback sessions. These findings are contained in the following chapter.

6. ANALYSIS AND MAIN RESULTS

The present chapter analyzes the limitations, benefits, and overall findings of the present research (including insights originated from qualitative interviews and prototype feedback).

6.1 Limitations

The list below highlights five relevant limitations of the current research, in no particular order. Such limitations arise both from technical aspects (items 1 and 2), as well as from methodological constraints (items 3 and 4). The fifth item, however, originates from the chosen modality of data representation employed by the final design.

1. In case the smartphone – for whatever reason – offers imprecise data (*e.g.*, imprecise North direction), that might largely impact the results of the simulation.

2. Slight simplification in countries' geometries might impact results, especially in coastal regions (*e.g.*, coordinates of a coastal city might, instead, point to the ocean).

3. Since the Geosciences Museum was closed during this research, no in-person tests were conducted.

4. Findings are not to be generalized, as participants were chosen by convenience (and in small number).

5. Since the final design is still heavily visual, users tend to focus on the screen, not on their own moves.

The last item of the list is considered the main limitation of the current project. Due to the author's previous experience with visual representations, it is plausible that this had manifested itself as a bias during the design process. As a consequence, the visual representation (*e.g.*, the virtual 3D globe) was privileged to the detriment of other means of conveying data (*i.e.*, the destination of the tunnel and its length) to the user (*e.g.*, auditory feedback).

In order to explain why the visual representation might have worked against the proposed embodied interaction, the following paragraphs draw upon literature, as well as feedback from participants that have tested the prototype.

With the goal of stimulating people to reflect on their own bodies, Höök (2018) devised a prototype that would gather data from their bodies and generate computer-supported abstract visual representations of such data. Those representations were projected in front of the users. Although users have reportedly enjoyed the visuals, the researchers noticed that users' attention was mostly focused on the visual representation – and that they were utilizing the movements of their bodies as a way to merely control the visualization:

> *"The visual focus of this prototype [Sarka] drew too much attention away from the user's inner experience of the movements."* (Höök, 2018)

A similar insight was obtained from one of the participants that tested the prototype, who mentioned that it was hard to know where to point the device to, in order to reach certain countries. This was mentioned in such a way that indicate the device was being used just as a tool to control a virtual tunnel. In a strict sense, this fails the fifth pedagogic principle, as listed in section 4.1.2, related to helping people locate themselves geographically. This principle was not addressed because situating yourself is supposed to be a reflective and internal process. However, it was being outsourced to the device.

Back to Höök's (2018) prototype, in order to prevent that focus on the visual component, a new version of the prototype was created. This version used audio feedback (not visuals) to communicate with the people experiencing it – thus allowing them to focus on their own body movements (Höök, 2018).

In retrospect, it is possible that this thesis would have benefited from a similar approach. Exploring auditory feedback – even though the author was unfamiliar with techniques to perform it – could have proven to be an interesting alternative to purely visual feedback.

6.2 Embodiment

This chapter briefly presents three benefits of "embodiment" on the final design. The first and second benefits, as listed below (on Figure 37), are closely related to the advantages of interacting with a tangible artifact. The third benefit, however, is more closely related to the concept of embodiment as used in the data physicalization field (*i.e.*, utilizing metaphors), as defined on section 2.1.4.

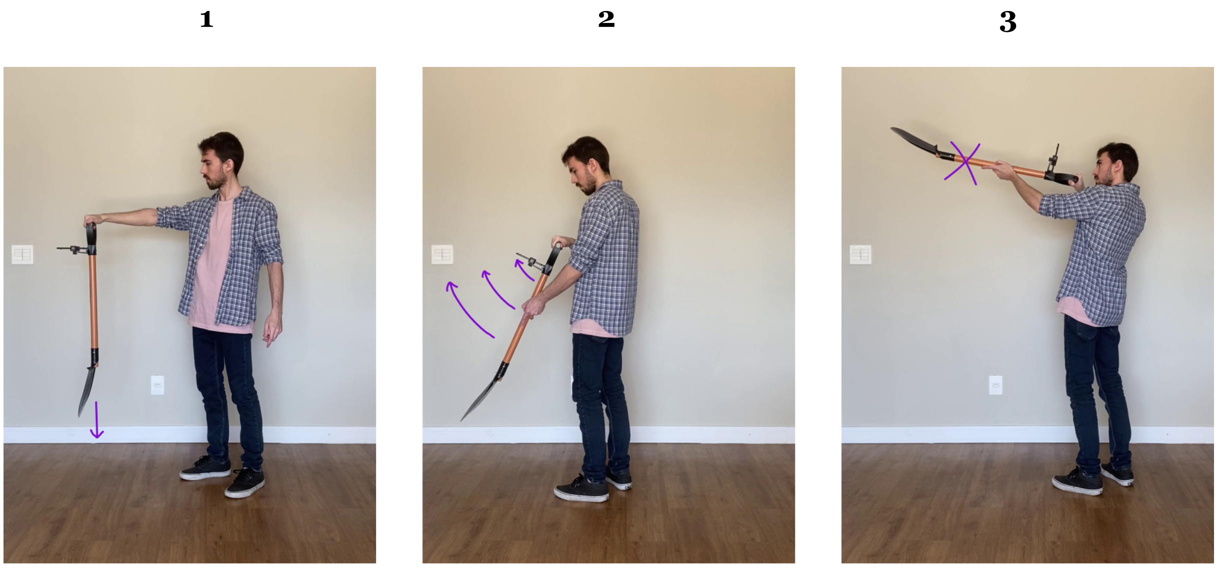

Figure 38. This sequence of images aims to represent three benefits of embodied interaction with the shovel. Images were overlayed with digital arrows and symbols.

