Ca’ Foscari
University
of Venice

Master's Degree programme
in Computer Science

Final Thesis

DataPhysKit
a 3D printed toolkit for data physicalization.

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Academic Year
2022 / 2023

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1 Introduction

1.1 Background motivation:

Information visualization is a multidisciplinary field that focuses on the representation of complex data in a visual format to facilitate understanding, analysis, and communication. Inside this broader field, Data Physicalization is the area of research that studies physical data representations (physicalizations), physical artifacts created to embody and represent data.

Due to their unique properties, physicalizations are powerful tools to increase engagement [2][13], foster reflection [18], and promote positive behaviour [16].

Furthermore, the use of participatory and constructivist scenarios where the audience is directly involved in the creation of a physicalization has been shown to impact the user experience positively. This practice, known as constructive visualization, provides non-expert users with the means to construct personal visualizations in simple and expressive ways [9]. This approach also allows users to engage more meaningfully with the data by facilitating reflection [18].

One particularly interesting project which fully uses this approach is *Data Walking* [5][8]. The project aimed to promote data literacy by organizing a series of workshops where participants produced visualizations based on data collected by walking in a city. *Data Walking* held many successful workshops but also required a certain degree of literacy in the field, as participants had to create their visualizations from scratch.

By researching the most effective ways to map location-relevant data to a constructive physical visualization, this thesis aims to support this process and provide a physicalization toolkit that can be used to carry out participatory data visualization workshops. The model proposed by this thesis focuses on the democratization of visualization promoted by the constructive visualization process [9]. To this end, a set of building blocks that can intuitively connect to each other to form a physical representation of data will be proposed.

All the objects designed in this project will be fabricated with a commercial 3D printer. This thesis will consider the advantages and limitations of this technology when developing the proposed toolkit.

Lastly, a workshop will be held using the proposed visualization toolkit and a survey will be conducted among its participants to evaluate the performance of the toolkit.

1.2 Research questions:

This thesis aims to contribute to the corpus of work that studies data physicalization to enhance the understanding of data by a broad and varied audience. The thesis aims to give an answer to the following research questions:

- How is it possible to ease the adoption of data physicalization, actively engaging citizens in the constructive physicalization process?
- How can a constructive physicalization be designed to represent environmental data gathered during a walk?

2 Theoretical Framework:

This chapter contains the literature review behind this thesis, starting with a broader look into data visualization and physicalization and presenting specific case studies.

2.1 Data Visualization:

Andy Kirk defines data visualization or information visualization in Data Visualization: A Handbook for Data Driven Design [11] as: "the visual representation and presentation of data to facilitate understanding", this definition can then be further elaborated upon by looking at its components:

1. **Data:** subject matter and fundamental element driving decisions during the design process.
2. **Representation:** how the data is portrayed.
3. **Presentation:** how to effectively deliver the visualization to its audience.
4. **Understanding:** the goal of the visualization, involves aiding the audience of the visualization in perceiving, interpreting, and comprehending the data. This goal can be achieved by designing visualizations that can be easily understood and that help viewers construct a mental model of the data.

This thesis aims to support the design and use of a constructive visualization, which is defined by Huron et al. (2014) [9] as: "the act of constructing a visualization by assembling blocks, that have previously been assigned a data unit through a mapping". This type of visualization aims to leverage the advantages of a constructivist pedagogical approach in order to make information visualization "accessible, understandable, and beneficial for the general population."

The authors refer to this goal as the "democratization of information" and propose constructivist methods to provide non-experts with the means to create visualizations and engage directly with the data. In particular, they declare that construction-based paradigms can have the following characteristics:

1. **Simplicity:** begets accessibility by lowering the skill barrier and rooting construction activities to everyday activities.
2. **Expressivity:** the process allows sufficient freedom to express ideas.

The paper also defines the components that define constructive physicalization:

1. **Token:** discrete visual mark representing a data unit by virtue of a given data mapping; it can be physical or virtual, and constitutes the basic unit of the final visualization.
2. **Token grammar:** mapping between properties of the token (color, position, size) and aspects of the data.
3. **Environment:** space that dictates constraints on how to assemble the tokens.
4. **Assembly model:** a set of rules of the construction process that defines how the construction and deconstruction is carried out.

2.2 Data Physicalization:

Data Physicalization is an area of research formalized in 2015 by Jansen et al. [10] to "help people explore, understand, and communicate data using computer-supported physical data representations.". These representations are called *physicalizations*, defined in the paper as "a physical artifact whose geometry or material properties encode data". In recent years, a large corpus of academic work has been developed to explore the potential of this kind of representation's potential, advantages, and limitations.

The core of this area of research, which is about representing abstract values by embodying them in a physical form, traces back as far back as clay tokens (see Figure 1) used in Mesopotamia, long before writing and paper was invented [14].
For example, tokens were used to represent units of measurement for various goods.

Figure 1. Tokens from present day Iraq, ca. 3300 BC. [19]

Even before 2015 the concept of "data sculpture" had been proposed by Zhao and Vande Moere in [23] as "a data-based physical artifact, possessing both artistic and functional qualities, that aims to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it."

An example of data sculpture is Loran Madsen's work in *CPI/Cost of Living* (see Figure 2) and *6'000'000'000 monkeys*, realized in 1995 and in 1999 [12]. Both represent the change of a particular variable over time by varying the dimensions of various layers to form a lamination of states.

Each layer that makes up the sculpture can be considered a token representing a set of data in a given time frame; in *CPI/Cost of Living,* each layer represents a year, and its horizontal and vertical dimensions are mapped respectively to the fuel and food costs indexes.

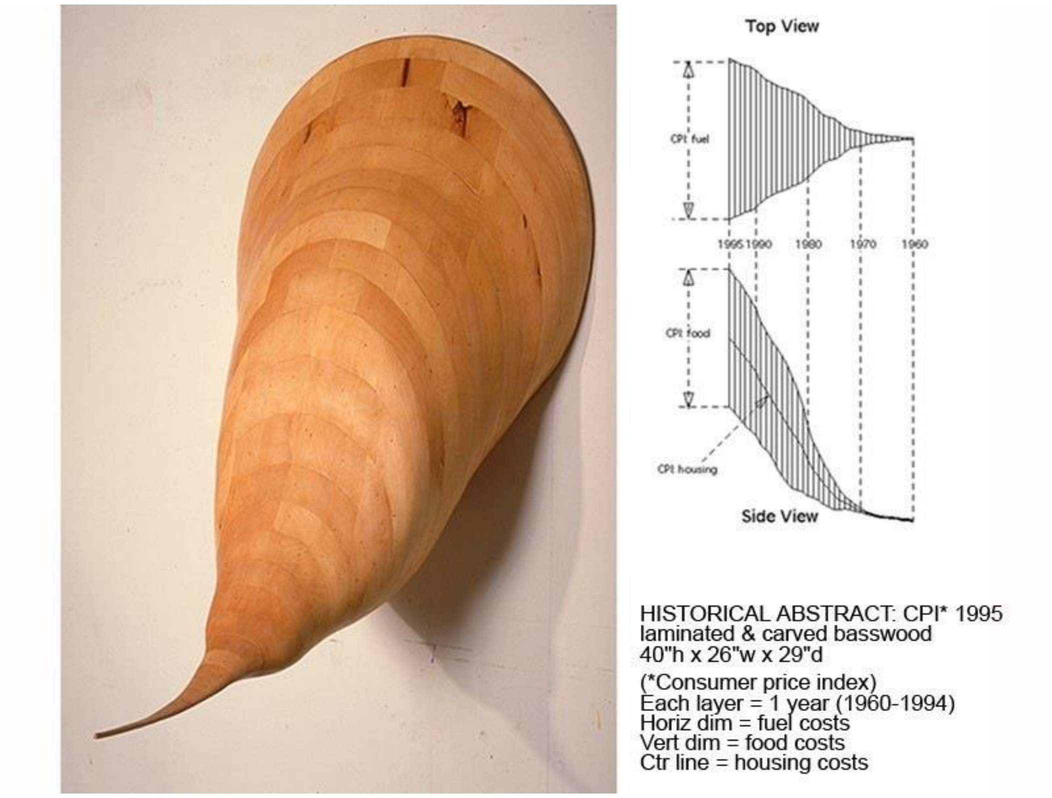


Figure 2. Loran Madsen, CPI/Cost of living, 1996.

Andrew Vande Moere in *Beyond the Tyranny of the Pixel* [21] discusses the use of affordances, the properties that influence how an object can be used. The author considers affordances to be a "potentially powerful "visual" cue to convey meaning, as it foregoes higher-level visual abstraction and enables multi-sensory human sensations and subjective emotions".

The author also discusses in the same paper how the data mapping metaphor used by a data sculpture may not be immediately understandable, but is meant to be discovered by reflecting on how the data is embodied in a physical form.

Furthermore, the author also notes that: "It is often the act of reflecting itself that brings forward unforeseen associations, which can then be considered the "data insights" communicated by the "visualization"".

Activity Sculptures [16], by Stusak et al., is a family of physical visualizations focused on representing data related to running activities in order to foster reflection and comparison. The physicalizations studied by the paper are composed of a series of unique tokens whose physical dimensions and shape depend on the data of a single run (see Figure 3). Four designs are proposed in the paper:

1. **Jar:** the tokens are round layers that can be stacked on top of each other to form a jar-like shape.
2. **Necklace:** the tokens are beads of a necklace.
3. **Lamp:** runs are represented as pillars plugged into a common base.
4. **Figure:** runs are represented as parts of a figure.

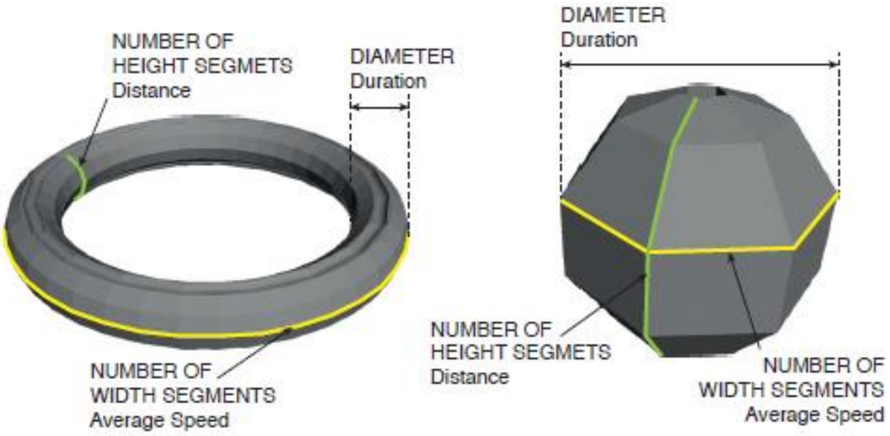


Figure 3. Tokens from the jar (left) and necklace (right) designs. In both cases the physical dimensions of the token are mapped to a certain aspect of the running activity they represent.

In the study, participants recorded their running activity through the use of a commercially available mobile tracking application. The data relative to each run was then translated into a token with the use of 3D modeling software and 3D printed, and the token was then shipped or handed directly to the participants who combined them with other tokens they already possessed (see Figure 4).

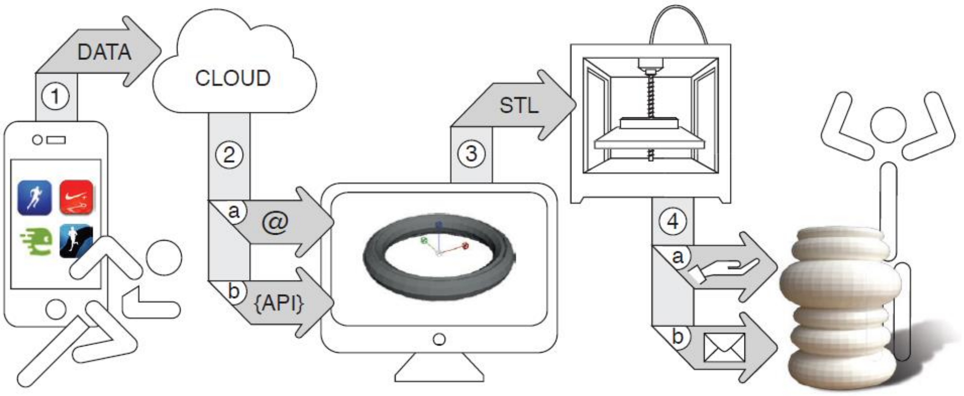


Figure 4. Activity Sculptures' fabrication pipeline.

The authors of the paper found that the physicalization of the participants improved their motivation and self-reflection, also noting how the sculpture promoted playfulness as participants changed their running routines to impact the form and aesthetics of the final sculpture.

While analyzing different data sculpture designs, Vande Moere and Patel [22] propose a useful nomenclature based on *representational fidelity*, which describes how the physical representation reflects the embodied data:

1. **Symbolic**: arbitrary data mapping with no meaningful conceptual connection to the data. Even if arbitrary, the mapping must be deterministic to remain faithful to the data.
2. **Iconic**: the representation resembles the embodied data utilizing a well-chosen metaphor.
3. **Indexical**: the representation directly relates (physically or causally) with the embodied data.

Bae, et al. [2] outline some emerging trends in the field that also encapsulate the benefits of data physicalization:

1. **Broadening participation:** the visualization of data is not targeted at experts only. The novelty of physicalization can be a hook to increase the engagement and understanding of data in different audiences.
2. **Supporting analytics:** data physicalizations can support various cognitive processes.
3. **Promoting creative expression.** Data can become a material to create new designs.

The authors also highlight some challenges for the field:

1. **Fabrication:** Bae et al. [3] show that the construction of data physicalizations involves a large design space, resulting in many possibilities that must be considered when designing physicalizations. This reveals a technical challenge in understanding how to map the data to any given material.
2. **Interpretation:** unlike the field of information visualization, physical visualization has no formalized design language**,** with single physicalizations either being based on 2D counterparts or feature encodings unique to each creator.

Unit-based data physicalizations, such as the previously discussed *Activity Sculptures,* represent data by mapping it to multiple objects (units), each representing a data point.

Stusak et al. [15] propose a set of physical variables for this type of physicalization. These variables are physical properties of the token that can be mapped to data to represent information. The authors considered the following variables:

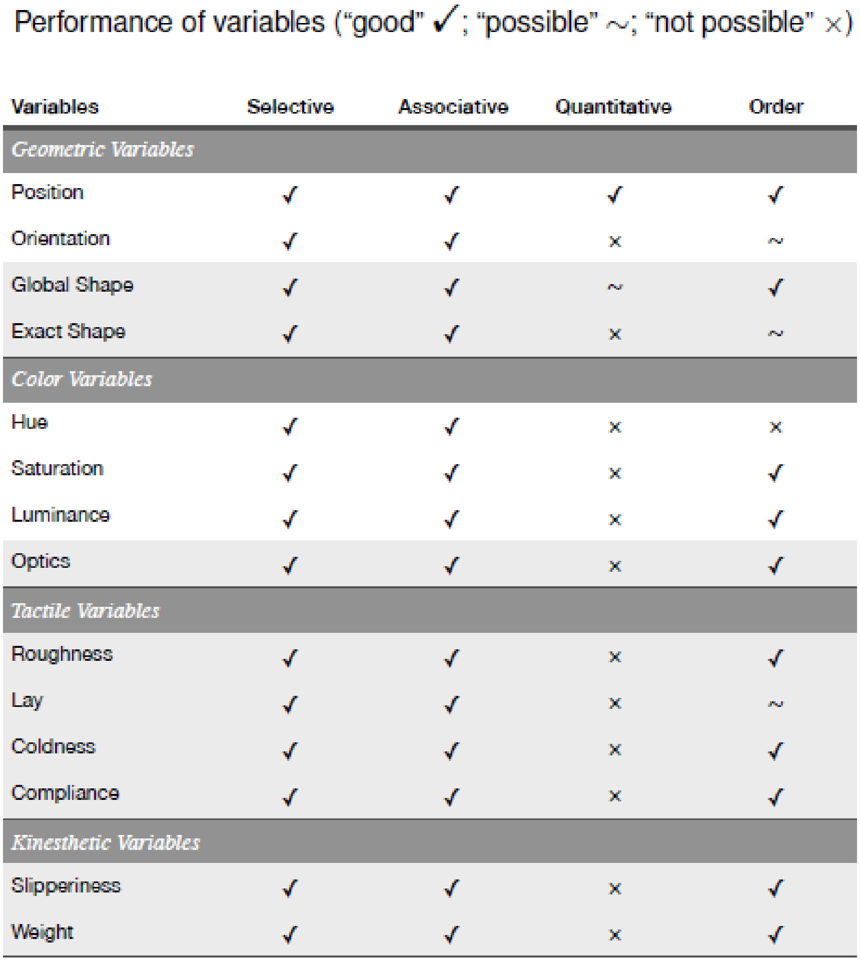
- Geometric variables
    - Position.
    - Orientation.
    - Global shape: the global dimension of the token, corresponding to its bounding box.
    - Exact shape: the contour or outline of a token defined by the number of its height and width segments.

- Color variables
    - Hue.
    - Saturation.
    - Luminance.
    - Optics: describes the optical behaviour of the token and it’s divided into Transparency and Reflection.
- Tactile variables
    - Roughness: the amount of irregularities and ridges present on the surface of the token that can be felt to the touch.
    - Lay: the direction of the predominant surface pattern.
    - Coldness: the perceived coldness of the token at room temperature.
    - Compliance: malleability, elasticity, and flexibility of the token.
- Kinesthetic variables
    - Slipperiness: friction exerted by the surface of the token.
    - Weight.

The performance of these variables is also discussed and evaluated along the four tasks introduced by Bertin [4] for visual variables:

1. **Selective**: a variable is selective if a change in this variable alone makes it easier to select that changed unit from all other units.
2. **Associative**: a variable is associative if a unit can be grouped according to this variable alone as they differ in other variables.
3. **Quantitative**: a variable is quantitative if the relationship between two units can be obtainable as a numerical difference of this variable.
4. **Order**: a variable is ordered if changes in this variable support a ordered readings of the units.

Table 1. Performance of physical variables as proposed by Susak et al.



Performance of variables ("good" ✓; "possible" ~; "not possible" ×)

Variables	Selective	Associative	Quantitative	Order
Geometric Variables				
Position	✓	✓	✓	✓
Orientation	✓	✓	×	~
Global Shape	✓	✓	~	✓
Exact Shape	✓	✓	×	~
Color Variables				
Hue	✓	✓	×	×
Saturation	✓	✓	×	✓
Luminance	✓	✓	×	✓
Optics	✓	✓	×	✓
Tactile Variables				
Roughness	✓	✓	×	✓
Lay	✓	✓	×	~
Coldness	✓	✓	×	✓
Compliance	✓	✓	×	✓
Kinesthetic Variables				
Slipperiness	✓	✓	×	✓
Weight	✓	✓	×	✓

The authors also propose a mapping of these variables (see Table 1) which expresses their suitability for the selective, associative, quantitative, and order tasks. This evaluation is a useful guide when designing a physicalization because it provides guidelines to decide which physical properties should be used for a specific data type.

For example, let us examine the use of the *global shape* and *hue* variables. *Global Shape* refers to the bounding box of a token, corresponding to the size of the object. *Hue* refers to the color of the token. Figure 5 shows some tokens of varying sizes and colors.

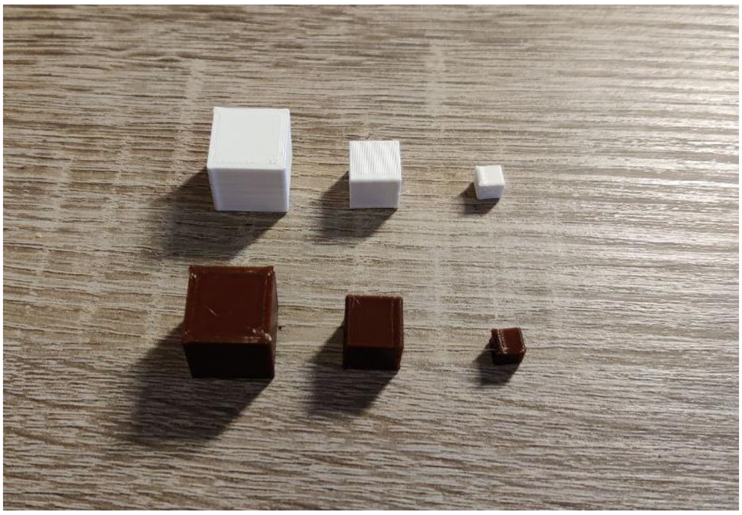


Figure 5. Cube-shaped tokens.

The performance of variables in relation to the tasks indicated by Stusak et al. can be considered as the ease with which questions related to the different tasks can be answered correctly.

1. **Selective:** which tokens differ from the rest in this distribution? (See Figure 6).

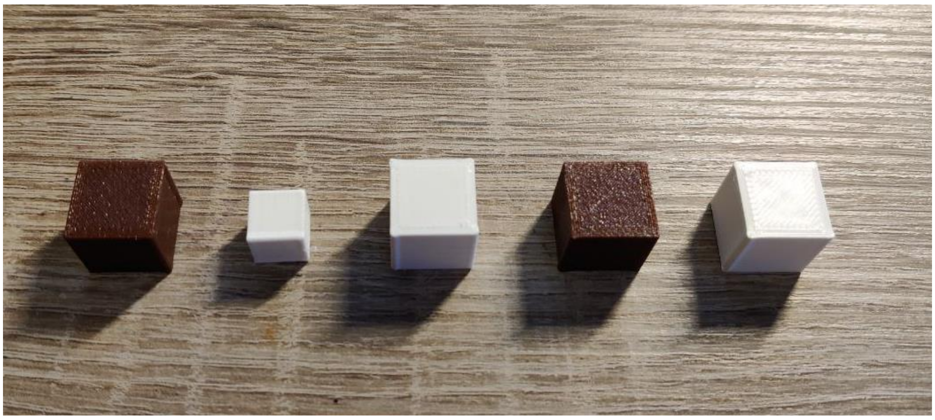


Figure 6. Size-based selection task.

A good performance in this task allows the viewer to detect tokens that differ in the given variable. Both global shape and hue allow to detect differences in tokens.

2. **Associative:** can these tokens (see Figure 7) be grouped?

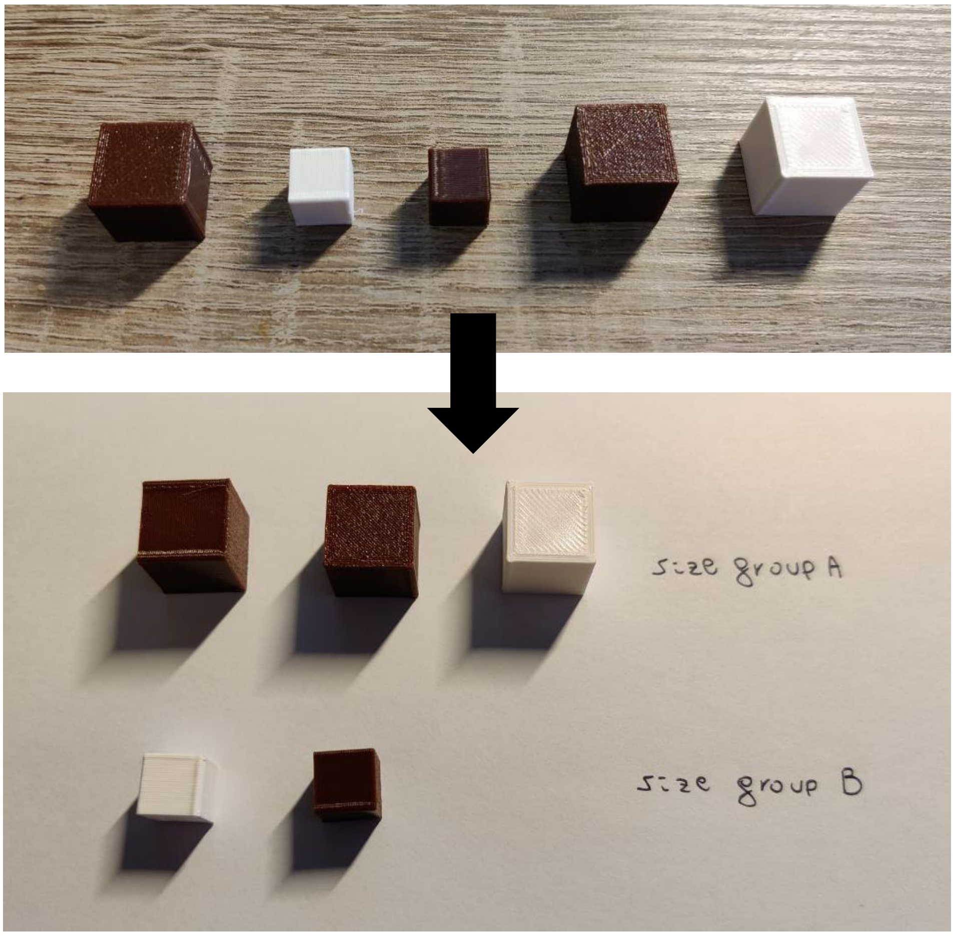


Figure 7. Size-based association task.