1. **Simulating a tunnel straight down is easier:**
   Due to gravity, a tunnel through Earth's core (an antipode) is easily simulated by simply holding the shovel loosely by its handle.

2. **Fine-tuning angles is easier due to lever effect:**
   If users were holding the phone directly, subtle movements would greatly shift the angle (this effect is minimized by holding the shovel instead).

3. **Pointing to the ground feels more natural:**
   The digging metaphor (embodied by the shovel itself) facilitates the intended use of the artifact (pointing the shovel downwards, not upwards).

It is worth noticing that the benefits above were perceived by the author himself, during test sessions with prototypes. Although these sessions have not followed any defined structure, they were strongly inspired by Höök's words on valuing the designer's own perceptions and experience during the design process, as the following excerpt states:

> *"[...] soma designing emphasizes a first-person, hands-on, active engagement and experience. The designer's lived experience must be in place to feel the fine nuances of different movements"* (Höök, 2018)

6.3 Findings

This chapter is dedicated to addressing the proposed research question, as stated in section 1.4. In order to seek an answer to that question, the most relevant insights came from the initial qualitative interviews with experts (researchers and practitioners), as well as from the of feedback provided by them after being presented with the first iteration of the project.

The present research indicates that embodied interaction might influence Earth sciences learning not by strictly teaching academic content to people, but rather by enticing people's own curiosity. It is worth noticing that such finding is aligned with the engagement approach devised and practiced by the Science Museum Group, as evidenced by the following excerpt:

> *"We ignite curiosity around STEM by assisting discovery through active participation and social interaction."* (Science Museum Group, 2020)

As tangible artifacts might enable people to actively (Prince, 2013) explore data, they might also stimulate people into formulating hypothesis (*e.g.*, trying to point the shovel to a specific country or discussing the feasibility of the tunnel with friends and family).

By referring back to the pedagogic principles (as listed on section 4.1.2), the present research indicates that interactive data physicalizations might help to ignite visitor's curiosity and to stimulate hypothesis formulation (principles 1 and 4). Furthermore, by employing metaphors (please refer to section 2.1.4 for details), interactive data physicalizations might also help to convey a new concept (*e.g.*, a tunnel through Earth) by associating it with a known reference (*e.g.*, shovels are tools for digging), which relates to the second pedagogic principle.

As stated in the limitations section (6.1), the present research was not able to observe people using the proposed interactive data physicalization within a real use situation (museum visits), due to methodological constraints. Therefore, there are no clear indications whether such artifacts might encourage social interaction (*e.g.*, experience exchange and discussions) among visitors (which is related to the third pedagogic principle).

7. DISCUSSION

7.1 Perceiving data through interaction

This chapter is dedicated to taking a step back from the proposed design and, from this new angle, analyzing the contribution of the present research to the fields of embodied interaction and data physicalization.

Even though the final designed could have benefited from more deeply exploring other senses (beyond vision) for conveying data, this research sought to explore opportunities at the intersection of data physicalization and tangible and embodied interaction.

By designing a data-driven artifact – which is, in reality, just an off-the-shelf shovel – and labelling it as a data physicalization, this research questions the definition of data physicalization by Jansen *et al.* (2015), as data is not encoded in the geometry or material properties of the artifact. Instead, data is only conveyed during interaction (Figure 38).

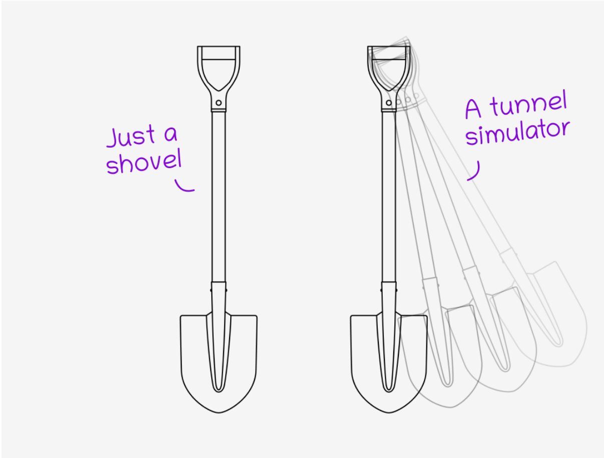

Figure 39. These drawings illustrate how data is only perceived during interaction. On the left, while no one is using the artifact, it could still be perceived as common shovel. On the right, only while someone is interacting with the shovel, it is able to become a tunnel simulator.