Global shape allows to easily determine two different groups as shown in the bottom portion of Figure 7. An alternative grouping could have been made using the *hue* variable instead.

3. Quantitative: how much bigger is a token compared to the other ones? (See Figure 8).

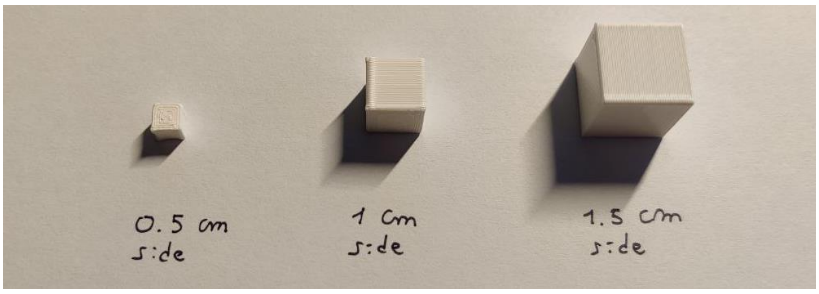


Figure 8. Three tokens with their side dimension.

Stusak et al. rate this task as *possible* using size, meaning it can be difficult to obtain the exact difference between two values encoded using the size of the token. While it's possible to notice a difference in size in the tokens in the picture, the exact numerical difference in size can't be measured with the naked eye.

4. Order: can these tokens (see Figure 9) be ordered?

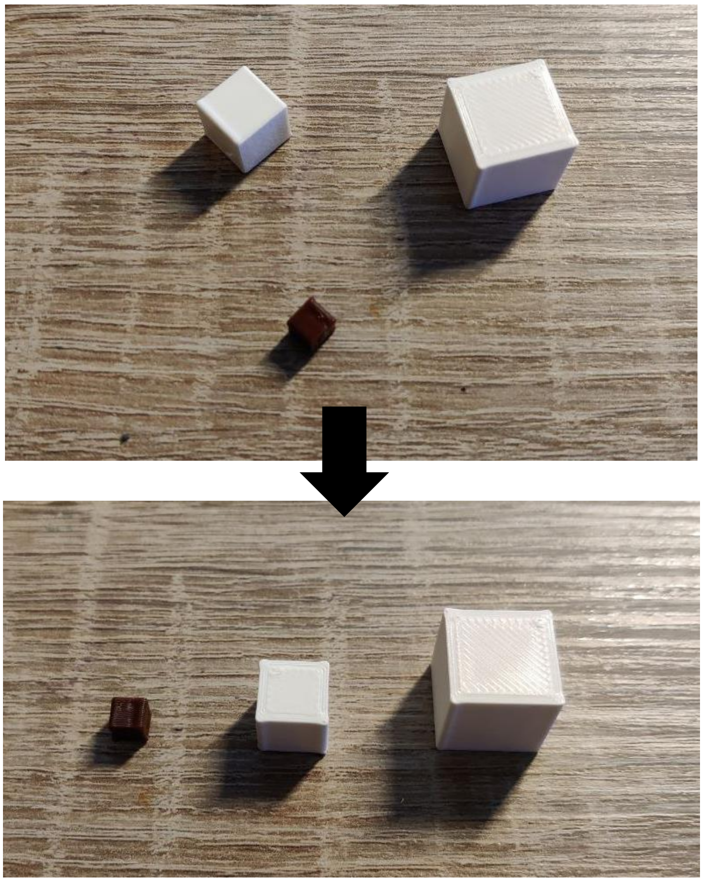


Figure 9. Size-based ordering of tokens.

Again, global size permits to order tokens from the smallest to the largest.

While this mapping is a powerful tool to aid the design of the physicalizations, as variables can be chosen to maximize the readability of the visualization, further considerations are needed for coming to the final solution.

Nissen and Bowers' *Data-things* [13] study the use of digital fabrication technologies in participatory data translation activities. In *Data-Things* physicalizations are digitally fabricated from the participant's data. In the first case study, data related to 24 hours of the Twitter activity of the participants were used to generate a wearable accessory that was 3D printed and handed to the participant (see Figure 10). In the second case study, data relative to the movement of a crochet hook during a knitting session was translated into path-like patterns and fabricated using multiple digital fabrication techniques (see Figure 11).

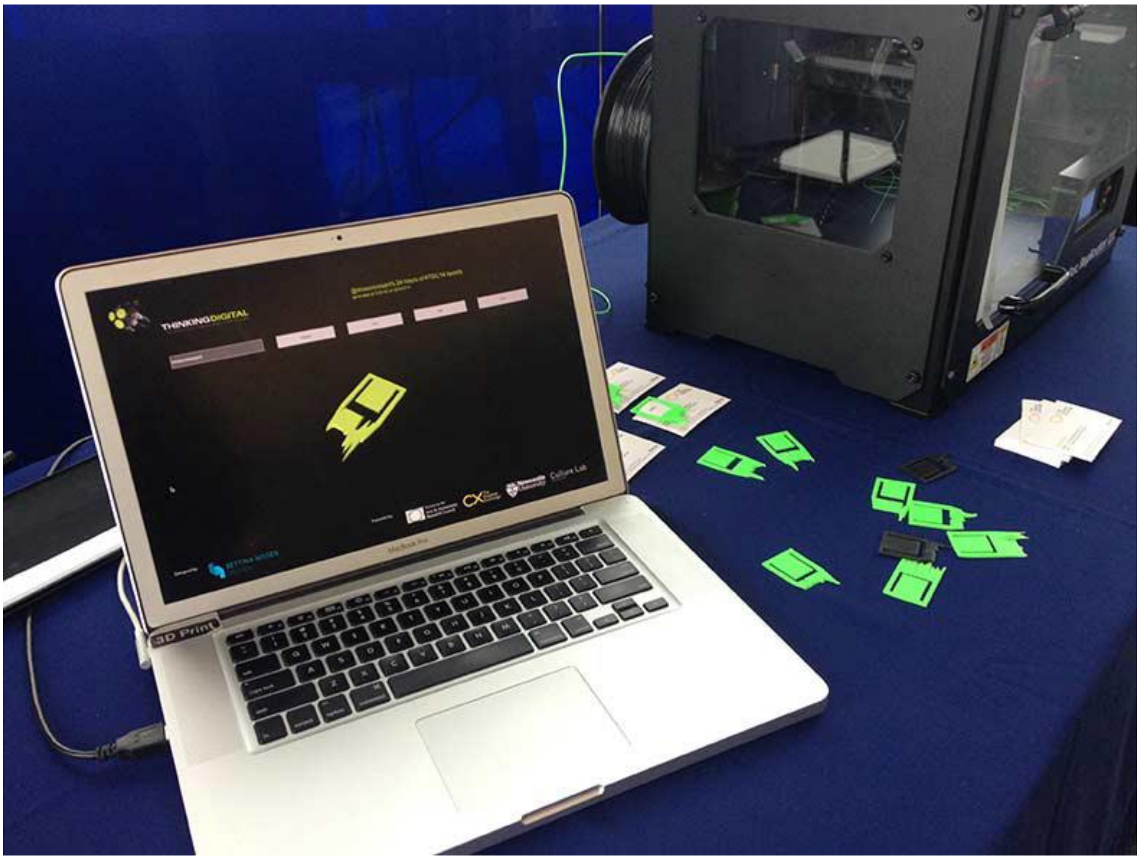


Figure 10. First case study: the accessory was generated with the participants' data as a 3D visualization in a laptop and 3D printed.

Figure 11. Example of the 2D data gathered in the second case study and translated to a series of physical representations obtained with different fabrication techniques.

The authors also noted that the participants' direct participation in the fabrication process can help them invest meaning into artefacts while facilitating reflection and engagement.

The authors of the paper formulate design concepts to help shape similar experiences in the future. The most relevant for this thesis are:

- **Data translation as meaning-making**: the paper suggests that participation in data capture and translation enriches participants' opportunities for meaning making; the same holds for taking part in the fabrication of the end product.
- **From data materialisation to data translation**: the user actively participates in creating the object and its meaning; data becomes a malleable medium in the hands of the user.

2.3 Constructive Physicalization

Constructive physicalizations are a subset of physicalizations designed to involve the audience in their creation.

Thudt et al. in *Self-Reflection and Personal Physicalization Construction* [18], state that “constructive physicalization has been shown to facilitate deep reflections on the data, personal context, actions, and values”.
The authors ran an experiment on personal physicalization construction where multiple participants individually created physicalizations based on contextual knowledge about their lives. The participants designed their own personal physicalizations, logging the data, deciding the physical mapping and producing tokens to combine into a single physicalization (see Figure 12).

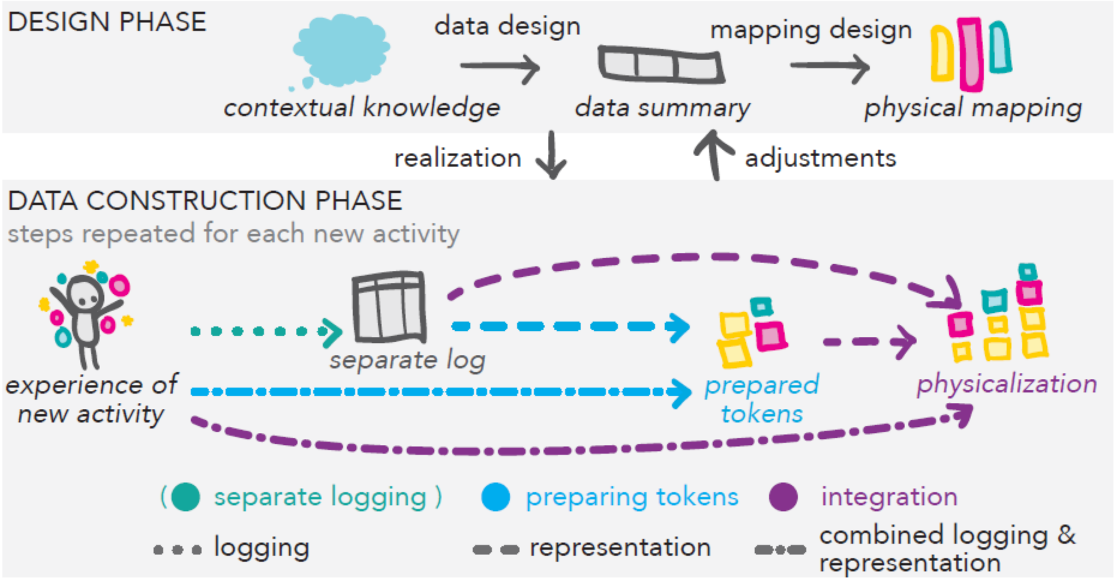


Figure 12. Overview of the physicalization process followed by the participants in the study. The process starts with a design phase followed by a data construction phase.

Most importantly, the authors also report on the types of reflection (see Figure 13) promoted in the participants during the whole process:

1. **Reflection on data:** identifications of trends and patterns.
2. **Reflection on context:** predictions, recollections, confirmation, and correction of previous expectations.
3. **Reflection on action:** motivation and development of actionable strategies.

4. **Reflection on values:** contemplation of personal values and attitudes.

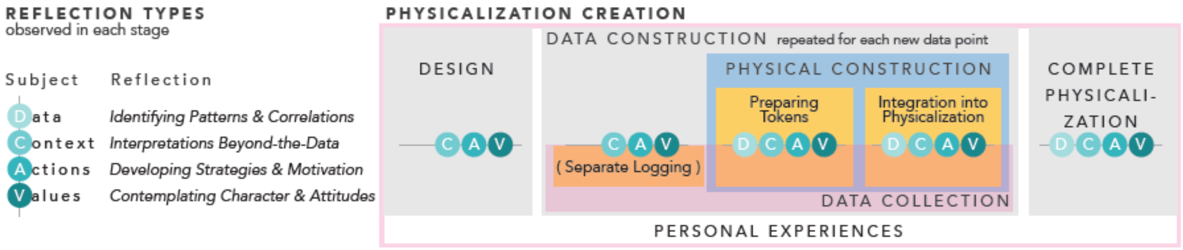


Figure 13. Overview of the personal physicalization creation process. The circles show which type of insight participants experienced during each step.

Furthermore, the authors also highlight the following challenges and benefits provided by the construction process:

1. **Personalization:** the process allows the participants to focus on personally meaningful aspects of the data, representing them according to their preferences.
2. **Physicality:** both a benefit, as the physical manipulation of the tokens was reported as an enjoyable experience, and a challenge, as the physical nature of the visualization posed some unexpected practical constraints.
3. **Manual effort:** the time spent to construct the physicalization allows the participants to reflect and internalize awareness of the chosen data. The time commitment also increased the participants' attachment and pride in their physicalizations.
4. **Presence in everyday life:** the daily presence of the physicalization serves as a reminder and allows the object to spark serendipitous reflection.

2.4 Data Walking

Data Walking is "a research project exploring the potential of walking to gather environmental data" as described by Hunter in [8] and by the *Data Walking* report available on the project's website [5].

The project was articulated in a series of workshops in different cities across the world that involved:

- Creating data-gathering devices.
- Gathering data along a walk.
- Visualizing and reflecting on the gathered data.

During the workshops different types of data were gathered (light, noise, temperature, air quality, people, and photographs) using different devices all tied to a specific time and location. The project aims to understand urban environments by gathering, analyzing, and visualizing data, promoting data literacy in participants.

The workshops produced a wide variety of data visualizations, both physical and visual, all documented in a final report. Particular attention was given to digital fabrication to produce visualizations, taking advantage of tools such as laser cutting, CNC milling, 3D printing, and digital embroidery machines.

The final report also exemplifies some workflows for recording and visualizing different data, recorded by portable data gathering devices. These workflows show some data processing techniques to create different visualizations based on the recorded data.

Among the many visualizations proposed in the final report, some are physicalizations. In particular, *Amongst the Leaves* (see Figure 14) by Brendan Dawes is a set of 3D printed physicalizations representing a year's sound data recorded around the Ravensbourne campus. These objects are modeled after a type of chestnut husk and 3D printed in a wood-like material, each representing three days of data. This physicalization was designed for being placed among fallen leaves and other debris and then being discovered and pondered by passers-by.

No further details are included about the mapping choices of this visualization.

Figure 14. Amongst The Leaves by Brendan Dawes.

Data Cylinders (see Figure 15) is another physicalization designed in the context of *Data Walking* using the data recorded in various walks from Stratford to Barbican. Each walk is represented by a cylinder made of multiple circular layers, each mapping a set of data to a picture of the location where the data was recorded. The environmental data represented includes light levels, sound, temperature, and air quality.

Figure 15. Data Cylinders.

The *Data Walking* report also proposes physicalization as part of one of a workflow for representing the sound levels recorded during a walk. The result is a 3D printable physical heat map (see Figure 16). Peaks on the map correspond to data points with higher sound levels.

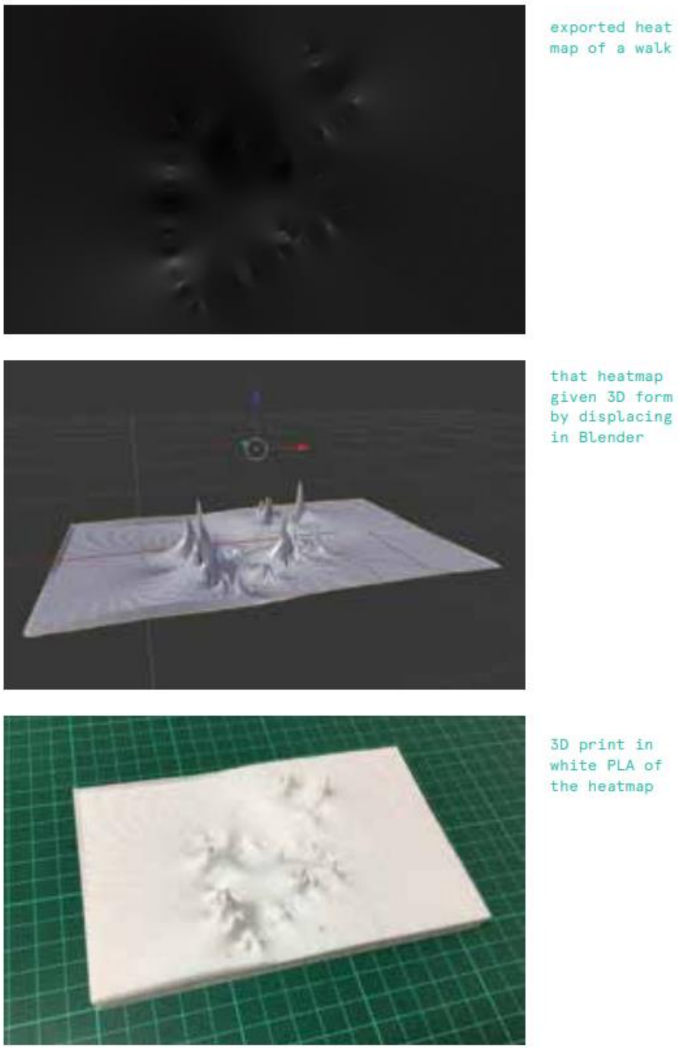


Figure 16. Overview of the sound heatmap proposed in the Data Walking report.

2.5 Data Physicalization and Location

The data that will be considered in this thesis are strongly related to the geographic location. This section presents a number of physicalizations to showcase how various designs tackle the task of representing data in relation to their spatial properties.

Cartographic representations

These physicalizations deal with data points relative to a certain position on a map or grid. *Global Cities* (see Figure 17) by Eliza Williams [7] represents the population density of the world's largest cities by mapping it to the physical height of a 3D map.

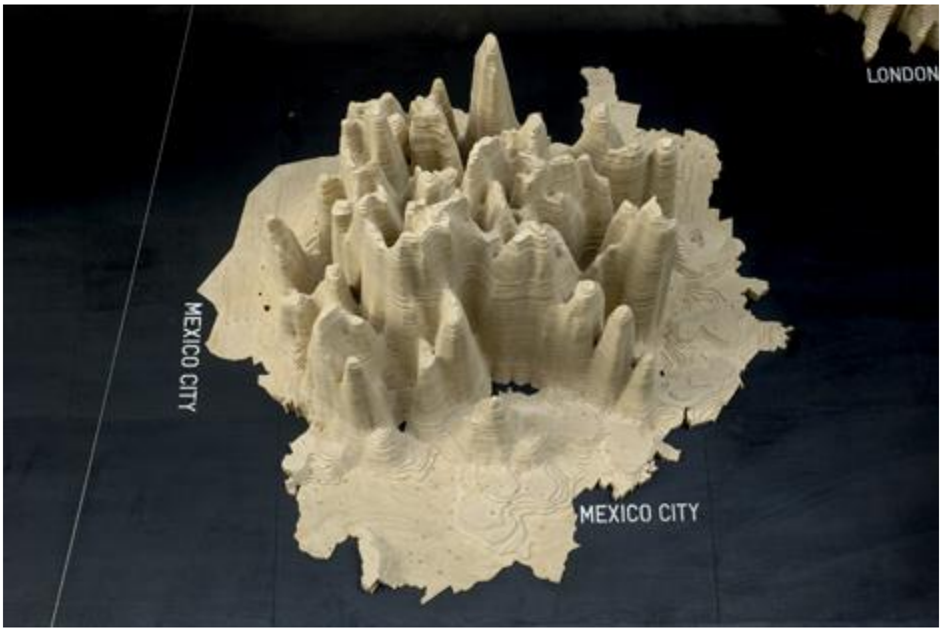


Figure 17. Global Cities by Eliza Williams. Mexico City.

Similar solutions are used in different works, some using different materials like *Can We Keep Up* (see Figure 18) by Hal Watts [20], which utilizes sponges to model a height map representing water consumption in the world. In this case, the map is discretized using countries' political borders.

Figure 18: Can We Keep Up by Hal Watts.

Djavaherpour et al. in *Physical Visualization of Geospatial Data sets* [6] propose a globe simplified as a polyhedron (see Figure 19). Different visualizations can be attached to the different faces to display certain datasets.

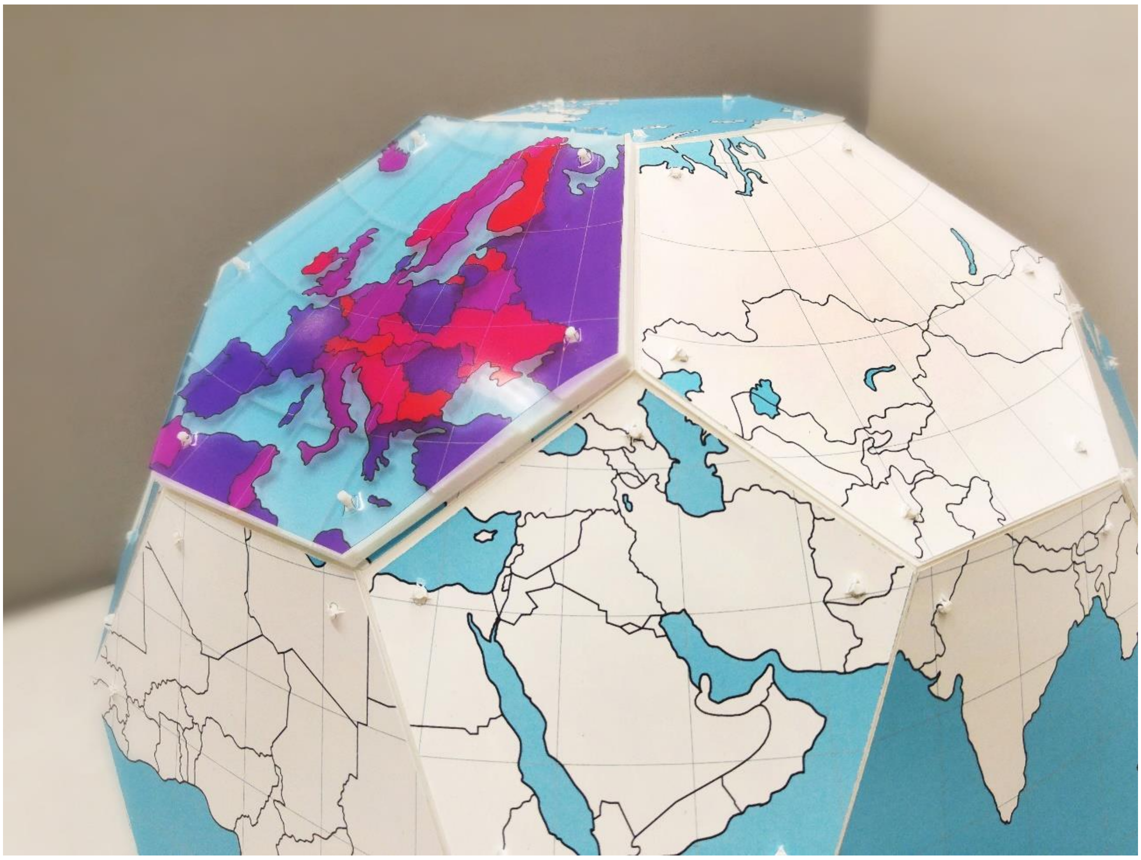


Figure 19. Djavaherpour et al.'s polyhedron.

Representations related to a single location

These physicalizations represent data points relative to a single geographic position, place, or area.

An example of this kind of physicalization is the following 3D paper model showing the shrinkage of the Aral Sea in Uzbekistan (see Figure 20) [1]. The surface outline of the lake is cut into different layers of paper corresponding to the water level between 1957 and 2007, showing the progression of the shrinkage.

Figure 20. 3D Paper Model of Shrinking Aral Sea by Peter Vojtek.

The following unit-based physicalization, *Summer in the City* (see Figure 21) by Carola Bartsch [17], represents different types of environmental data recorded during four weeks in Lugano, Switzerland. Measurements are represented as discs of different colors fixed to wires representing a single day. The visualization can be read horizontally, showing the progression of each type of data over four weeks, or vertically, showing the measurements relative to a single day.

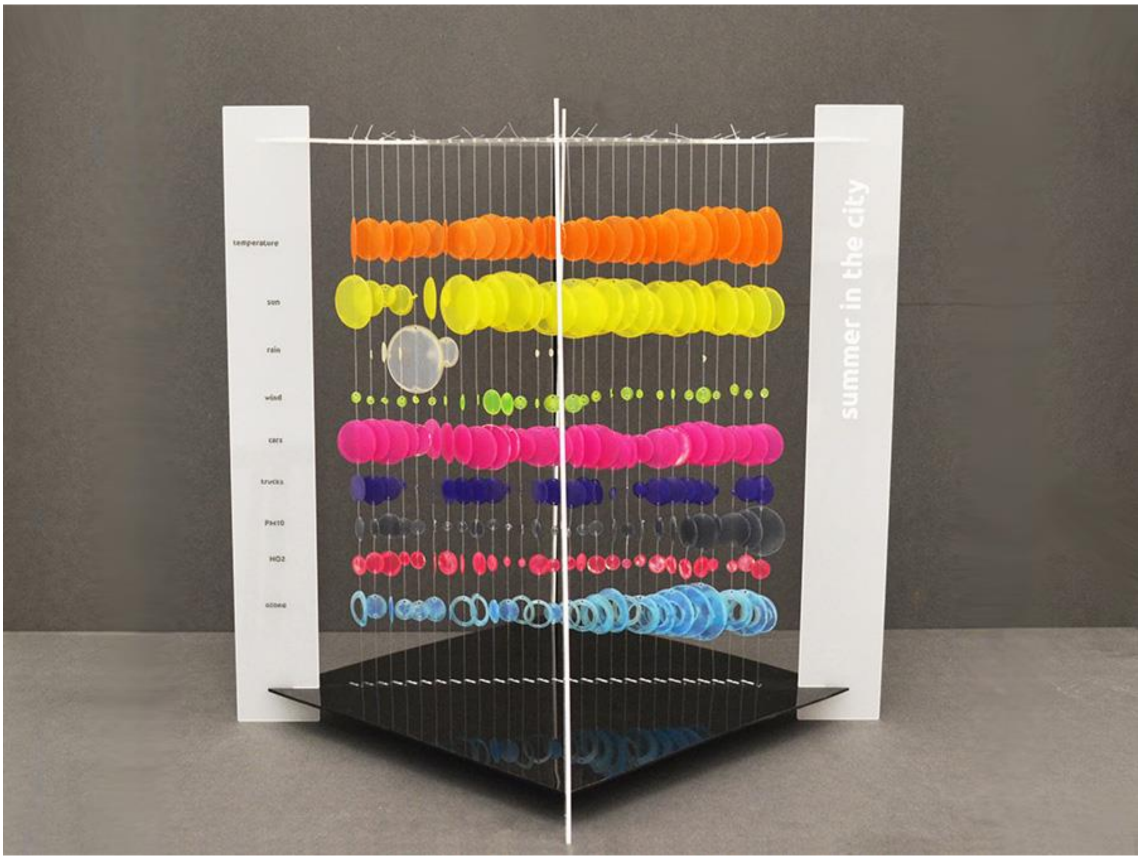


Figure 21. Summer in the City by Carola Bartsch.

3 Project foundation

This chapter discusses the issues that led to the conceptual project of this thesis, including some initial project specifications.

3.1 *Data Walking* Analysis

This thesis recognizes the value of the workshops and visualizations proposed by *Data Walking*. It aims to improve some of its aspects to provide a more inclusive experience for workshop participants.

Furthermore, this project aims to frame the work done in *Data Walking* inside the data physicalization field by providing a more analytical approach, with the goal of coming to a proper mapping between variables and physical features.

We propose to reach this goal with a workshop activity, where participants will be provided with a set of building blocks that can be combined into a physical visualization. The blocks will be provided as part of a toolkit to facilitate workshops similar to *Data Waking*.

The design process will lead to the creation of a physicalization toolkit, a set of building blocks that can be combined to form a physical visualization. The process will start by reviewing the design of the *Data Cylinders* physicalization and the workshop structure used in *Data Walking*.

The documentation on *Data Walking* provided by the report and the related paper [5][8] doesn't contain any specific information about the specific mapping choices used for *Data Cylinders*. Each cylinder is made of multiple discs, each pertaining to a specific data point; it is not clear if the discs can be disconnected from the cylinder or manipulated in any way. The cylinders encode environmental data by embodying it into the physical shape of the discs. A picture taken where the data was recorded is used as a texture for the surface and side of each cylinder. However, the process and mapping of the image isn't documented.

Furthermore, the stack-like structure hides a large part of the images, only the first image is visible in this configuration.

Overall, this physicalization presents some challenges that this thesis aims to overcome; the following design directions will drive the design process:

D1. **Clear mapping**: information mapped to the physical properties of the tokens should be clearly readable.
D2. **Occlusion:** the representation should limit situations where its information is partially or completely occluded.
D3. **Expressive mapping:** in Data Cylinders the number of variables embodied in the visualization is limited. Working on more expressive mapping is needed for representing more complex situations.

While *Data Walking*'s workshops didn't set requirements for the participants, the example workflows provided in the report require a certain level of data and computer literacy that should not be taken for granted, especially with younger audiences.

In particular, the construction of the data-gathering device, which was part of *Data Walking* workshops, may also hinder the democratization of the experience. Pre-built devices could also offer the opportunity to use more powerful sensors and specialized hardware to improve the overall experience.

Two more design directions can be highlighted regarding the workshop experience:

D4. **Low barrier for entry:** the workshop shouldn't make assumptions on the participants' skill level, requiring no specialized knowledge or computer literacy.
D5. **Device development:** the building of the data-gathering device, while potentially valuable for the participants, shouldn't be required to run the workshop. When using pre-built devices, the participant-device interaction should still be meaningful.

3.2 Constructive Physical Visualization

Data Walking involved its participants in designing and fabricating their own personal visualization. This thesis aims to reap the many benefits of a constructivist approach to information visualization by using the constructive physicalization process discussed by Huron et al. in [9]. This process involves:

1. Establishing the construction environment and its constraints.
2. Mapping data to tokens: assigning properties of the data to properties of the token.
3. Assembling the tokens.
4. Allowing for modification of the tokens and of the visualization they make up.

In this work, similarly to *Data Walking* workshops, participants will record environmental data by walking with a data-gathering device. Furthermore, they will be asked to record with pen and paper some data relative to the walk that they consider to be relevant. This will help evaluate whether the proposed visualization model can account for a degree of personalization.

Instead of having participants design their visualization from the ground up, participants will be given a toolkit of building blocks. Participants will produce a physical visualization of their walk by selecting the provided building blocks to represent the data as tokens, and then combining the tokens into a final physicalization.

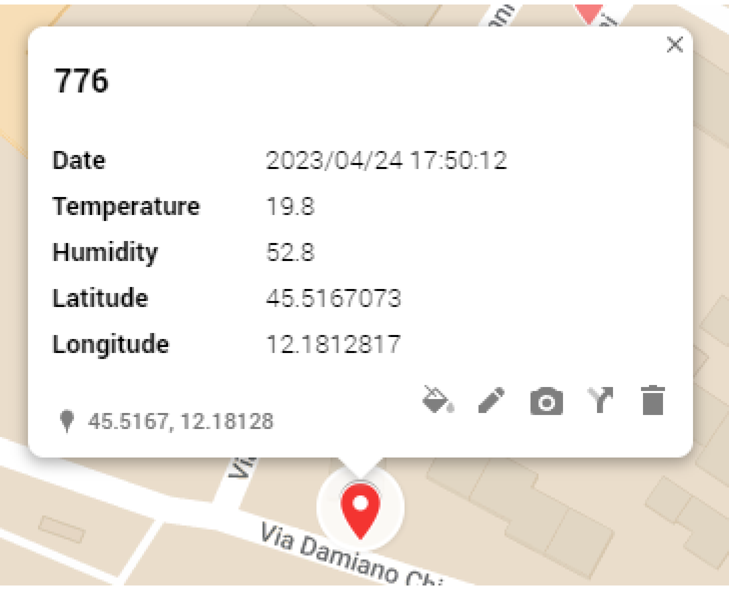
A workshop carried out with the proposed toolkit will aim to:

1. Have a better understanding of the environment where the workshop takes place.
2. Promote data literacy by involving non-experts in collecting, analyzing, and visualizing data.
3. Democratize the construction of physical visualizations.
4. Spark reflection on the data gathered by the participants and their meaning as described by Thudt et al. [18].

3.3 Location-specific datasets

This thesis will propose a physicalization model and toolkit to represent data in relation to its geographic location.

This type of location-specific dataset can be visualized as a set of markers with an associated data point (see Figure 22) scattered on a map.



776

Date	2023/04/24 17:50:12
Temperature	19.8
Humidity	52.8
Latitude	45.5167073
Longitude	12.1812817

45.5167, 12.18128

Figure 22. Values of a data point

It’s important to consider how these data points are measured and the relationship between them to design an optimal way to visualize the dataset. Generally speaking, the way the data is gathered and the location of each data point can produce three different spatial structures:

1. **Point:** all data points belong to the same geographic location or area, usually gathered at different times. It usually corresponds to data recorded by a single device.
2. **Grid:** the recorded data points are relative to a certain region of space, and the data from multiple locations is present at once. It usually corresponds to data recorded by multiple devices positioned in different places.

3. **Path:** data points are gathered sequentially along a path, they differ in both time of recording and location. Corresponds to data recorded by a single device carried along a walk (see Figure 23). This thesis focuses on this specific data structure.

Some examples of physical visualizations based on these configurations were illustrated in the previous chapter.

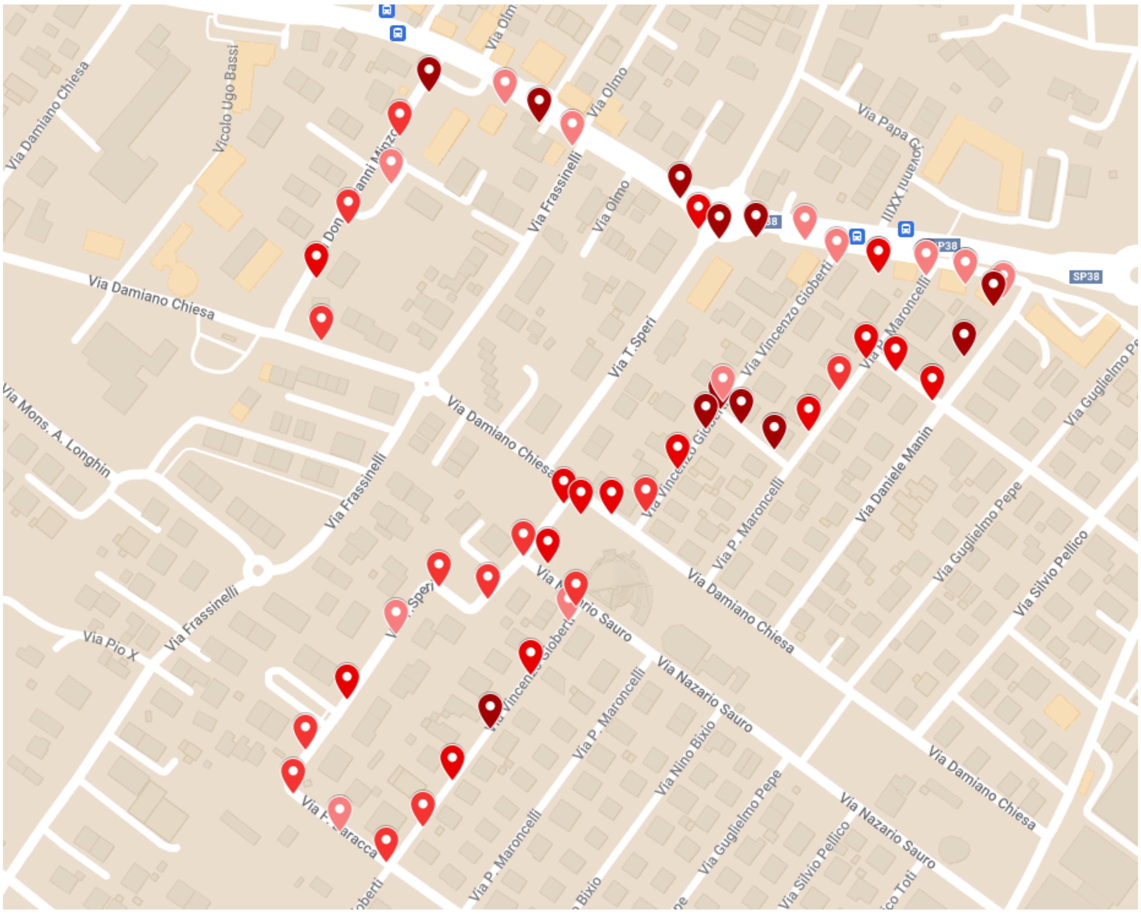


Figure 23. Map featuring a set of data points recorded during a walk.

3.4 Mapping and Location

The classification of location-based data discussed above should also be considered when designing a physicalization. The spatial configuration of the data points should also be reflected in the final physicalization to represent better how the data was gathered.

Point

This configuration describes a set of data points recorded in a single place or area. For example, a weather station positioned outside a certain building can record data in this configuration.

Physicalizations based on such a dataset usually reference one or more of the following aspects of this configuration:

- **Time:** data recorded for a single place or area is usually relative to a certain time frame. *Summer in the City* [17] clearly shows how data can be read as a set of daily data points while also showing the progression of each data field during the whole four weeks period.
- **Place:** *Amongst the Leaves* [8] is metaphorically linked to trees, parks, and fallen debris by adopting the shape and color of a chestnut conker. The spikes mapped to the sound data are used to create this metaphor.

The paper model of the *Aral Sea* [1] discussed previously references both properties; the layering of the different shore levels suggests a sequence of states in time while also clearly showing which geographical feature is being represented.

Grid

This configuration entails multiple data points, possibly recorded simultaneously, in different geographical areas and can be considered an extension of the *point* configuration.

Datasets in this configuration often produce physicalizations related to maps, representing the distribution of a type of data in space. These maps can also be discretized using arbitrary subdivisions, such as political borders or grids (see Figure 24).

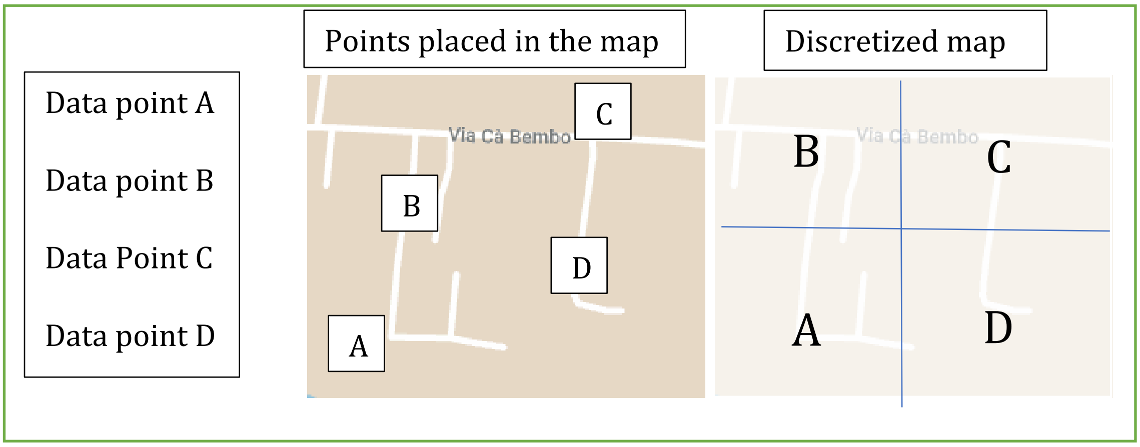


Figure 24. Overview of grid-based datasets. Data points can be placed in map featuring the exact place where they were recorded or assigned to cells in a grid formed by discretizing the map.

The way the map is split creates different effects. For example, *Can We Keep Up* [20] uses political borders to show that the data is recorded on a per-country basis. Other visualizations, such as *Global Cities* [7] and the *Workshop 3* map from *Data Walking* [5], plot the data as a continuous 3D function representing the data on the Z axis, and a map of the space where the data were recorded on the X and Y axis.

Path

The type of data configuration that will be considered in this thesis. It describes a set of data points recorded while moving the recording device along a path.

The most important feature of this type of data is the sequence in which the data points were recorded. This sequence can be expressed as an ordered list of data points, with the ordering based on the time of measurement. *Data cylinders* [5] reflects the sequence of these measurements by representing each recorded data point in the walk as a disc, with discs connected to form a whole. The profile of the visualization created by the layering of the discs in *Data Cylinders* is used to produce a unique fingerprint for each walk. This fingerprint makes the physicalization unique, and this can create further engagement in a workshop-like scenario by suggesting comparisons between different paths.

The geographical information of the path can include:

- The geographical shape of the path.
- The landmarks.
- The type of environment.

These and other features aren't necessarily described by numerical data and can be encoded in the representations if deemed relevant. In *Data Cylinders*' case, this is achieved by featuring in each disc a picture of the spot where the data was recorded.

An intuitive way to represent these properties in a physicalization is to design tokens that are meant to be connected in the same order the data points they represent were recorded (see Figure 25). This ensures that the sequence of data points is represented as a unique sequence of tokens. Geographical information about the shape of the path can be retained if deemed important, *Data Cylinders* [8] doesn't retain this information about the shape of the path; however, this physicalization is formed by a sequence of tokens in the same way the data set of the path is made of a sequence of data points.

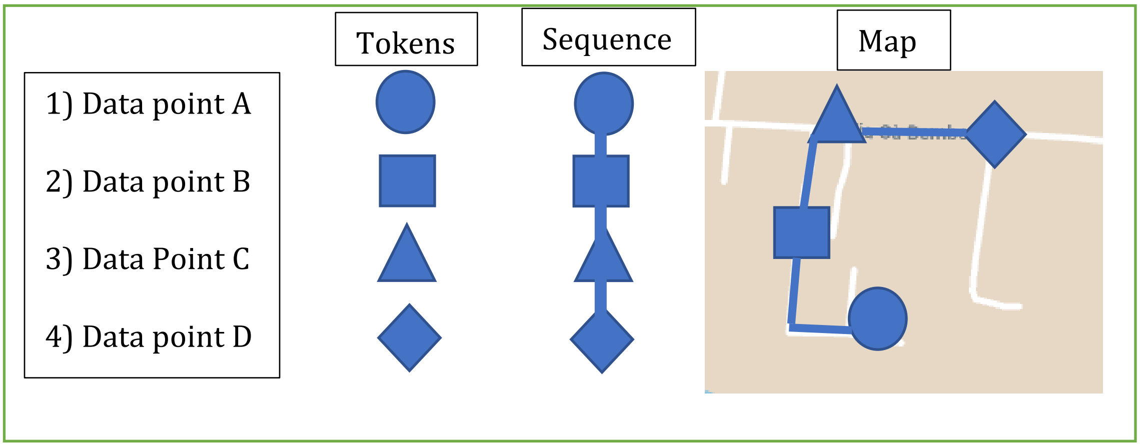


Figure 25. Data points gathered on a path can be represented by tokens. Tokens can be connected to represent the sequence of measurements in time and rebuild the shape of the path.

3.5 Materials

3D printing has been chosen as the main fabrication technique for this thesis. This manufacturing technique has been used successfully in many data physicalization projects; the most relevant advantages for this project are the following:

1. **Rapid prototyping:** 3D modeling software produces models that can be tested and modified quickly and efficiently.
2. **Commercial availability:** 3D printing equipment is easily available and relatively affordable, making the physical shapes used in the workshop organized for this thesis easy to reproduce.
3. **Shareability**: 3D models are commonly shared on the web by the 3D printing community, allowing a vast audience of makers to access, modify, and improve pre-existing models. Similar practices could be used to enable future developments of the toolkit.

3.6 Final Proposal

Starting from the issues discussed in this chapter, the project of this thesis will aim to produce a physical visualization of data gathered during a walk that is:

1. **Participatory:** multiple participants/viewers will be involved in gathering the data and creating the visualization in a workshop-like scenario.
2. **Constructive:** participants will build their physicalization using a set of building blocks.
3. **3D printed:** the proposed building blocks will be 3D printed.

4 3D printing

This chapter will feature an overview of the 3D printing technology that will be used to fabricate the toolkit discussed in this thesis. Furthermore, it will discuss some constraints that must be considered while designing the toolkit, due to the limits of this 3D printing technology.

4.1 FDM 3D printing technology

The 3D printer technology used for this thesis is Fuse Deposition Modeling (FDM). It is one of the most diffused and cheap digital fabrication technologies, and for this reason it has been preferred to other technologies. This type of printer works by heating and extruding a thermoplastic filament, additively layering a small amount of material from the bottom up to create a solid object. An FDM 3D printer (see Figure 26) usually includes the following components:

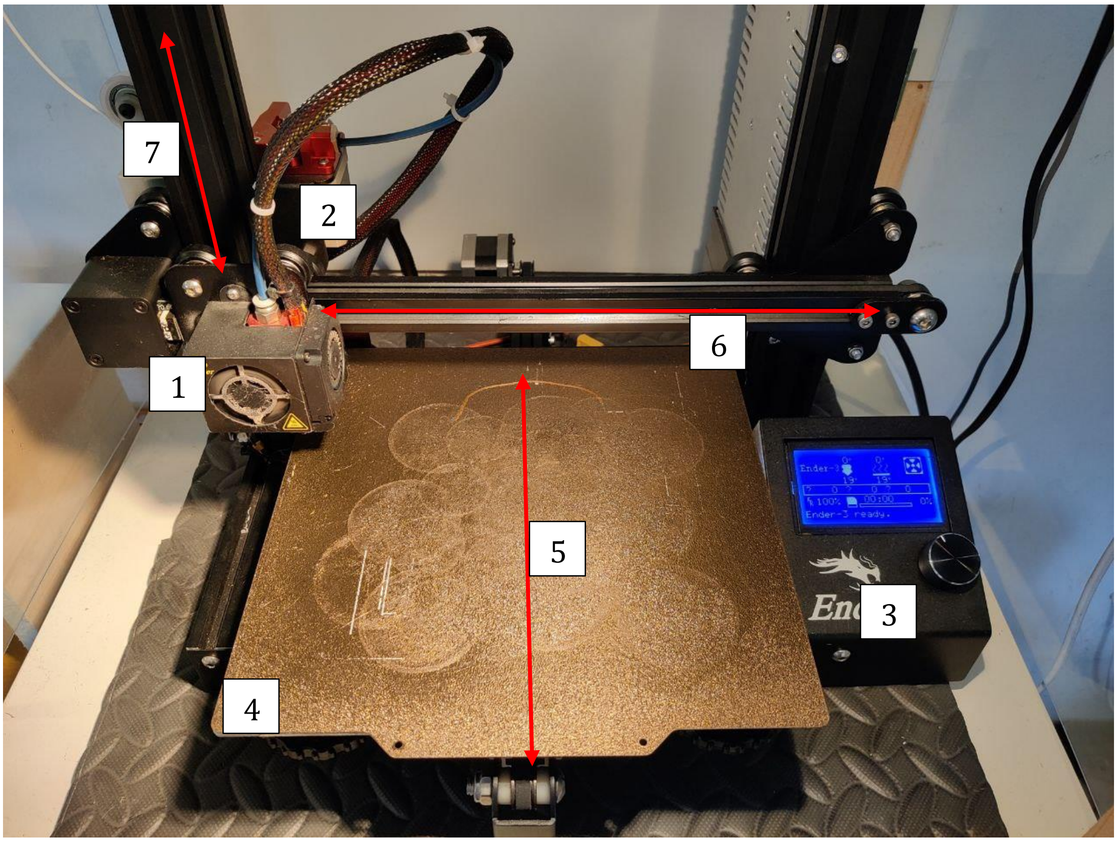


Figure 26. Overview of the Creality Ender 3 FDM 3D printer used in this thesis.