It is worth emphasizing that this report does not intend to propose a new definition of data physicalization, instead, its goal is to point to future research opportunities in conveying data not through an object's shape, but only through human interaction with it.

7.2 Future work

As mentioned in the end of the design process chapter (number 4), this research is to be considered a work in progress. Therefore, there are many opportunities for future research to address:

1. Conducting user tests in a real museum situation (*e.g.*, to study social interactions around the artifact).

2. Experimenting with embedded (*e.g.*, invisible) technology (not simply attaching phones to objects).

3. Exploring other senses, which could even improve accessibility (*e.g.*, using audio to indicate destination).

4. Studying how the environment affects visitors' perception (*e.g.*, using shovel while on ground level – above soil – *versus* at the top of a building).

5. Exploring the intersection between tangible and embodied interaction and data physicalization – more specifically, investigating ways to convey data not through an object's shape, but through our interaction with it.

8. CONCLUSION

This research sought to bridge embodied interaction and the emerging field of data physicalization. By focusing on visitors of an Earth sciences museum, it tried to understand how interactive data-driven artifacts could influence learning. In order to do so, qualitative interviews with experts in related areas were conducted. On top of that, an interactive data-driven artifact was designed. It consists of a shovel (equipped with electronic components) that simulates a hole through Earth, indicating where in the world users would end up if they were to dig in a certain direction. Feedback from participants indicate such embodied interaction might influence learning by igniting visitors' curiosity and stimulating hypothesis formulation. In a broader sense, this research also points to future opportunities on investigating ways to convey data not through an artifact's shape, but through our interaction with it.

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APPENDIX

1. Guideline questions for **Arielly Tomazia Costa**, Geosciences Museum mediation intern:

Broad questions:

1. Could you walk me through your typical day at the museum (prior to the pandemic)?
2. How do you imagine your typical day to change after the pandemic?
3. Could you tell me about a fun situation while mediating school visits?
4. Could you tell me about a challenging situation while mediating school visits?
5. When you think about "interactive resources for education", what comes to mind?

Specific questions:

1. How does learning in a museum differs from learning in a classroom?
2. Could you point out examples of qualitative data related to Earth sciences?
3. Could you point out examples of quantitative data related to Earth sciences?
    a. Which kinds of quantitative data could be related to the past (*e.g.*, historical data)?
    b. Which kinds of quantitative data could be related to the present (*e.g.*, real-time data)?
    c. Which kinds of quantitative data could be related to the future (*e.g.*, simulation data)?
4. Which kinds of concepts children often have a hard time grasping? Why?
5. How would you describe the social interactions around the following artifacts?
    a. The tangible dinosaur skull?
    b. The fossil sandbox?
    c. The "touch table"?

2. Guideline questions for **Júlia Giannella, Ph.D.**, data visualization researcher:

Broad questions:

1. Could you tell me about your experience with data physicalization (*e.g.*, thesis, meetup)?
    a. Could you tell me about a fun situation while teaching either data visualization or data physicalization?
    b. Could you tell me about a challenging situation while teaching either data visualization or data physicalization?
2. Have you ever taught dataphys to kids (8 to 12)? Could you tell me about it?
3. Have you ever used dataphys to teach something else? Could you tell me about it?
    a. What would you say was the most challenging situation while doing so?
4. How would people's relation with data physicalization change after the pandemic?
5. When you think about "interactive resources for education", what comes to mind?

Specific questions:

1. How does learning in a museum differs from learning in a classroom?
2. How does dataphys connect to the learning process of children?
    a. Is there a specific educational theory connecting both?
3. How would you define interactive data physicalization?
4. How does the "Solar Radiation Dowsing Rod" (Hogan & Hornecker, 2013) project fit this definition?
5. How does the "Dataseeds" (Dulake & Gwilt, 2015) project fit this definition?

3. Guideline questions for **Fernanda Silva**, primary school teacher:

Broad questions:

1. Could you walk me through your typical day at the school (prior to the pandemic)?
    a. What do you teach?
    b. To which age groups?
2. How do you imagine typical day to change after the pandemic?
3. Could you tell me about a fun situation during science-learning activities?
4. Could you tell me about a challenging situation during science-learning activities?
5. When you think about "interactive resources for education", what comes to mind?

Specific questions:

1. How does learning in a museum differs from learning in a classroom?
2. Could you point out examples of qualitative data related to Earth sciences?
3. Could you point out examples of quantitative data related to Earth sciences?
    a. Which kinds of quantitative data could be related to the past (*e.g.*, historical data)?
    b. Which kinds of quantitative data could be related to the present (*e.g.*, real-time data)?
    c. Which kinds of quantitative data could be related to the future (*e.g.*, simulation data)?
4. Which kinds of Earth science concepts children often have a hard time grasping? Why?
5. Could you tell me about a hands-on learning activity you brought to your students?
    a. Which artifacts were involved?
    b. How did children interact with them?
    c. How did adults interact with them?
    d. How did children interact among themselves?
    e. How did children and adults interact among themselves?