1. **printer hot end**: this payload carries the heating element that melts and extrudes the thermoplastic filament through a nozzle;
2. **extruder motor**: this component feeds a precise amount of filament into the hot end;
3. **LCD interface**: allows the user to operate the printer;
4. **Bed of the printer**: the surface objects are printed on the top of; it can also be heated to ensure better adhesion of the object while printing;
5. **Y axis**: one of the printer's three axes; a motor moves the printing surface back and forth;
6. **X axis**: a motor moves the hot end from left to right;
7. **Z axis**: a motor moves the hot end and the X axis vertically;

The operations' workflow for obtaining a 3D printed object can be divided into three steps:

1. **Modelling**: a 3D model of the object to print is produced using computer-aided design (CAD) software. *Autodesk Fusion 360* has been used in this thesis.
2. **Slicing**: the 3D model is fed to a specialized software (slicer) to translate it into instructions for the printer. *Ultimaker Cura* and *Raise3D ideaMaker* have been used in this thesis. In this step, the following parameters are also set:
    a. Temperature and speed of printing;
    b. Support structures;
    c. Percentage of infill of the printed object;
    d. Surface texture of the material, if the slicer allows for it;
3. **Printing**: the sliced model is uploaded to the printer and printed.

4.2 Remixing

Remixing is an interesting aspect of 3D printing and its community of *makers*, and it defines the practice by the users of sharing on the web 3D printable models, to modify and customize the work of others, usually also adapting it to their needs. Remixed models are shared on the web, allowing other users to modify them in turn.

Similar practices could be used to facilitate further developments of the toolkit. Therefore, the following design process will be targeted to the creation of objects, shapes, and features that can be obtained with a commercially available, single filament, single extruder FDM 3D printer with minimal or no modifications. This will allow more makers to print the physicalization toolkit developed in this thesis or to start from it for creating alternative toolkits.

4.3 Limitations of 3D printing

While FDM 3D printing provides many opportunities as a digital fabrication technology, it also poses some challenges and limitations to its users. The following will need to be accounted for when designing the final toolkit:

- **Limited print volume**: the size of the printer bed and the length of its vertical axis affects the maximum size of the printer object. The printer used in this thesis can produce objects that fit inside a 20 centimeter-sided cube.
- **Details:** the resolution of the print depends on the size of the nozzle that extrudes the plastic filament and on some user-specified parameters. The printer used for this thesis can't print details smaller than 0.1 mm.
- **Printing time:** the time necessary to print an object depends on its size, shape, infill, desired level of detail, and the mechanical components of the printer. The one used in this thesis can print at around 60 millimeters per second using a 0.4 millimeters nozzle. Multiple objects can be printed at once.
- **Commercial availability:** the variety of textures, colors, and materials of the printed objects depends on which filaments are currently commercially available.
- **Objects with multiple colors:** while printers capable to print with multiple filaments at once have been developed, they are costly and not widely available. The printer used in this thesis can only print a single filament at once; however, by pausing the print and swapping the filament spool, it's

possible to obtain multi-colored prints, but each layer can only be made with a single type of filament.

- **Supports:** As the printing is realized from the bottom up, support structures are needed to make it possible to print objects with significant overhangs (see Figure 27). Supports can be user-specified or generated by the slicer software, but their use comes at the cost of a longer printing time and higher consumption of filament.
- **Bed adhesion:** During the printing, objects need to be strongly anchored to the printing bed; objects with a small footprint may need specialized support structures to be printed successfully.
- **Infill:** This user-specified parameter describes the percentage of space filled inside the printed object. Different infill patterns can be generated by the slicer software (see Figure 28). Higher infill percentages correspond to structurally stronger objects but also require more material.

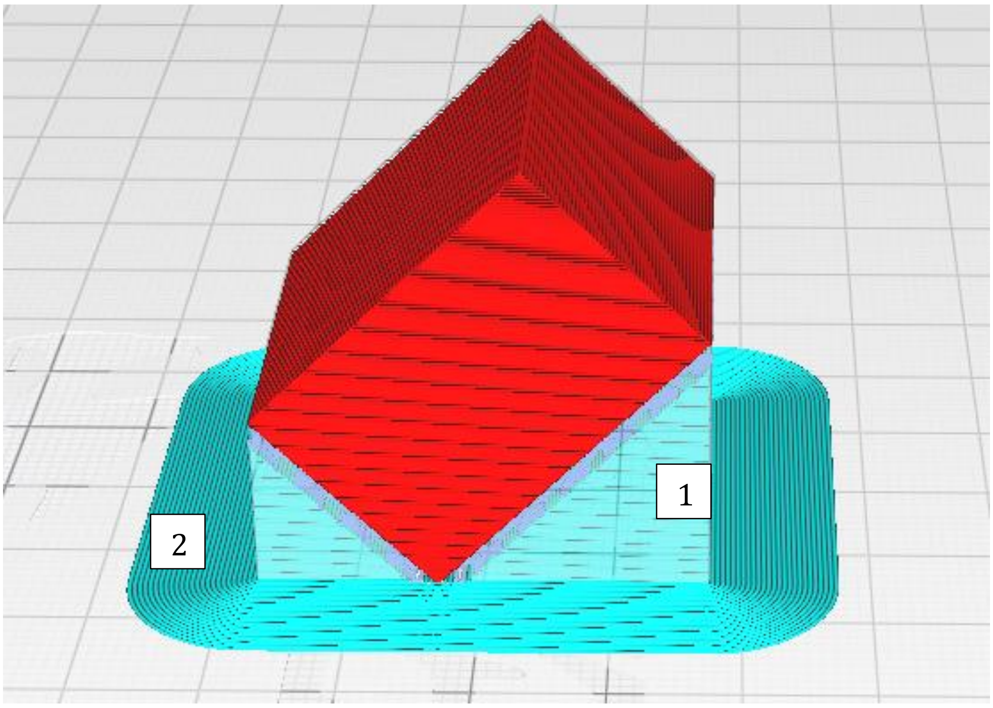


Figure 27. Preview of a printed object from a slicer software. 1: Overhang support. 2: Bed adhesion support.

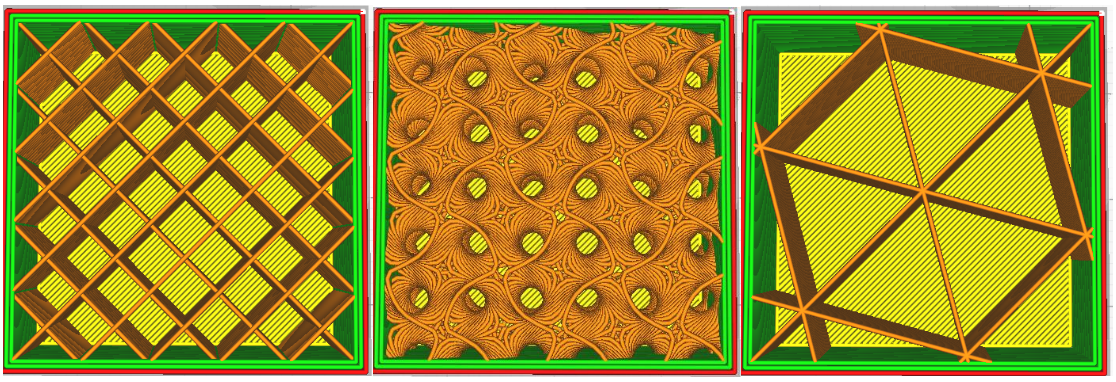


Figure 28. Different patterns at a 10% infill rate. From left to right: lines, gyroid, and triangles pattern.

4.4 Physical mapping variables and 3D printing

Stusak et al.'s variables [15] can be further classified in *design* and *material* variables:

- Design variables: can be expressed by modeling the printable object.
- Material variables: are intrinsic property of the 3D printable filament and can't be modified by the maker.

Table 2 summarizes this classification.

Table 2. Classification of physical mapping variables for 3D printing.

Mapping variable	Design	Material
Position	x	
Orientation	x	
Global Shape	x	
Exact Shape	x	
Hue		x
Saturation		x
Luminance		x
Optics		x
Roughness	x	
Lay	x	
Coldness		x
Compliance		x
Slipperiness		x
Weight	x	

4.5 Material limitations

The use of 3D printable materials also creates some limitations in relation to the mapping variables discussed by Stusak et al. [15]. These limitations can be categorized as follows:

- L1. The variable is incompatible with the material or can only assume a single value.
- L2. The material can’t express all the possible values of the variable.
- L3. The variable is dependent from other properties of the material.

In particular, these limitations affect the variables that are intrinsically related to the material the filament of the printer is made of:

1. Color variables
    a. Hue
    b. Saturation
    c. Luminance
    d. Optics
2. Tactile variables
    a. Coldness
    b. Compliance
3. Kinesthetic variables
    a. Slipperiness

L1

This limitation refers to the use of variables that can’t be controlled with 3D printed materials. Due to the properties of the material, these variables can only assume a single value. For example, the *Coldness* variable, which describes if the object is hot or cold when touched, depends on the thermal conductivity of the material the object is made of. As all objects produced from FDM 3D are made of various types of plastic, there is no way to modulate this variable enough to create differences that can represent changes in data.

L2

This limitation is mainly related to the commercially available materials, and therefore depends entirely on the manufacturer and distributors of 3D printed filaments. Some material variables may then not be fully represented by the filaments that are available for purchase.

This is an issue primarily for the variables related to the color of an object, as the color of a 3D printed object depends entirely on the filament and can't be combined with others like in a normal 2D printer. Filaments of a specific hue can be particularly hard to source consistently, and it may be impossible to purchase filaments for every possible value of the *hue* variable.

L3

This limitation surfaces when a physicalization unit is designed to use multiple variables in parallel. It's sometimes not possible to grant the selection of specific values for all the variables involved. For example, specific hue-saturation-luminance (HSC) combinations may not exist; or it may not be possible to purchase filaments of the same hue, but with different saturation, as illustrated in Figure 29.

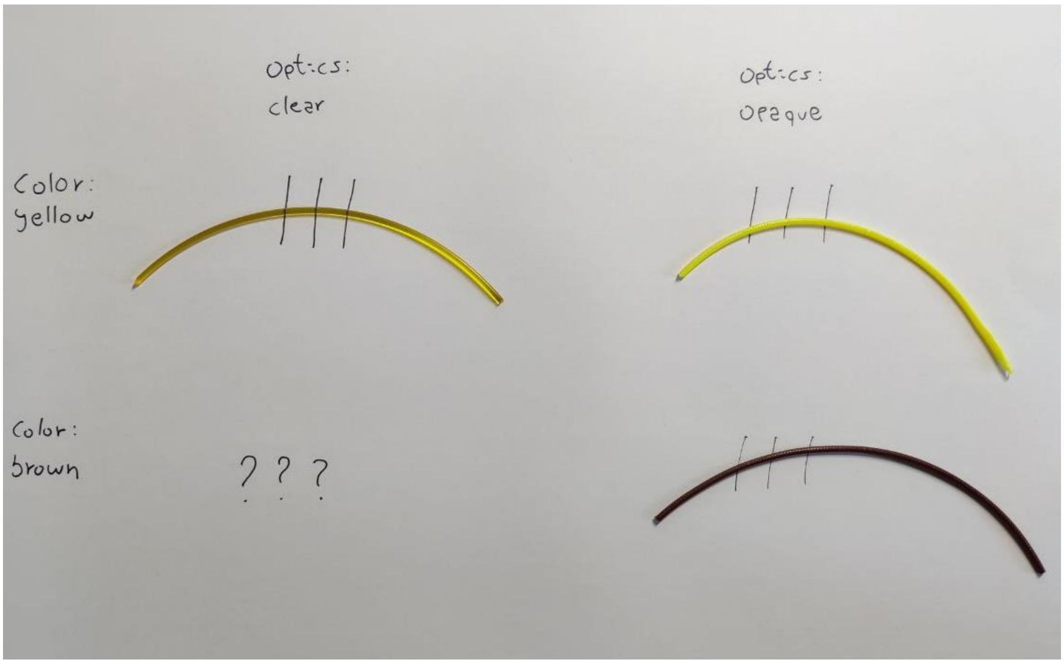


Figure 29. An example related to the limitations of material properties. While yellow filament is available both in opaque and clear variants, no clear brown filament exists.

This limitation can make it impossible to manage independently the values of different variables for a single object.

Table 3 summarizes the limitations discussed above for each variable related to the filament material.

Table 3. Material variables affected by the various limitations discussed in this section.

Variable	L1	L2	L3
Hue		x	x
Saturation		x	x
Luminance		x	x
Optics			x
Coldness	x		
Compliance		x	x
Slipperiness		x	x

4.6 3D printed variables visual guide

This section will show some examples of how some of the physical variables discussed by Stusak et al. [15] can be translated into physical objects using 3D printing.

Material

While the use of multiple variables related to the printing material will be avoided in this thesis, the choice of the material used to print the toolkit remains important.

The printing material will affect the look and feel of each object by dictating its color, finish, and haptic properties (see Figure 30). These properties can achieve interesting effects for a more aesthetically pleasing physicalization.

Figure 30. 3D printable material swatches.

The materials considered in this thesis are the most commonly used in FDM 3D printing, in particular:

- **PLA** (Polylactic Acid): the most commonly used 3D printable material, it's a hard plastic available in various colors and finishes.
- **PETG** (Polyethylene Terephthalate Glycol): visually similar to PLA, it's more resistant to temperature, shocks, and chemical agents.
- **TPU** (Thermoplastic Polyurethane): the most widely available flexible material for 3D printing.

Each material exists in a variety of colors. While specific hues might not exist, the most common colors are generally available from various manufacturers.

Although TPU is available with different levels of flexibility, the variety of commercially available flexible materials is less than that of hard plastics. The unique physical properties of this material can make certain shapes particularly challenging to print and could require specialized hardware.

The finish of the material could be an interesting property to consider when trying to suggest a certain property of the data, and it also affects the material's texture. Three main finishes are usually available:

Natural: the natural finish of the material, usually slightly glossy. PETG tends to be naturally glossier than PLA (see Figure 31).

Figure 31. White PLA spool.

Glossy: highly shiny, metallic-like finish, usually very sleek to the touch (see Figure 32).

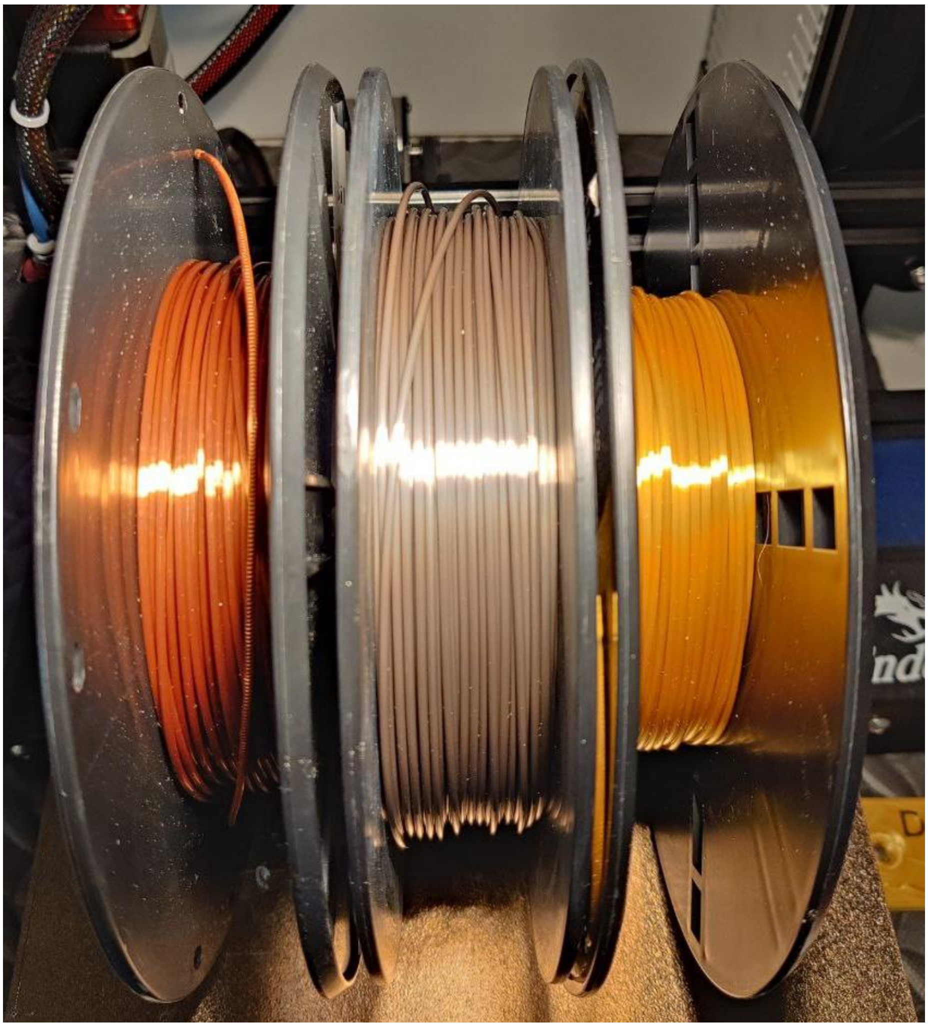


Figure 32. "Silk" (highly glossy) PLA spools.

Matte: flat finish, usually slightly rough to the touch (see Figure 33).

Figure 33. Black PLA spool.

Some materials combine color and finish to imitate the properties of other materials. For example, the spool of PLA in the picture below is infused with wood fibers to recreate the look and texture of real wood (see Figure 34).

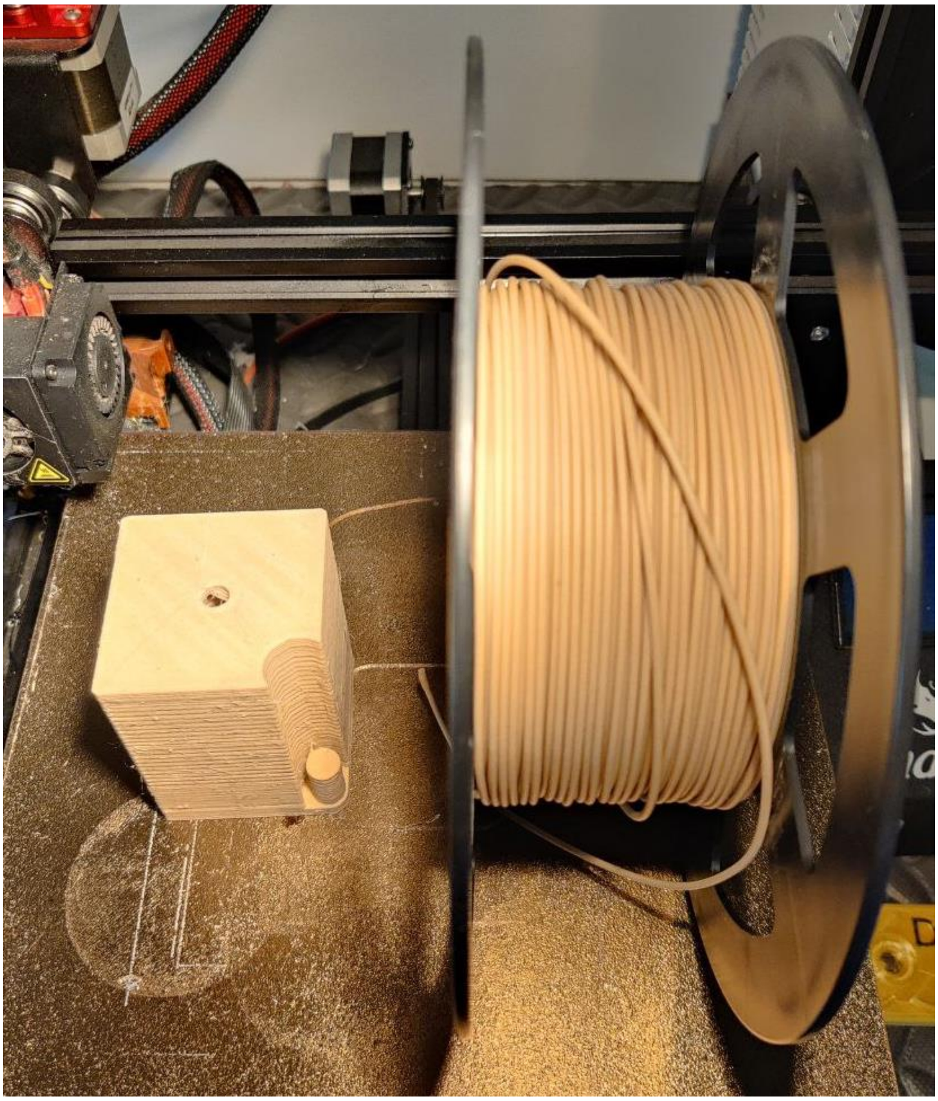


Figure 34. Wood PLA spool and 3D printed object made from the same material.

Optics

This variable encompasses the optical properties of an object, the one subject to the most control by the designer is an object's transparency.

While strictly related to the physical possibilities of the chosen materials (as some filaments are completely opaque) transparency can be modulated by carefully designing the printable objects. In particular, the thickness of the object's outer shell, infill percentage, and pattern are user-specified parameters that can affect transparency. The use of clear 3D printable materials can be particularly interesting as it allows the object's internal structure to be visible (see Figure 35).

Figure 35. two objects printed in clear PETG, their infill patterns (left: 10% cubic, right: 15% gyroid) are visible through their surface.

While the filament is completely clear, objects printed with it tend to be cloudier due to small imperfections created during printing. Backlighting is usually needed to notice changes in the transparency level of an object

Figure 36. 3D printed Lithophane.

Transparency can also be used to great effect when printing with materials that aren't fully transparent. The image above (see Figure 36) is printed in an opaque white material of varying thickness that produces the following greyscale image when sufficient backlighting is applied (see Figure 37).

Figure 37. Backlit 3D printed Lithophane.

Weight

While weight-based effects can be achieved with 3D printing alone, small weights can be embedded into the printed objects to alter their overall weight by a more significant margin, offering a fully kinesthetic variable largely independent from the object's appearance.

Figure 38. Weighted 3D printed cylinders.

The two cylinders in Figure 38 are identical, the cylinder marked with "C" is hollow, whereas the one marked with "A" is filled with a small lead sheet, resulting in different overall weights (see Figure 39).

Figure 39. Weighted 3D printed cylinders on a scale.

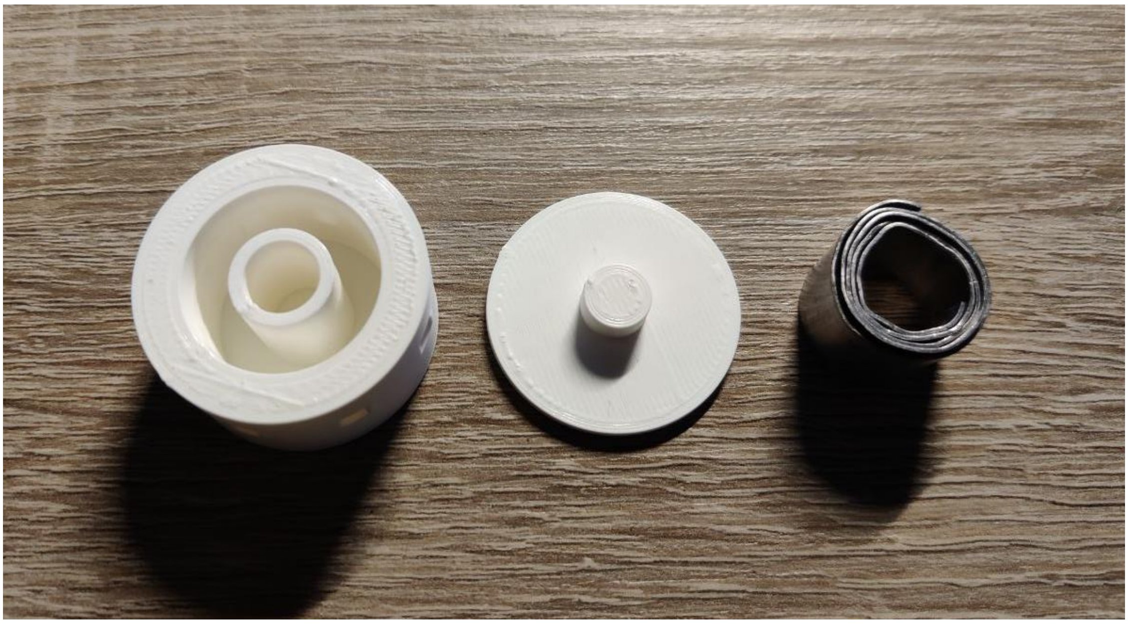


Figure 40. Structure of a weighted 3D printed cylinder.

Each cylinder is made of a hollowed main structure and a cap; the weight is inserted into the main body, which is then sealed with the cap (see Figure 40). A similar technique can embed different objects inside a 3D-printed token.

Roughness and lay

These two variables can be expressed by the surface texture of an object. Physical textures increase the expressivity of a token by providing haptic feedback to the users that manipulate it. They can also be used to imitate the surface of certain materials to suggest properties of the represented data.

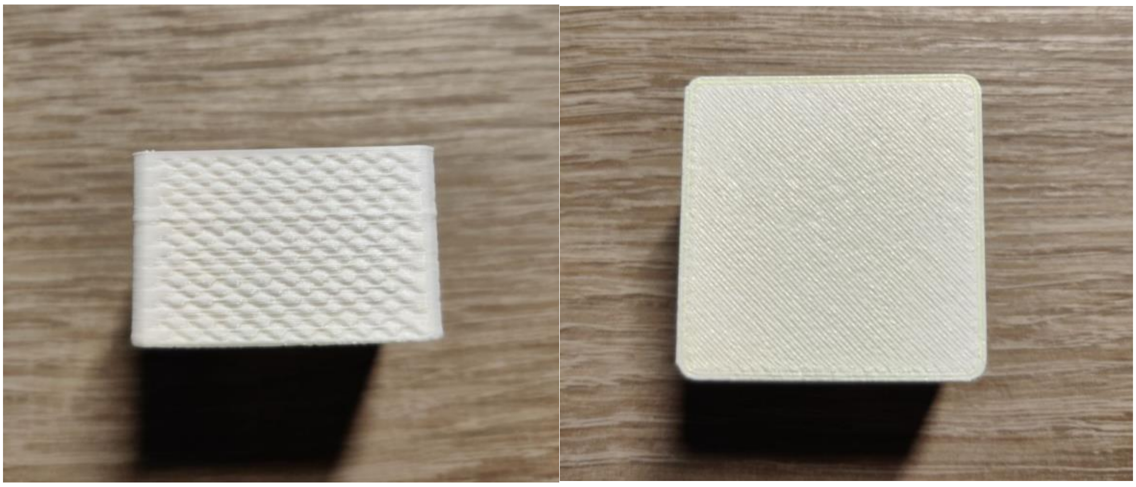


Figure 41. Patterned surface (left) and flat surface (right). The printing process creates the layer lines visible on both pictures and can't be fully removed without post-processing.

As previously mentioned, it's possible to map any 2D texture to a 3D model using specialized software. In Figure 42, the texture on the left has been mapped on the 3D object on the right. It is the same process used to model the object in the previous Figure 41 (left).

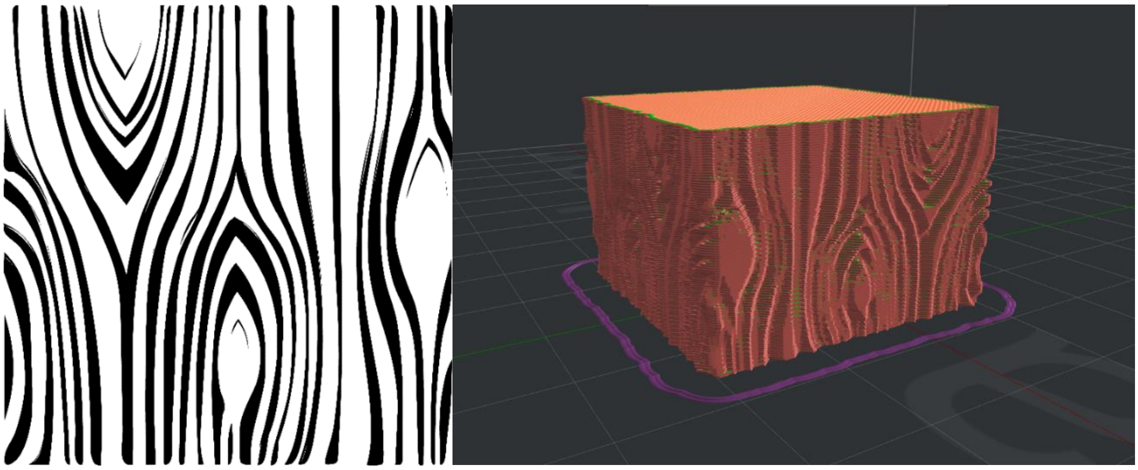


Figure 42. 2D texture (left) and in-software view of a patterned 3D model (right).

5 Data recording devices

5.1 Mobile data stations

The data discussed in this chapter are collected with mobile, battery-powered data stations designed to be carried by participants during a walk. Unlike *Data Walking*, the workshops won't require the users to build the data recording devices for the following reasons:

1. The process of building electronic devices, as simplified as it may be, provides a further barrier to the democratization of the workshop.
2. Features that are more difficult to implement, such as networking and user interfaces, can be developed for the devices without involving participants in work that could be outside the workshop's scope.
3. Designing and implementing the devices beforehand can improve their durability and reusability.

The data recording devices implemented for this thesis are driven by a Raspberry Pi Zero and are outfitted with an array of sensors, an external removable SD card for storage, and a mobile network adapter; a user interface is also provided through a led button used to control the station's operation and an RGB LCD screen to display the recorded data in real time.

Figure 43. data recording device, front.

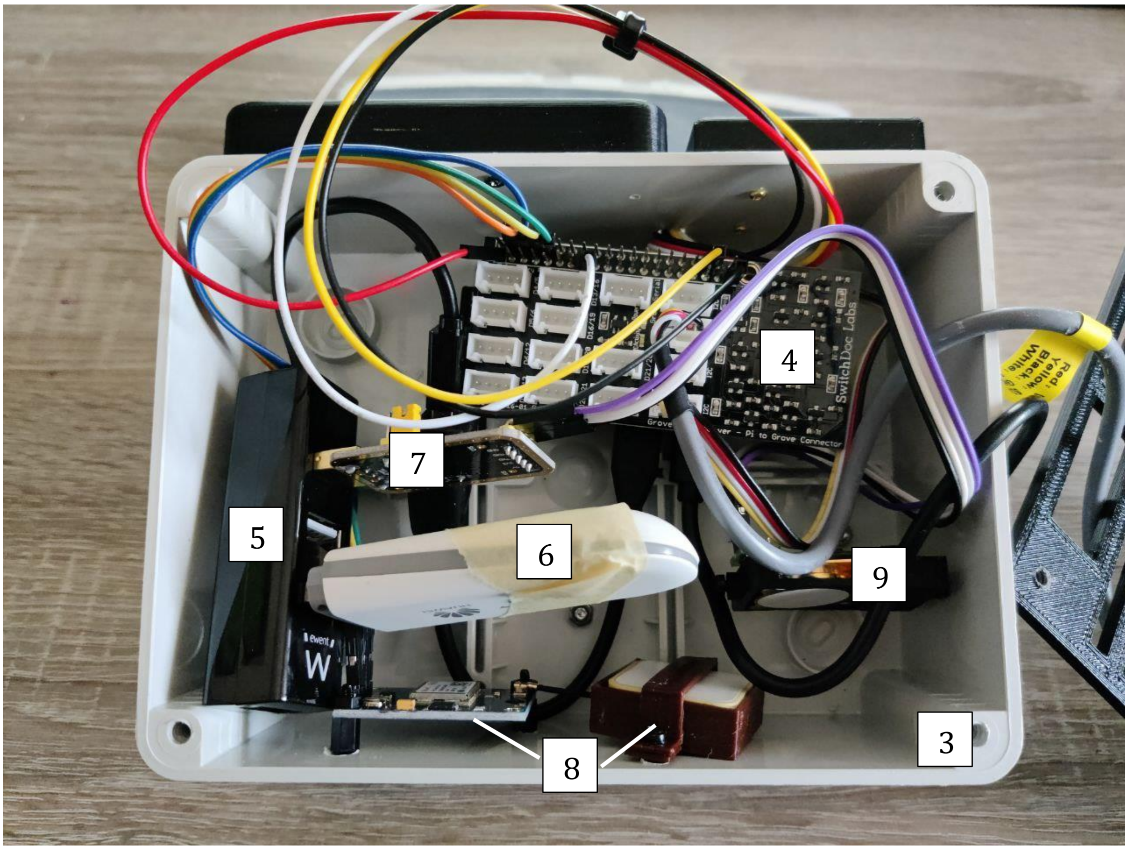


Figure 44. data recording device, inner components.

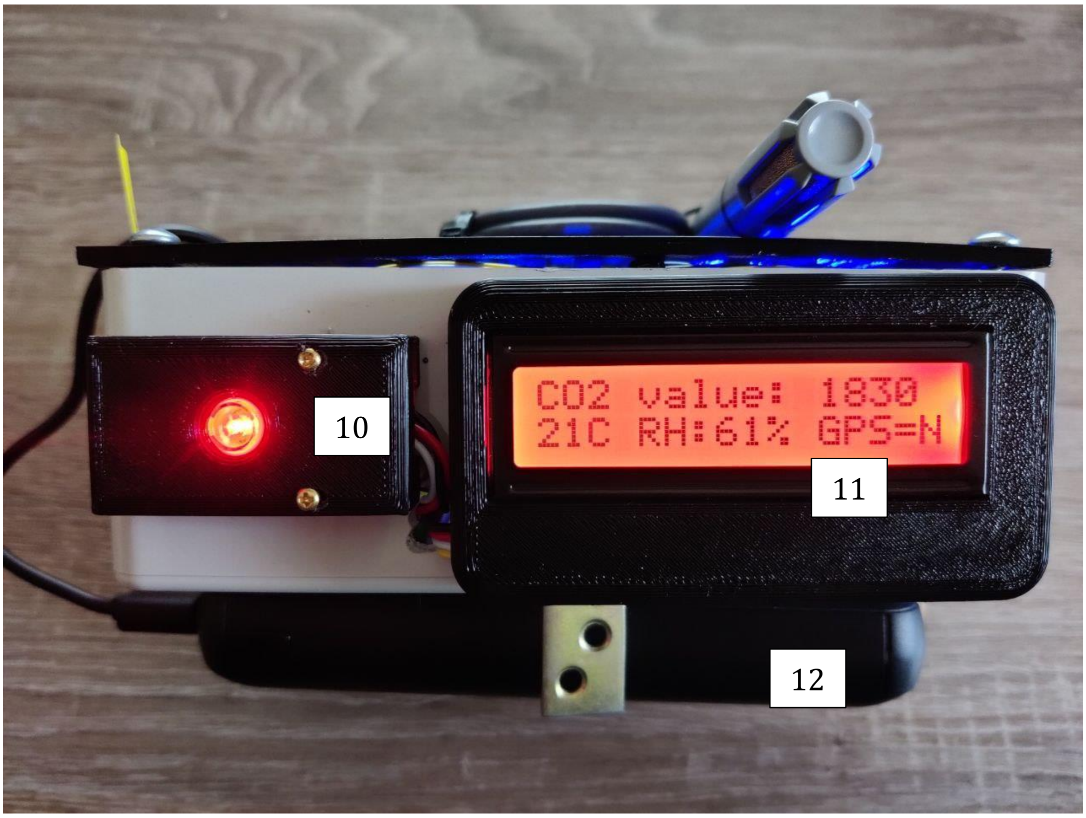
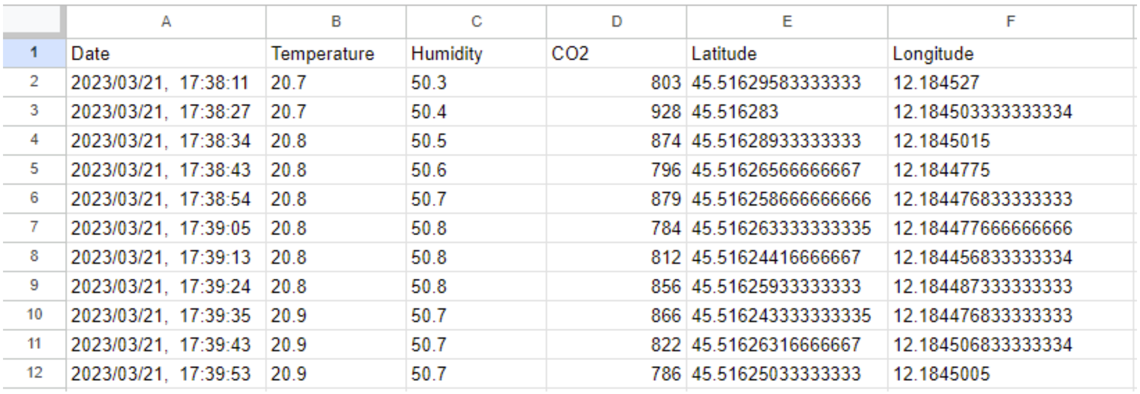


Figure 45. Data recording device, upper side.

The data recording devices are visible in different angles in Figures 43, 44, and 45. They include the following list of components:

1. 3D printed cover.
2. AM2315 temperature and humidity sensor
3. Main plastic body.
4. Raspberry Pi Zero and Pi2Grover hat.
5. USB Hub.
6. Mobile internet adapter.
7. USB to serial adapter.
8. GY-GPS6MV2 GPS module (left)and antenna (right).
9. CozIR-LP-5000 CO2 sensor.
10. GROVE LED button.
11. GROVE RGB LCD screen.
12. Power Bank.

The data recorded by the sensors is stored locally in the Raspberry Pi's removable memory in a CSV (comma-separated values) file. Data are also streamed in real time to an online spreadsheet service (see Figure 46). Each station creates an individual sheet for every walk uniquely identified by the station's codename and other parameters.



	A	B	C	D	E	F
1	Date	Temperature	Humidity	CO2	Latitude	Longitude
2	2023/03/21, 17:38:11	20.7	50.3	803	45.51629583333333	12.184527
3	2023/03/21, 17:38:27	20.7	50.4	928	45.516283	12.184503333333334
4	2023/03/21, 17:38:34	20.8	50.5	874	45.51628933333333	12.1845015
5	2023/03/21, 17:38:43	20.8	50.6	796	45.51626566666667	12.1844775
6	2023/03/21, 17:38:54	20.8	50.7	879	45.516258666666666	12.184476833333333
7	2023/03/21, 17:39:05	20.8	50.8	784	45.516263333333335	12.184477666666666
8	2023/03/21, 17:39:13	20.8	50.8	812	45.51624416666667	12.184456833333334
9	2023/03/21, 17:39:24	20.8	50.8	856	45.51625933333333	12.184487333333333
10	2023/03/21, 17:39:35	20.9	50.7	866	45.516243333333335	12.184476833333333
11	2023/03/21, 17:39:43	20.9	50.7	822	45.51626316666667	12.184506833333334
12	2023/03/21, 17:39:53	20.9	50.7	786	45.51625033333333	12.1845005

Figure 46. Spreadsheet with data recorded using the data gathering device.

5.2 Sensors

The dataset recorded by the stations has the following structure:

Data	Unit	Min	Max
Position	Latitude, Longitude	-90, -180	90, 180
Temperature	Celsius	-20	80
Relative Humidity	%	0	100
CO2	ppm	400	5000

Table 4. Data types and ranges of the values recorded by the devices.

Data readings occur every 15 seconds, although delays are possible due to the internal latency of the sensors. The time and date of each measurement is also recorded. The data recorded by the sensors will be assumed to be free of errors aside from obvious outliers.

5.3 User Interface

An LED button and an RGB LCD screen are the components of the interface needed to operate the device. The LCD screen will also display the recorded data in real-time, changing color according to the CO2 levels. The color of the LCD screen will change from green to red, as displayed in Figure 48.

Figure 47. Data recording device, closeup of the LCD interface.

The information visualized by the RGB LCD screen (see Figure 47) includes:

1. CO2 value in ppm
2. Temperature value in Celsius degrees.
3. Relative humidity value.
4. GPS reception status.

The following pictures exemplify the change in color with different levels of CO2. Color intervals are arbitrary but are used to easily identify relevant changes of CO2.

Figure 48. Different colors of the RGB screen.

6 Design

6.1 Tasks

In order to design the physicalization and selecting the best variables, it's important to focus on the tasks people are expected to complete when reflecting on data. The following list contains relevant tasks that could correspond to an understanding of the data gathered during a walk:

1. **Group similar situations to form categories:** for example, based on the environment where the data was recorded (city, park, main road, suburbs).
2. **Notice patterns emerging from data.**
3. **Highlight interesting situations encountered during the walk:** for example, important landmarks or unexpected values in the data.
4. **Quantify amounts when considering numerical data:** people should be able to see the numerical data change in values.

6.2 Structure

Following the discussion of the previous chapters, the physicalization is designed as a set of stacked layers, each representing a data point. Participants are asked to create the layers and then assemble them into the final physicalization.

It's crucial to allow the participants some level of layer manipulation to reap the benefits of the constructivist approach fully. This is achieved by creating a set of smaller artifacts that can be connected to larger platforms, the tokens, to fully represent a data point. These smaller artifacts will be referred to as add-ons.

This structure presents the benefits discussed in Chapter 3, such as showcasing the sequence of the measurements and creating a unique fingerprint for each walk. This should allow participants to better create a mental model of the walk and provide the means to make each token more significant based on their experience.

The walks planned for this project are of a relatively small scale and simple structure. For this reason, no plan was made to represent the geographical path of the walk.

The list of components of the toolkit designed for this project are the following:

1. A set of tokens.
2. A set of add-ons.

This latter category can be split in different subcategories, with different uses.

6.3 Tokens

Tokens make up the main structure of the physicalization and are the starting blocks of the construction effort by the participants. The full physicalization is planned to contain a limited number of tokens (e.g. 10), each representing a section of the walk.

Each token represents a section of a walk and each section represents an average of the values gathered data. There are multiple reasons for this:

- Averaging can give in many cases meaningful values.
- Sections help participants to annotate their observations in a way that can be incorporated into the physicalization.
- Sections are flexible and can be divided based on the type of environments found during the walk.

Tokens are the primary component and numerical values will be mapped to the tokens using their *global shape* variable. As shown in Chapter 2, this variable is well suited to display differences, even if the exact associated value can't be extrapolated.

In this thesis the focus of investigation led to map tokens to the values of carbon dioxide gathered using the devices previously described. Mapping CO2 values to different sizes of the main token made sense because:

1. They are the more significant values recorded.
2. Mapping these values to size immediately highlights problematic parts of the walk.

3. The representation of the exact value, expressing the parts per million of CO2, isn’t particularly relevant for non-expert users.

Furthermore, mapping only one variable to a token decreases the number of tokens that must be printed to account for all possible combinations. For the same reason, a single 3D printable material will be used for all tokens. Add-ons, which are smaller and cheaper, can be printed in bigger numbers to map additional data to the token.

Tokens will be shaped as cylinders since the surface on the side of a cylinder doesn’t present hard edges that can make the overall size of the token hard to evaluate correctly. Circular edges make it easier to add specific add-ons using flexible patterns.

As representations of the exact shape of the walk aren’t relevant, tokens are designed to be stacked similarly to the discs of the *Data Cylinders* visualization discussed previously (see Figure 50). Tokens are stacked using magnets to allow for the physicalization to be taken apart. This allows to:

1. Inspect every single token after the physicalization is assembled, in order to make partially occluded information more visible.
2. Rotate tokens freely without disassembling the physicalization.
3. Potentially reuse the tokens, as the stacking isn’t permanent.

Furthermore, the combination of the stacking structure with the varying size of the tokens creates physicalizations with a unique fingerprint. The profile of the physicalization can also be used as a rough plot of the CO2 levels during the walk, referencing the sequence of the data points.

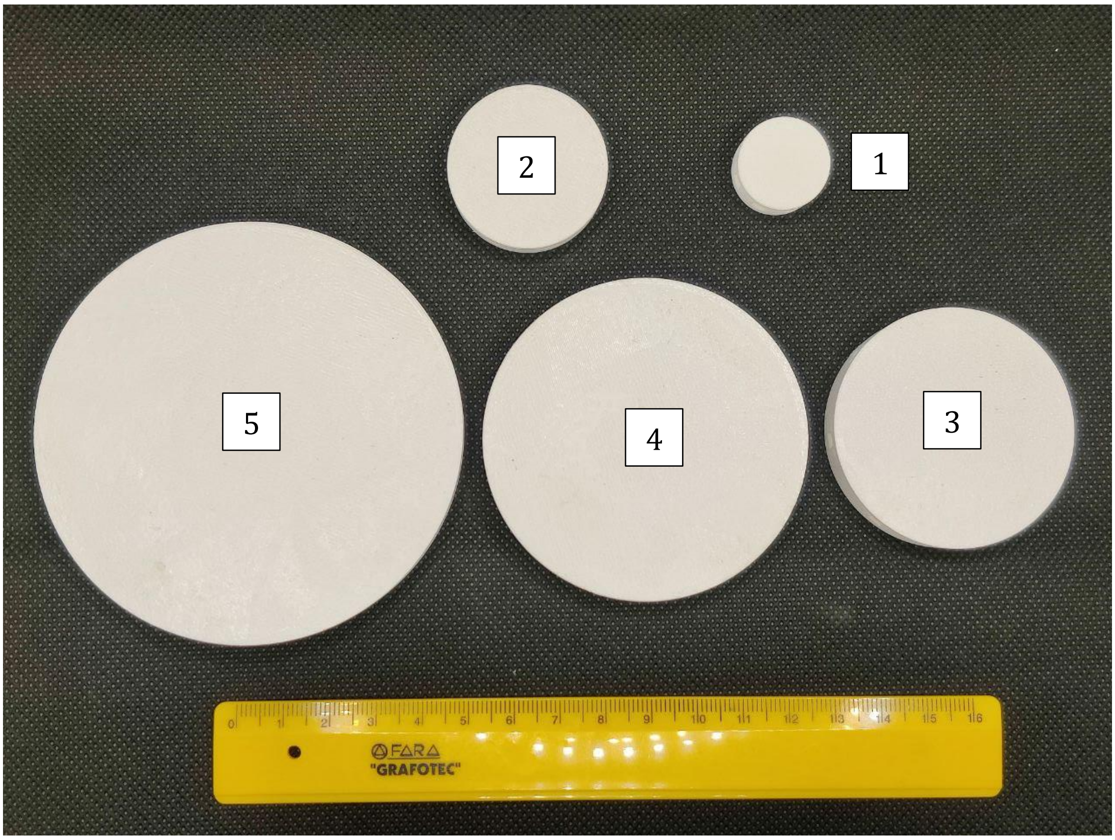


Figure 49. Token sizes.

Figure 50. Stacked tokens. The slots where add-ons can be inserted are visible on the side surface of each token.

Tokens were designed in five sizes to represent different levels of CO2 (see Figure 49). The specific interval of CO2 ppm mapped to each token depends on the range of values recorded during the walk.

6.4 Add-ons

Add-ons are small artifacts that can be connected to a token to represent additional data. They're connected to the tokens using small pegs that fit into one of eight slots on the curved surface of each token. We can distinguish different types of add-ons, value, markers, and shape modifiers.

Value add-ons

Value add-ons can be mapped to data to represent a certain value. Similarly to the tokens, they also use *global shape* to represent differences through their size. Since color variables such as hue, saturation, and luminance perform well in the selective and associative tasks, these variables, with the limitations described in Chapter 4, will be used as well. Different materials will be used to print these add-ons to represent additional data types in the same token.

An example of value add-ons connected to different tokens can be seen in Figure 52.

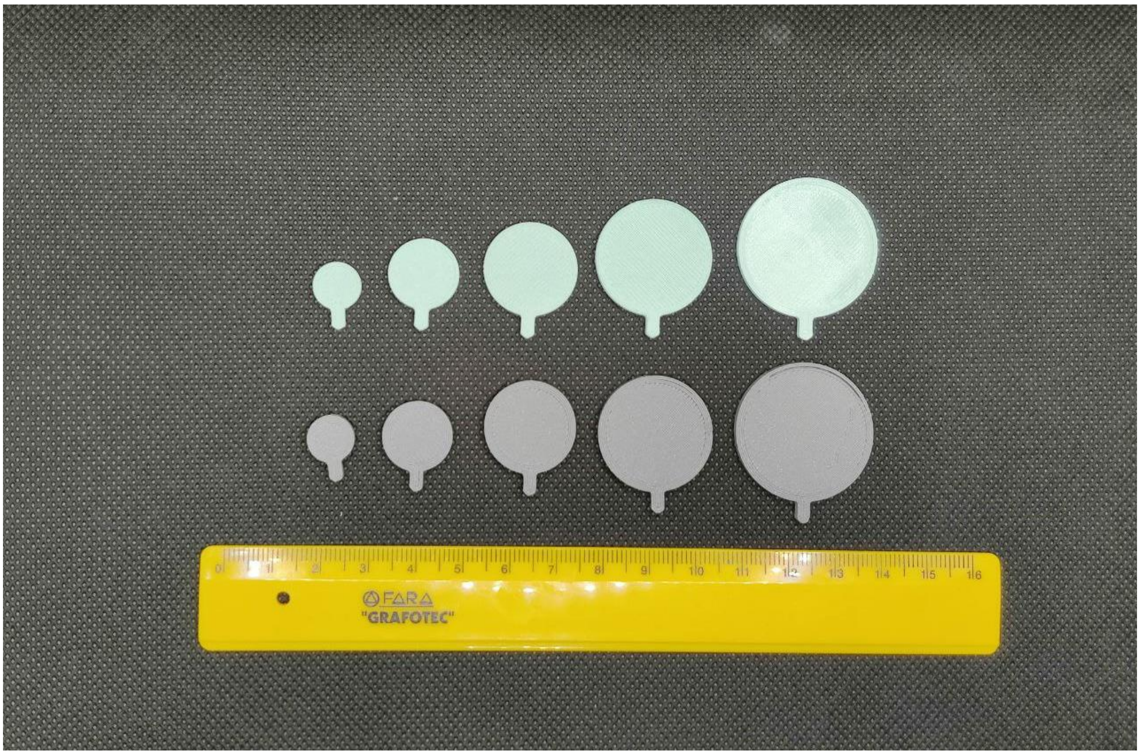


Figure 51. Value add-ons made in different colors and sizes..

Figure 52. Value add-ons of different sizes connected to the tokens.

Value add-ons are available in five sizes in a circular shape (see Figure 51) because that shape allows for easier reading of the overall dimension of the object. An alternative asterisk-like shape is used to present participants with a different mapping choice and the latter add-ons come in only three sizes (see Figure 53).

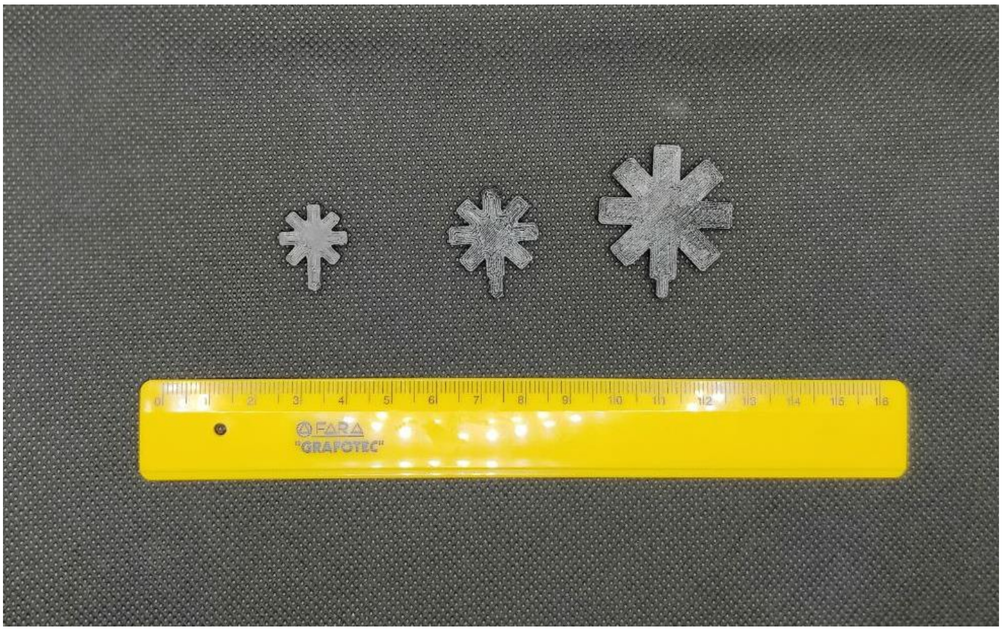


Figure 53. Asterisk-shaped value add-ons.

Markers

These add-ons bring the user's attention to a certain token, representing a particular property of the path. Therefore, they can also be used to categorize tokens based on the features of the walk section they represent.

For example, one of these add-ons could be inserted in a token to show the presence of a particular landmark, and another one could be used to mark all tokens related to parts of the walk near parks.

This type of add-on will be made available in a variety of shapes as shown by Figures 54 and 55, some abstract and some iconic:

1. Map pins: come in two sizes for easier readability in partially occluded tokens.
2. X shape.
3. House.
4. Tree.
5. Magnifying lens.
6. Factory.
7. Building.
8. Stop sign.

Some of these add-ons will come in only one material, such as green PETG for the tree, the others will be printed in various materials with different finishes and haptic properties. An example of this type of add-ons connected to tokens can be seen in Figure 56.

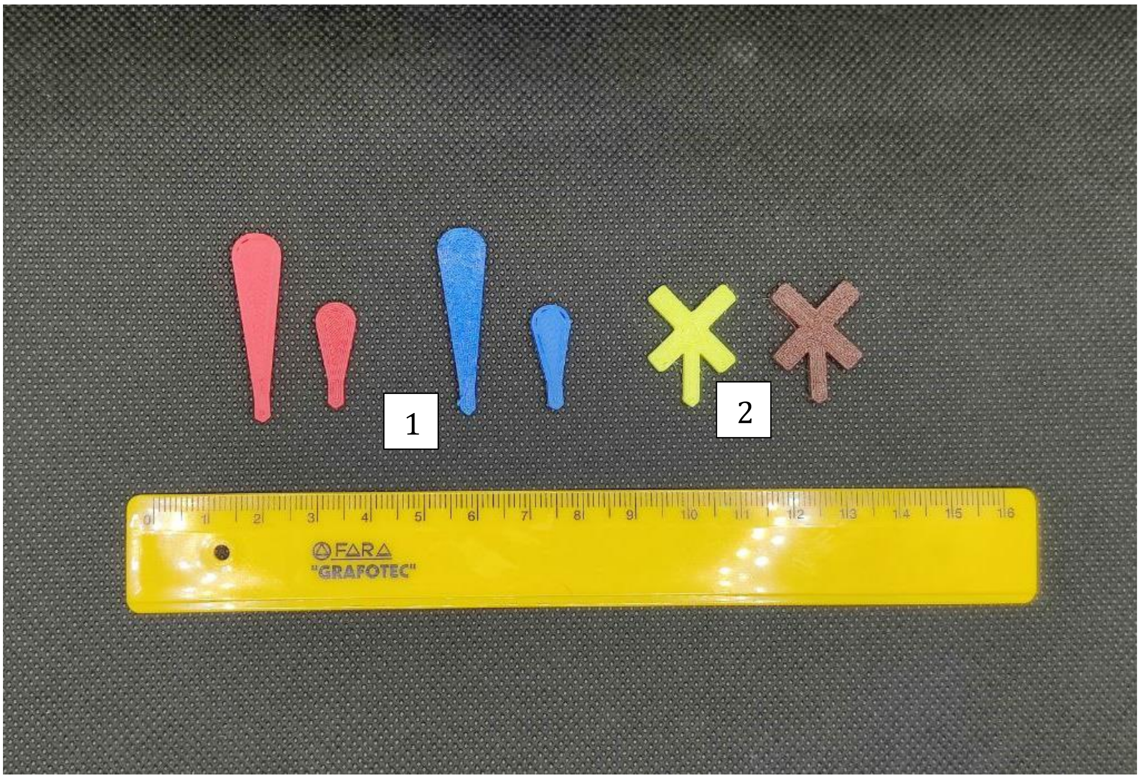


Figure 54. Marker add-ons (1).

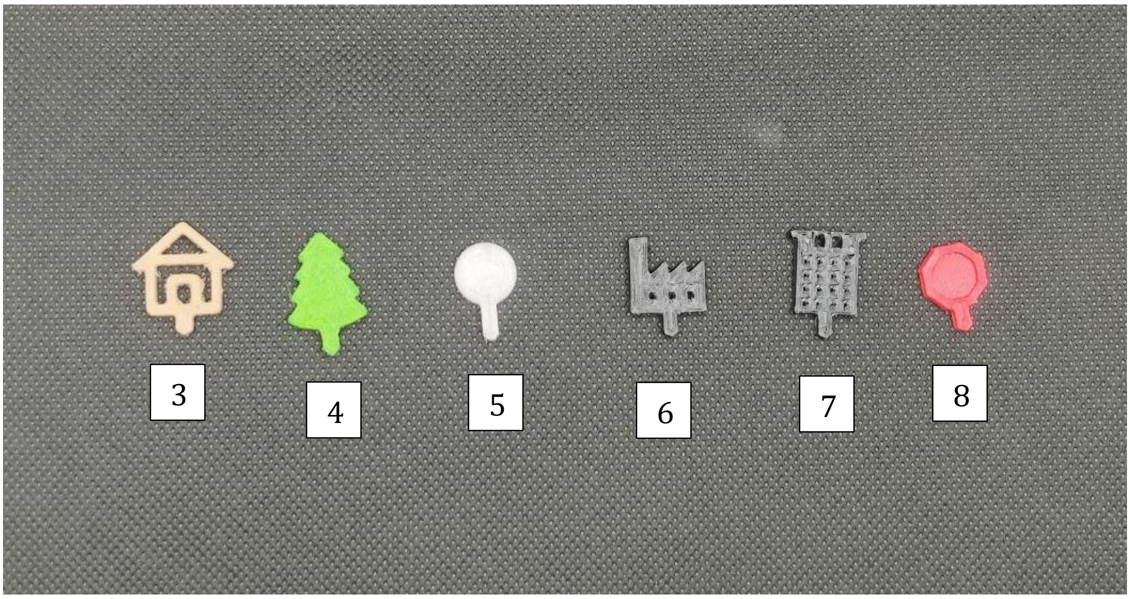


Figure 55. Marker add-ons (2).

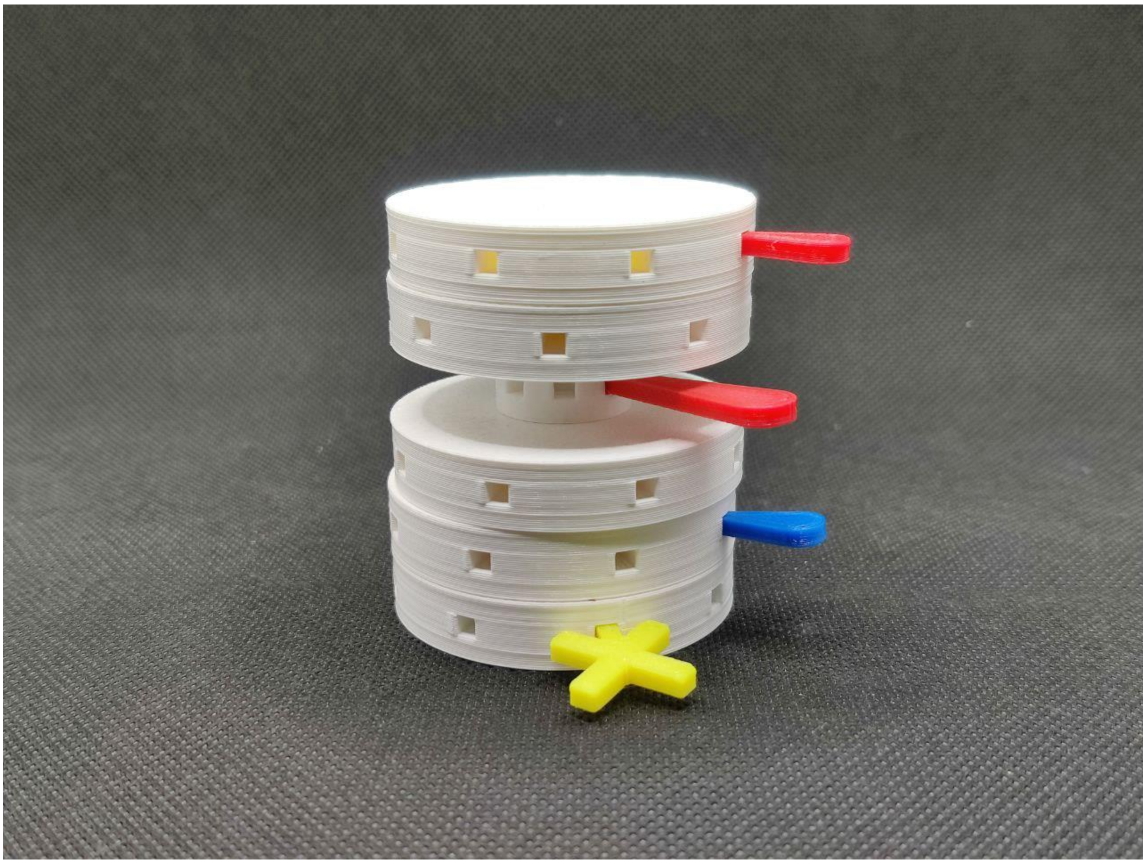


Figure 56. Marker add-ons connected to some Tokens.

Shape Modifiers

By changing the profile of the token they're connected to, these add-ons allow users to modify the exact shape of a token by adding edges to its profile (see Figure 57). Unlike the other add-ons, they are modeled to have the same material and thickness as the tokens to blend into them seamlessly.

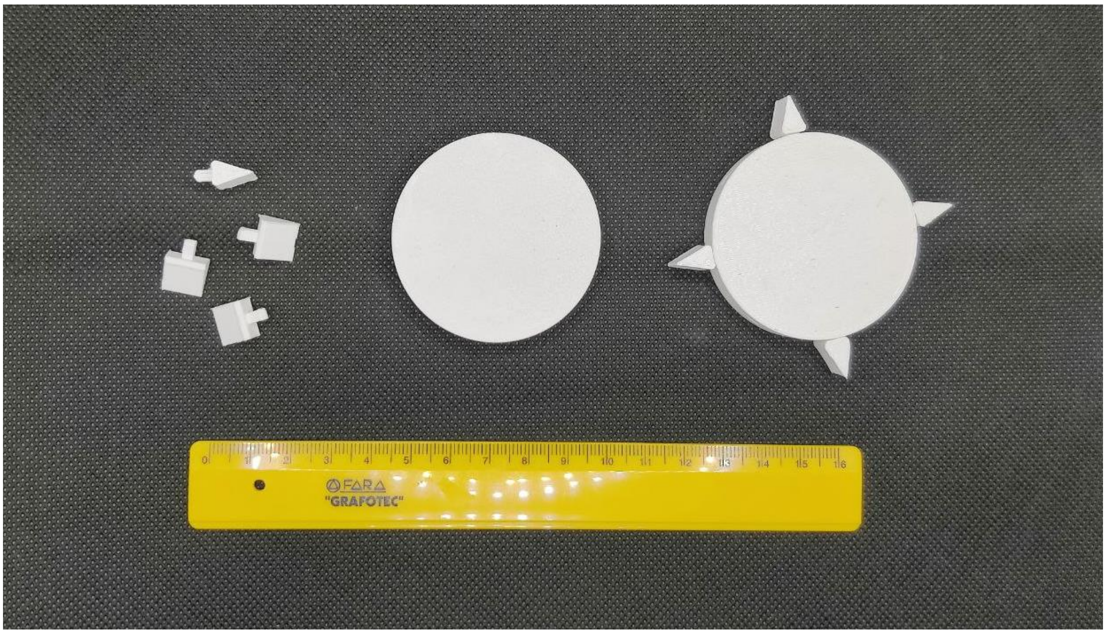


Figure 57. Shape Modifier add-ons.

6.5 Construction example

This section will detail a possible workflow to construct a physicalization using the proposed toolkit.

First, the data recorded during the walk is divided into smaller sections (see Figure 58). Each can have the same length or be established taking into account the different environmental context.

Figure 58. Overview of a walk divided into six sections.

Values gathered in the different sections are then averaged (see Table 5).

Table 5. Section averages.

Section	CO2	Humidity	Temperature
1	707 ppm	53%	20 C
2	721 ppm	52%	20 C
3	725 ppm	56%	20 C
4	706 ppm	55%	20 C
5	727 ppm	57%	19 C
6	691 ppm	58%	20 C

In a workshop, the table above would be handed over to the participants, which would then build the physicalization by adding for each section other data they observed during the walk. For example, the environmental context of each section:

1. Residential area.
2. Main road, houses, school.
3. Residential area, small fields.
4. Residential area.
5. Riverbank, woods.
6. Rural area.

The task of selecting the scale of tokens to use to represent the data might be assigned to the workshop participants. For example, starting from Table 5, the size of the tokens might be chosen based on the following intervals:

1. Less than 700.
2. Between 700 and 720.
3. More than 720.

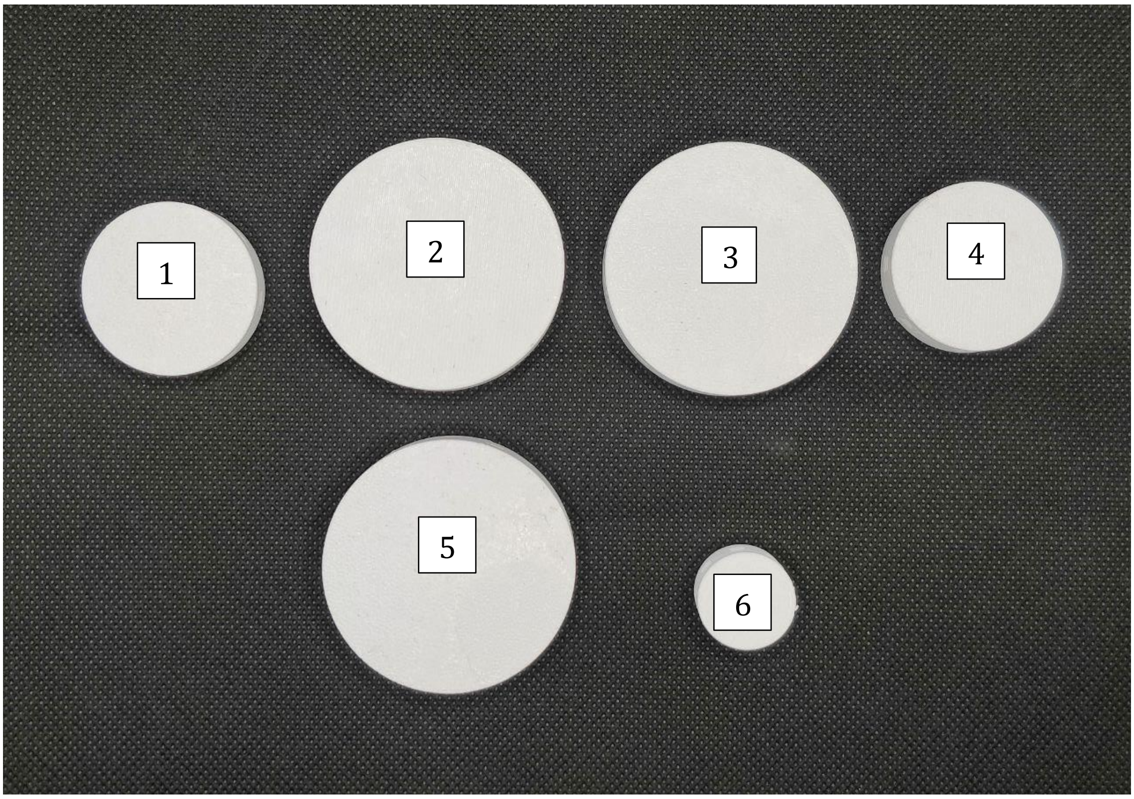


Figure 59. Tokens chosen for each section.

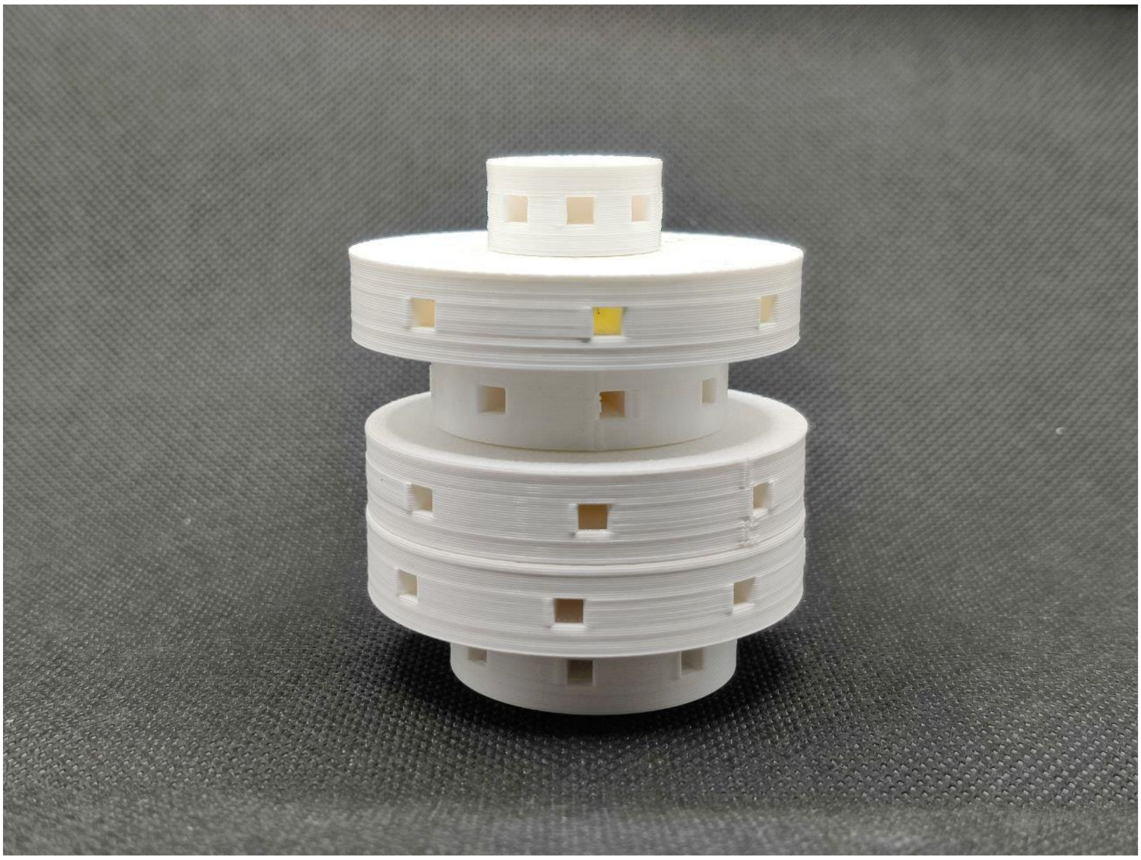


Figure 60. Tokens chosen for each section, stacked.

After a token has been selected for each section (see Figures 59 and 60), the next step will be the selection of the add-ons for representing additional data and information relative to the section. In this example (see Figures 61, 62, and 63):

- Shape modifiers identify the starting section.
- Light blue value add-ons are mapped to the humidity. Each of the five add-on sizes describes an interval of 20% humidity, so in this case size 3 (40%-60%) has been used for all tokens.
- Residential areas are marked with a house-shaped add-on.
- A wood-colored map pin marks rural areas.
- The section containing a main road is marked with a stop sign.
- A golden map pin represents the school located in section two of the path.
- A blue pin marks section five to represent the presence of a river and a tree to signal a heavily wooded area.

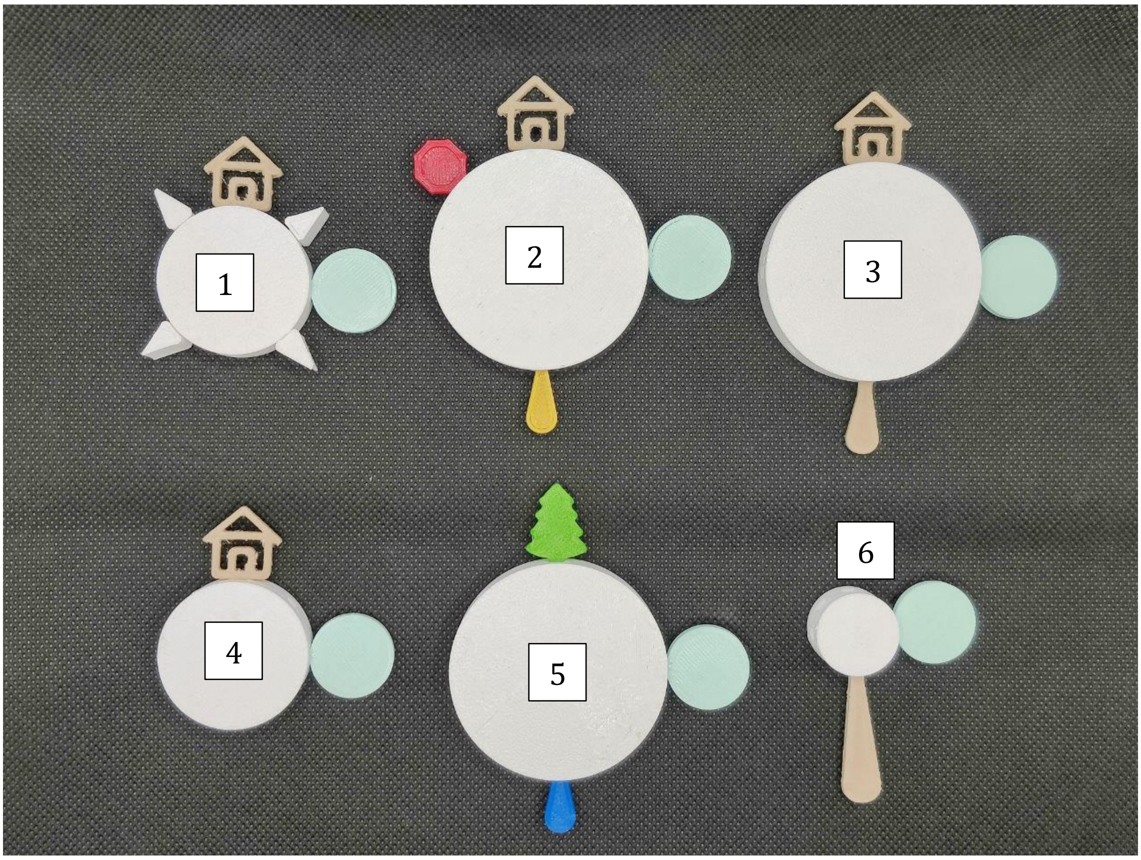


Figure 61. Tokens combined with different add-ons.

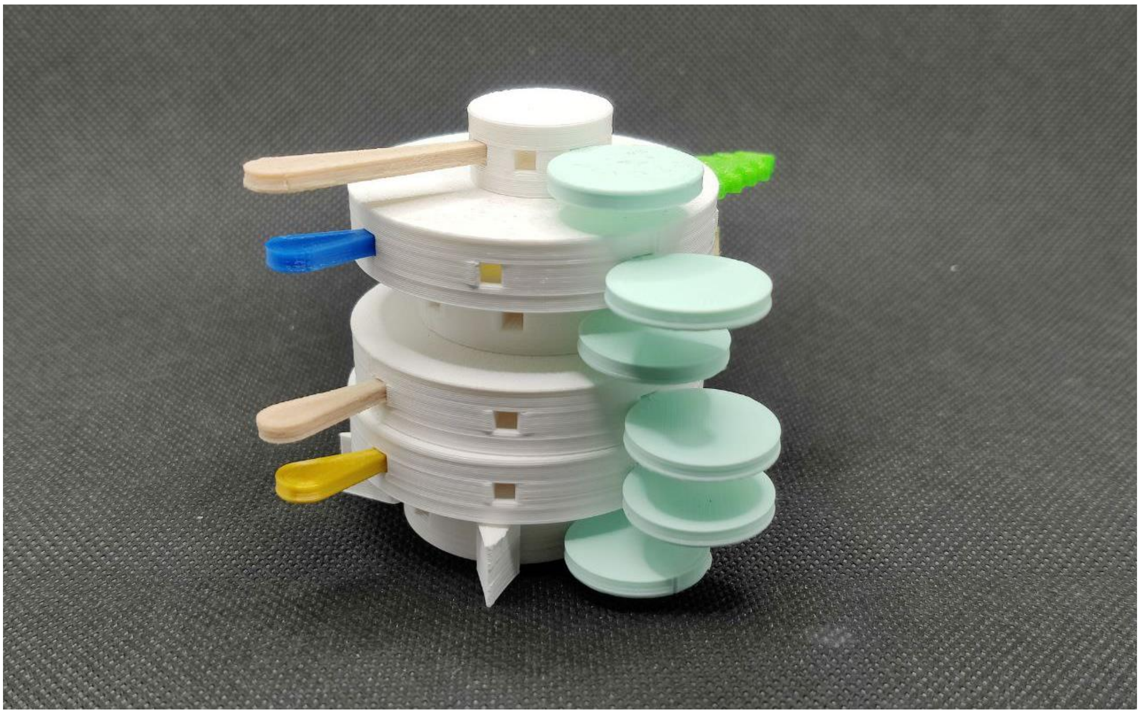


Figure 62. Stacked tokens and add-ons.

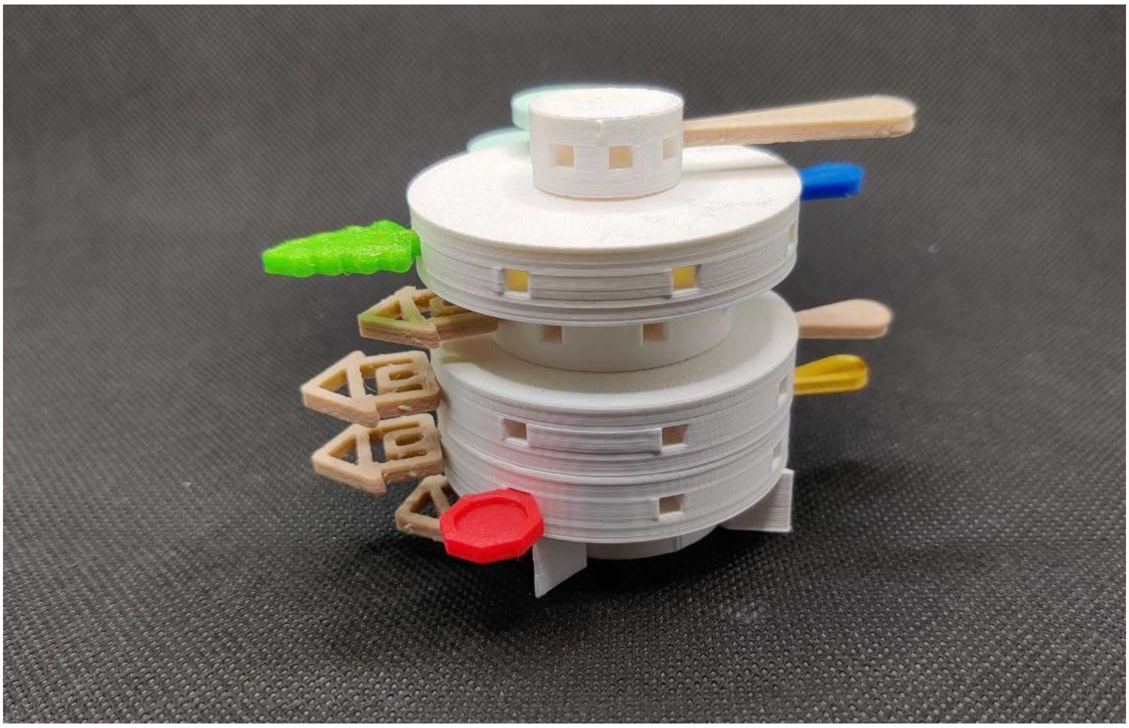


Figure 63. Stacked tokens and add-ons, different angle.

In a workshop scenario, participants will then discuss the physicalizations they created.

For example, Figure 61 shows tokens two and five having the same size (size-based association). However, these tokens differ from their add-ons (exact shape and color selection), so participants could discuss how the naturalistic area represented by token 5 could have a similar CO2 level as the more urban token two.

7 Workshop

This chapter describes a Data Physicalization workshop held in May 2023 near the Scientific Campus of Ca’ Foscari University of Venice. Three voluntary participants participated in the workshop.

7.1 Locations

The university campus was chosen as the ending point of three walks performed by the participants. These walks encompassed different environments around the campus. In particular:

1. **Walk 1:** starting near the Porto Marghera industrial complex and passing by Porto Marghera’s train station, which is commonly used by students.
2. **Walk 2:** a more naturalistic walk starting at the San Giuliano Park, a large public park facing the Venetian lagoon.
3. **Walk 3:** from Mestre’s main train station to the university campus, passing by heavily trafficked areas.

Some pictures taken on these walks can be seen in Figures 66, 67, and 68. The walks were split into segments of around 270 meters, as this size allows to have a dedicated section for each environment (see Figure 64).

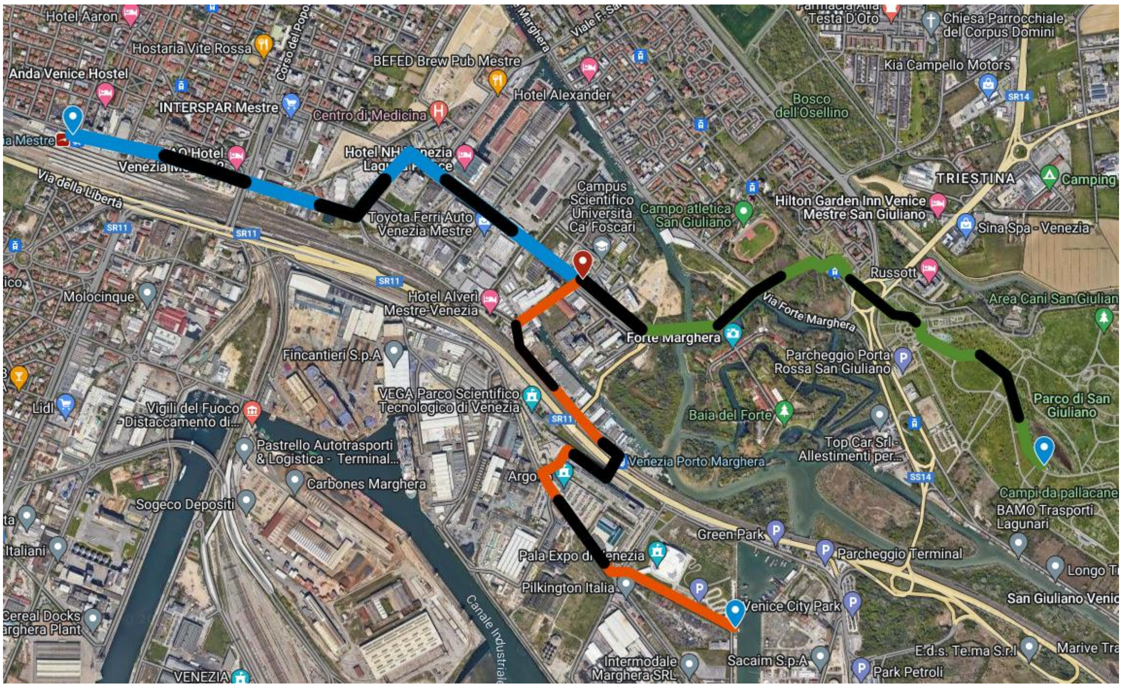


Figure 64. Map of the three walks.

7.2 Brief

After the arrival of the participants, a short brief was held to prepare them for the workshop.

Participants were introduced to the subject of the workshop and the type of data they would be collecting. Some background information was given on CO2 and how it's produced by human activities and by the environment.

The participants were also instructed to record some data on the walk they found interesting or relevant. The data recorded by participants can be both numerical (number of cars, trees, people encountered) or qualitative (noise level, crowdedness, type of environment). The purpose of this data is to provide a way for the participants to personalize their visualization as a way to increase their engagement. This type of data will also be used to complete the visualization by adding geographical references to help associate the data of each token to the places where it was recorded.

Each walk was illustrated and assigned to a different participant, and special care was given in explaining the section-based structure of each walk. To allow participants to comfortably record information during the walk, they were each given some printed sheets already divided into sections.

Participants were also given a quick guide to the data gathering devices and some troubleshooting tips. They were also instructed to mark the time when they entered each section in case of a GPS malfunction.

7.3 Walk

Figure 65. Picture taken by a participant during their walk.

Participants were given a map of their respective walk already divided into sections and a data recording device (see Figure 65), and they each set off to complete their walk.

Figure 66. Pictures taken during walk 1.

Figure 67. Pictures taken during walk 2.

Figure 68. Pictures taken during walk 3.

7.4 Construction

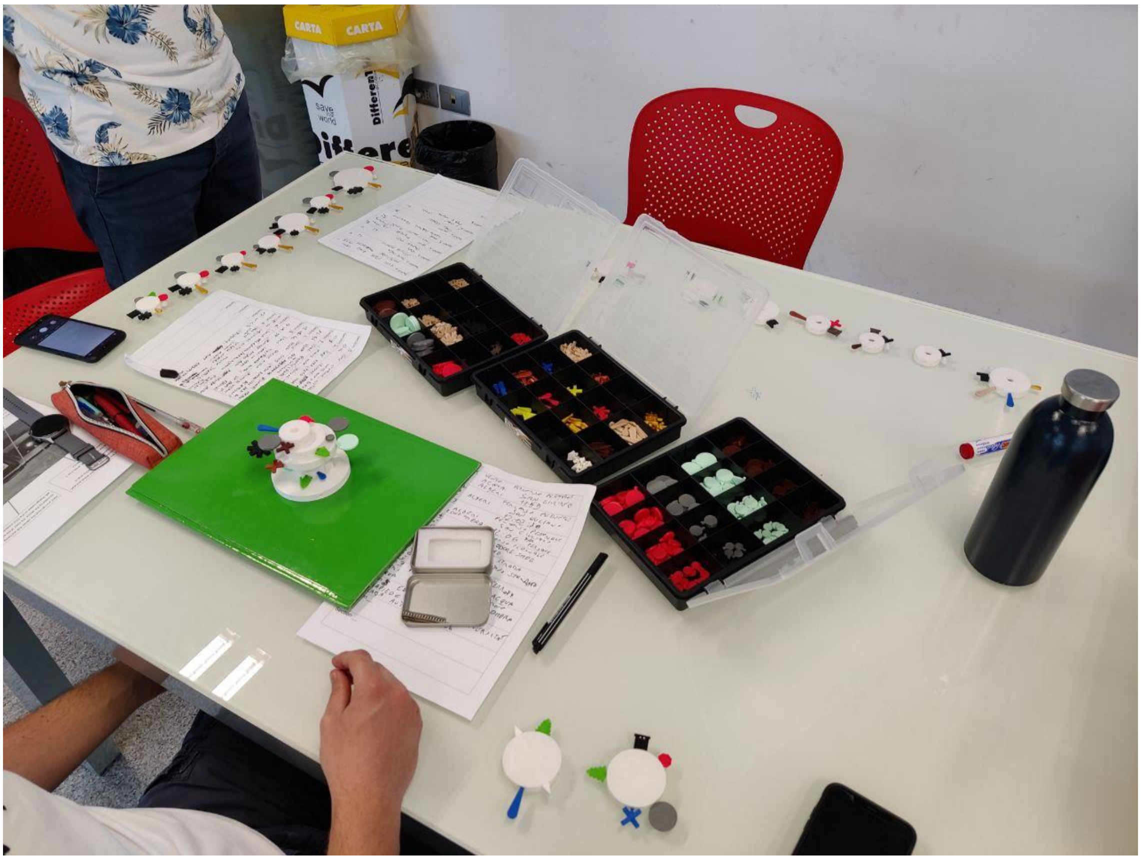


Figure 69. Picture taken during the construction phase of the workshop.

After the walk, the data were collected from the participant's devices and processed. The three final tables with the averaged data were then showed to the participants.

Participants were then asked to decide how to map the recorded CO2 levels to the token sizes. In this workshop, the participants decided to use three token sizes, each being associated with the following ranges of values:

- Size 2: CO2 values less than 575.
- Size 3: CO2 values between 575 and 599.
- Size 4: CO2 values above 599.

The participants avoided using the smallest token, as they felt it should have represented values closer to the theoretical minimum, which is around 400.

After this first choice, the full selection of available add-ons was presented to the participants, who began working on them (See Figure 69). After the tokens were completed with the add-ons, the participants gave a brief presentation on their visualization, showcasing the data they had represented and what add-ons they had used.

7.5 Physicalizations

This section shows the physicalizations produced by the participants and details their mapping choices. A figure featuring the layers created by combining tokens and add-ons is provided for each walk, along with figures showing the fully assembled physicalization. A table with the data recorded by the participants for each walk is also provided.

Walk 1

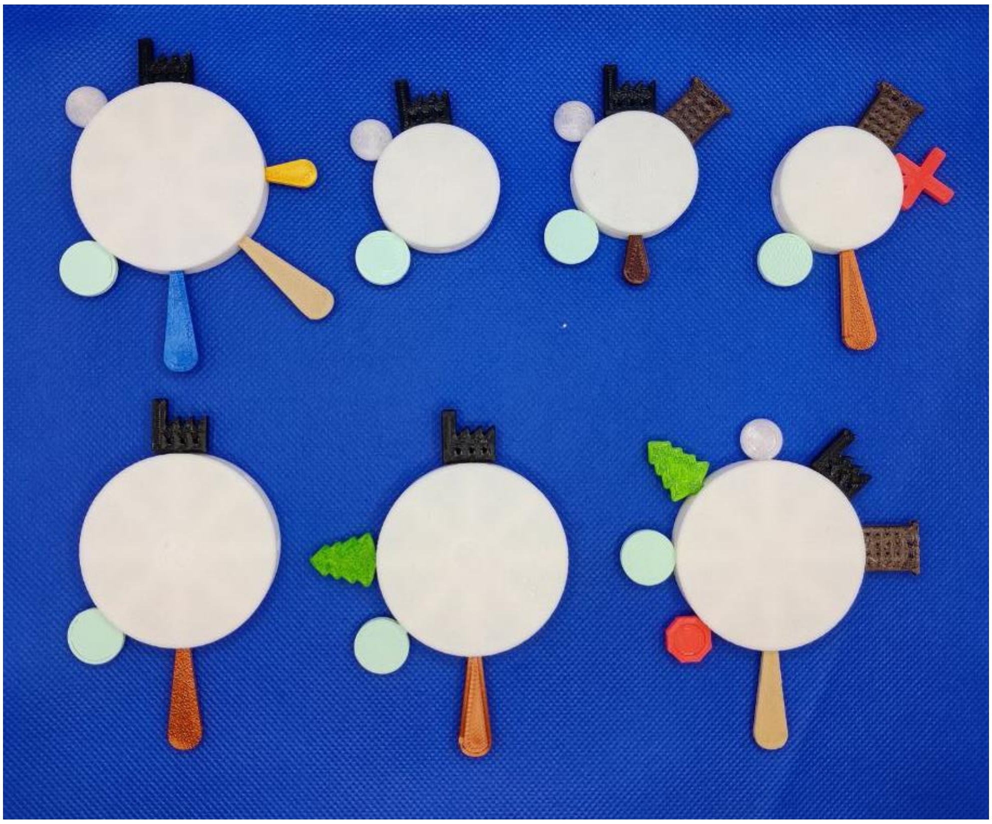


Figure 70. Physicalization of walk 1 – overview of the layers.

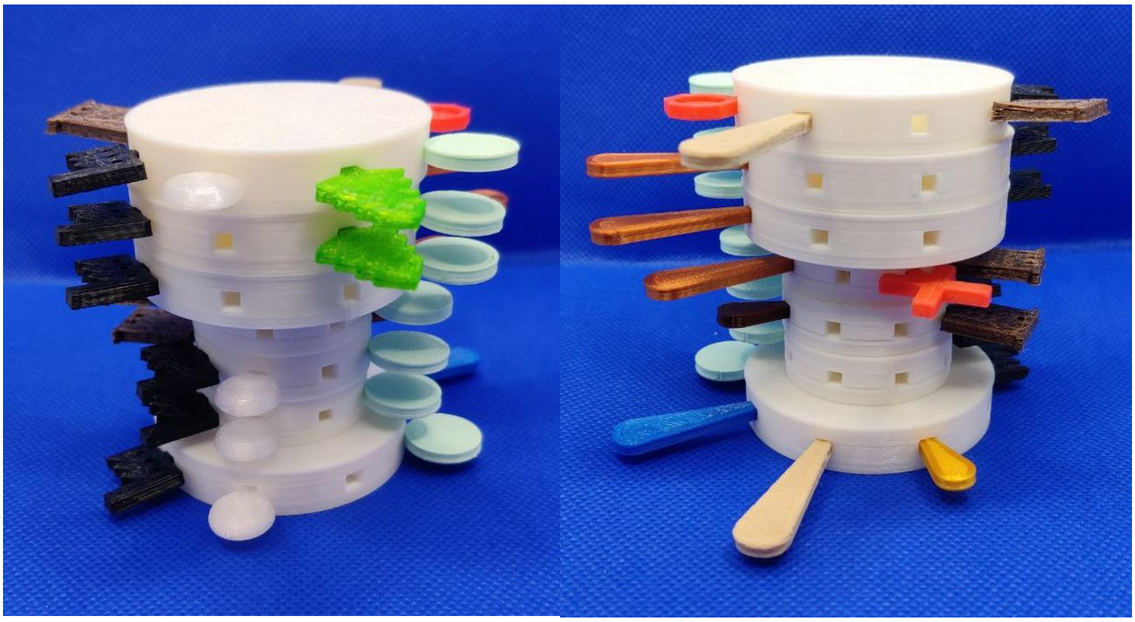


Figure 71. Physicalization of walk 1 – assembled layers.

Table 6. Walk 1 – data.

Section	Temperature	Humidity	CO2
1	29,09	32,79	578
2	29,53	31,68	571
3	30,37	29,83	559
4	30,94	29,95	567
5	30,92	29,32	577
6	31,34	30,33	596
7	30,77	30,15	575

Legend (by the participant):

- Building: large buildings.
- Tree: presence of trees.
- Factory: presence of factories.
- Red X: Train station.
- Copper-colored map pin: sections of the walk near a railway.
- Small golden map pin: Pala Expo building.
- Blue map pin: sections of the walk near water.
- Small brown map pin: VEGA restaurant.

- Stop sign: sections of the walk near a main road.
- Lens: sections of the walk with strong wind.
- Light-blue value add-ons: relative humidity.

Walk 2

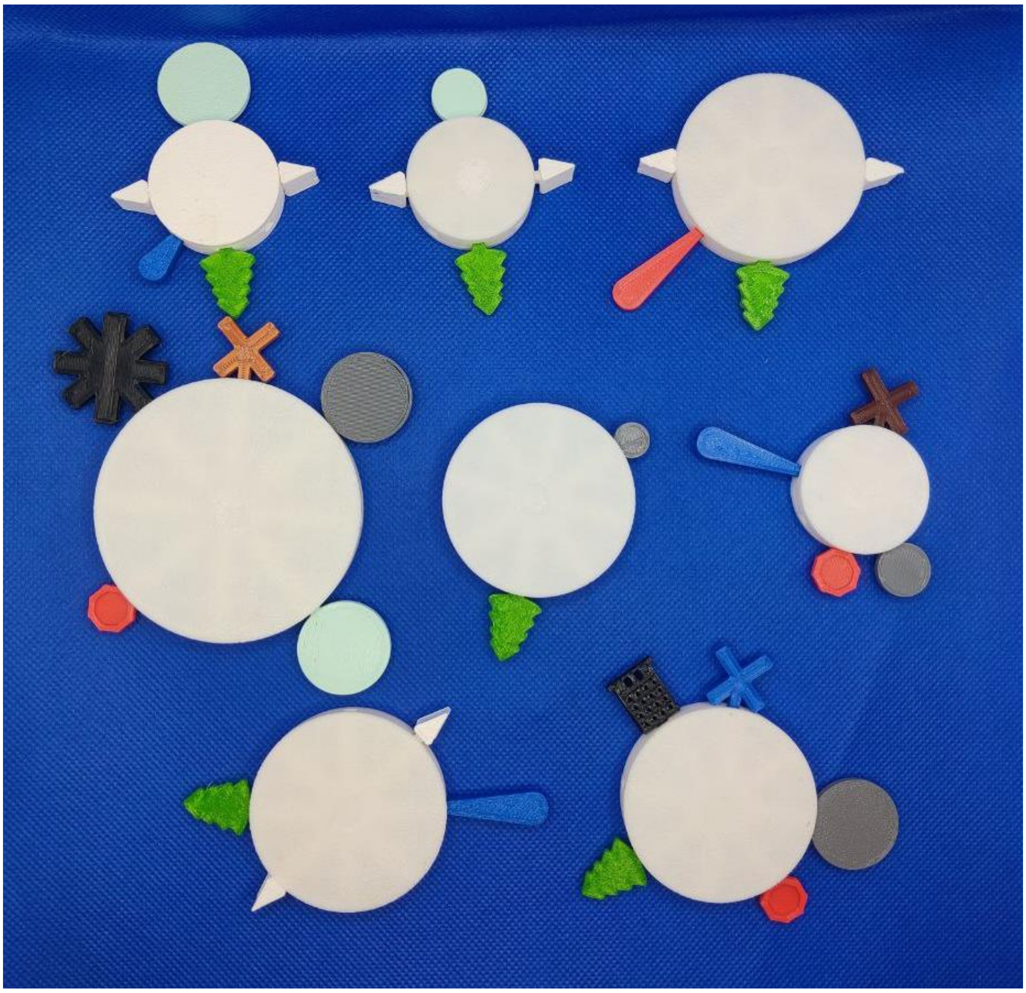


Figure 72. Physicalization of walk 2 – overview of the layers.

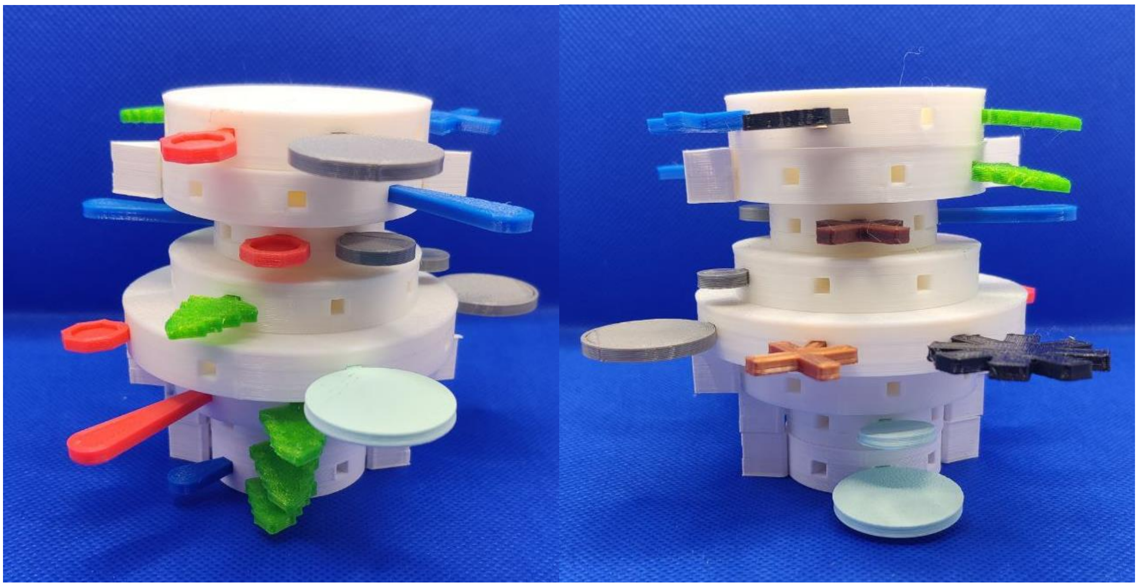


Figure 73. Physicalization of walk 2 – assembled layers.

Table 7. Walk 2- data.

Section	Temperature	Humidity	CO2
Zona 1	28,37	38,14	574
Zona 2	28,86	38,75	561
Zona 3	28,95	38,56	575
Zona 4	29,23	35,45	604
Zona 5	29,82	33,85	576
Zona 6	30,39	33,60	559
Zona 7	30,28	32,60	590
Zona 8	30,06	32,72	583

Legend (by the participant):

- Building: large buildings.
- Tree: presence of trees.
- Large black asterisk: the participant marked that section of the walk to signal a strong smog-like odor in that section.
- Stop sign: major road.
- Large red map pin: presence of crowds.
- Blue map pins: parts of the walk near water.
- Blue X: University Campus.
- Brown X: Fort Marghera.

- Copper X: bridge.
- Shape modifier add-ons: mark sections of the walk in a park.
- Grey value add-ons: number of cars.
- Light-blue value add-ons: strength of the wind.

Walk 3

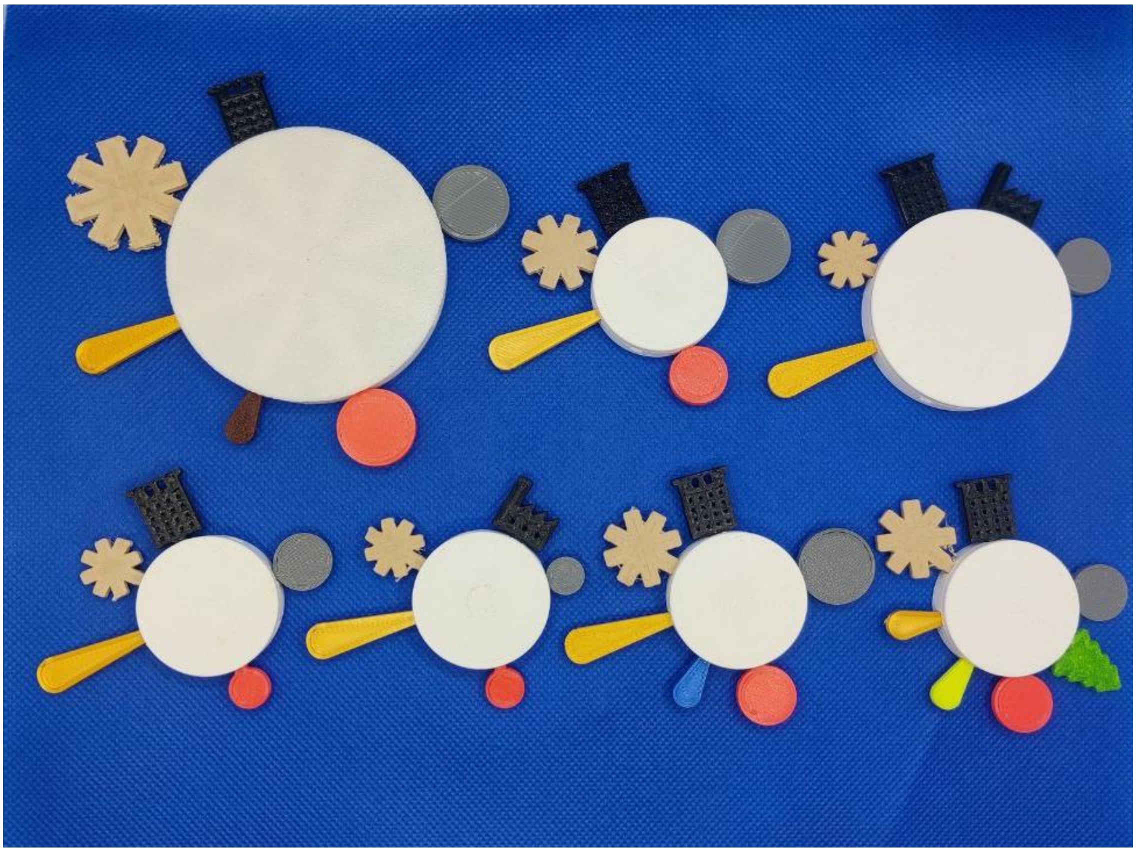


Figure 74. Physicalization of walk 3 – overview of the layers.

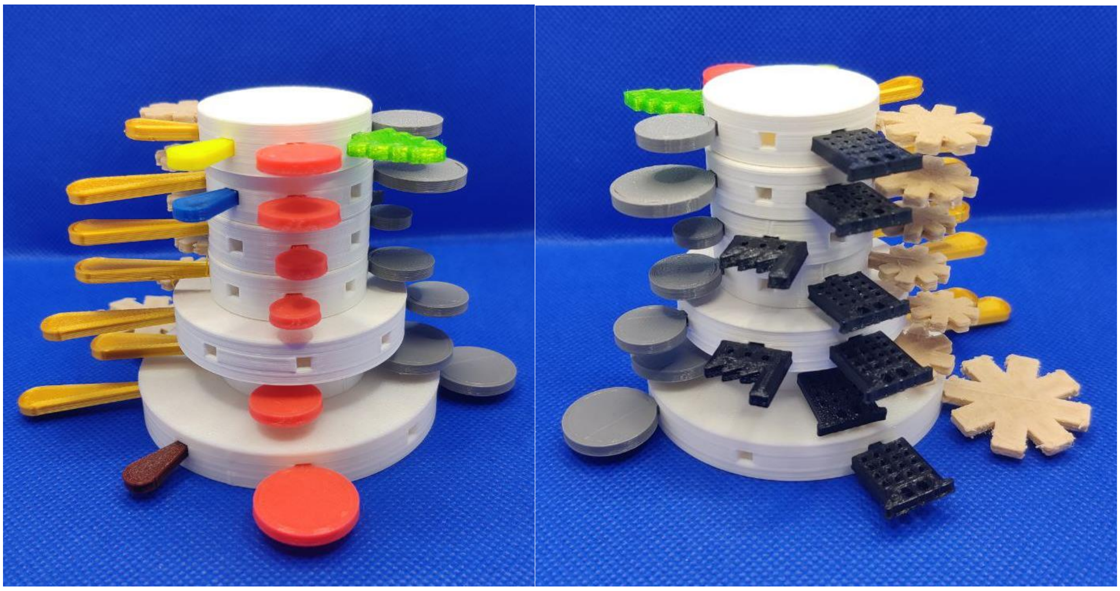


Figure 75. Physicalization of walk 2 – assembled layers.

Table 8. Walk 3 – data.

Section	Temperature	Humidity	CO2
1	29,73	29,25	600
2	29,38	29,82	573
3	29,38	30,06	579
4	31,22	27,01	570
5	30,27	29,57	566
6	30,44	28,35	566
7	30,35	28,90	567

Legend (by the participant):

- Building: large buildings.
- Factory: presence of factories.
- Tree: presence of trees.
- Asterisk value add-ons: noise level.
- Blue map pins: Laguna Palace (large hotel).
- Brown map pin: Train station.
- Yellow map pin: university campus.
- Grey value add-ons: number of cars.
- Red value add-ons: amount of people encountered during the section.

- Large golden map pin: parts of the walk exposed to the sun.
- Small golden map pin: parts of the walk featuring shaded areas.

7.5 Observations

This section contains some observations on the physicalizations built by the participants.

All three participants made use of the *marker* add-ons featuring concrete shapes to represent features of the walk. Iconic shapes were used each time the participants identified a semantic relation to the topic to represent.

The add-ons featuring abstract shapes were also used by the participants, although in a less uniform way. Some ambiguity was present due to the different sizes of the *map pin* add-ons, which were used differently by the three participants. In particular, one participant used the different sizes of the golden *map pin* add-ons to represent the exposure to the sun of each section instead of using them for coping with occlusion problems. However, all participants used the blue *map pin* to represent water.

All participants used the *value* add-ons to represent numerical data recorded during the walk. However, one participant used a large asterisk-shaped one as a *marker* instead.

Only one participant used the *shape modifier* add-on, particularly to represent parts of the walks inside parks. This choice was made to differentiate the green areas inside parks and the ones in an urban setting, creating a more nuanced representation than just using the *tree* add-on.

8 Workshop evaluation

In order to have feedback about the workshop activities, a survey was conducted among the workshop participants.

The survey is divided into the following sections:

1. Demographic questions.
2. Questions about the structure of the physicalization.
3. Questions related to the workshop organization.

These questions were used to detect possible flaws in the proposed design and to highlight future developments of the toolkit. The survey was made up of 33 total questions and implemented using Google Forms.

8.1 Demographic questions

These questions are aimed at collecting demographic information about the participants, such as their age, occupation, and grade of education.

8.2 Questions on the structure of the physicalization

This section contains questions related to the general structure of the physicalization. The participants were asked to give feedback about the following features:

- The choice of mapping the CO2 values to cylindrical token.
- The fact that the visualization didn’t feature the shape of the walk.
- The fact of basing the representation on a single token.
- The effectiveness of the various types of add-ons.
- The occlusion issues.

Furthermore, participants were also asked to answer some open-ended questions on the following topics:

- How they would have represented the shape of the walk.
- Which type of data would they have given more importance to.
- How they would manage the occlusion issues, if any.
- Which types of add-ons or tokens they would have liked to add to the toolkit.
- The points of strength and weakness of the toolkit.
- How they would increase the expressiveness of the proposed visualization.

8.3 Questions related to the workshop organization

This section contains questions about the workshop organization. The participants were asked for opinions on the following aspects of the workshop:

- The workshop brief.
- The data recording device.

They were also asked open-ended questions about the following topics:

- Whether the workshop brought them to pay more attention to certain aspects of the environment.
- How they would improve the workshop brief.
- How they would improve the workshop as a whole.

8.4 Results

This section will discuss the results of the survey.

Structure of the physicalization

The participants found the choice to map the CO2 levels to the cylindrical tokens to be appropriate for the representation but had different opinions on the importance of the shape of the walk.

One participant suggested the use of connected parallelepiped-shaped tokens to represent the shape of the path, while another one suggested to place the tokens on a map.

The participants agreed that CO2 was the more important data type to represent but also suggested the use of additional environmental variables to represent.

The participants experienced some occlusion issues in their visualizations and proposed to increase the height of each token to diminish the problem. One participant instead proposed to use spacers to increase the distance between tokens.

Add-ons

The participants were generally satisfied with the variety of the provided add-ons. The survey shows that they appreciated the add-ons featuring concrete shapes the most, and while they also found the ones featuring abstract shapes to be effective, they used them to a lesser extent. In particular, the participants used abstract-shaped add-ons only when a concrete one wasn't available for that feature.

Participants that represented humidity and temperature values found the mapping of the value add-ons to numerical values recorded during the walk to be effective. The shape-modifying add-ons were, however, not deemed to be as effective. This is probably because they were perceived as part of the token rather than representations of other data types.

The participants also proposed to include add-ons for meteorological conditions in the toolkit and increase the amount of building-specific add-ons.

Additional feedback

When considering the strengths and weaknesses of the visualization as a whole, the participants particularly enjoyed its physical nature. In particular, they appreciated the engagement that comes with the construction process and the fact that the process led them to something tangible that remained after the end of the workshop. Another positive aspect tied to the physicality of the visualization was the possibility of observing the visualization from multiple angles and at different levels of completion.

Furthermore, the participants considered the personalization opportunities offered by the toolkit as one of the points of strength of the visualization.

The participants noticed the occlusion issues that could be present in the visualization and would have liked the tokens to also encode the type of environment with their color. Furthermore, they would have preferred larger tokens with less difference between size to accommodate for the low variability in CO2 values they encountered.

Workshop organization

The participants enjoyed the workshop as a whole and found the initial brief useful to carry out the tasks. Furthermore, they found the data gathering device comfortable to carry around but not all of them observed the data gathering device's screen during the walk.

All participants observed the environment more attentively during the walk, and declared that they paid attention to features they don't normally notice.

8.5 Feedback

While limited in scope and in the number of participants, the preliminary survey discussed in this chapter provided useful feedback and showed some areas where the toolkit could be improved, related in particular to the issue of occlusion and the shape of the path.

Offering tokens made of different colors, while an interesting suggestion, still presents some issues due to the large number of possible combinations that will have to be printed, leading to a consistent and unsustainable waste of materials.

8.6 Improvements on the toolkit

Following the feedback detailed in this chapter, some possible future developments of the toolkit were highlighted.

While during the design phase of this toolkit the shape of the path was not considered important, the survey showed that it could be an interesting feature to visualize for some users. In light of the fact that personalization is an important feature of the toolkit, a new type of add-on was developed to allow users of the toolkit, to connect tokens to recreate the shape of the walk. Using add-ons instead of incorporating the shape of the walk in the visualization grants an additional option that can be used at the discretion of the person constructing the visualization.

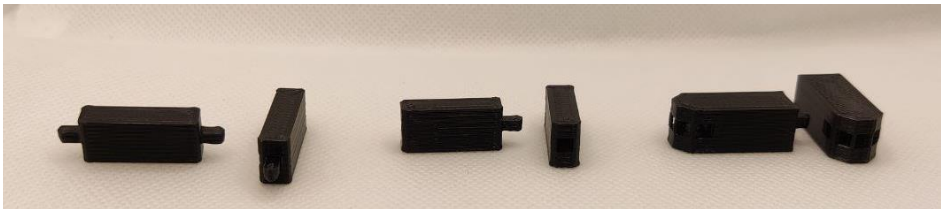


Figure 76. Connector add-ons.

This new type of add-ons will feature three shapes (see Figure 76):

1. A male-to-male connector.
2. A male-to-female connector.
3. An angled connector with different plugs angled at 0, 45, and 90 degrees (see Figure 77).

An example of the used of these add-ons can be seen in Figure 78.

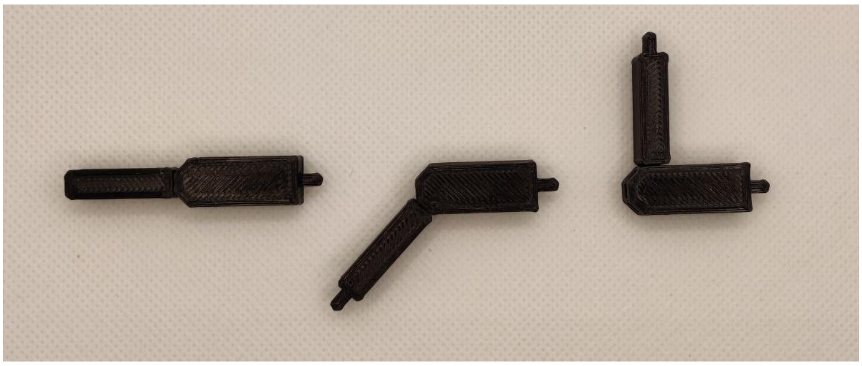


Figure 77. Angled connector add-on.

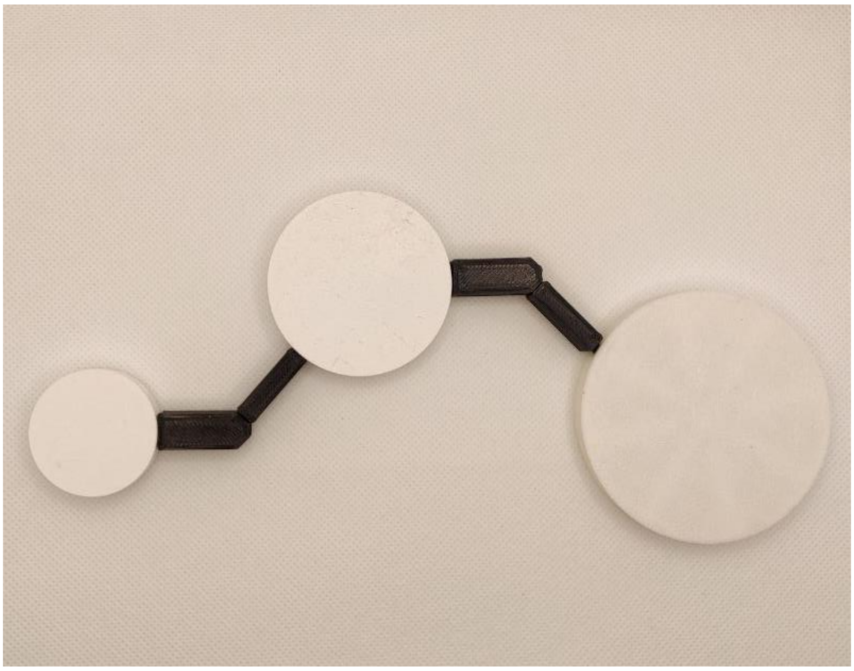


Figure 78. Example of the connector add-ons' usage.

Occlusion is an issue that is difficult to overcome when dealing with a stack-like structure. As a solution to this issue, the use of token spacers is proposed (see Figures 79 and 80). These spacers will provide additional space between tokens to make them more readable when stacked. This will diminish the occlusion of the visualization, hopefully reducing situations in which a token is hidden by its neighbors.

Figure 79. Token spacers.

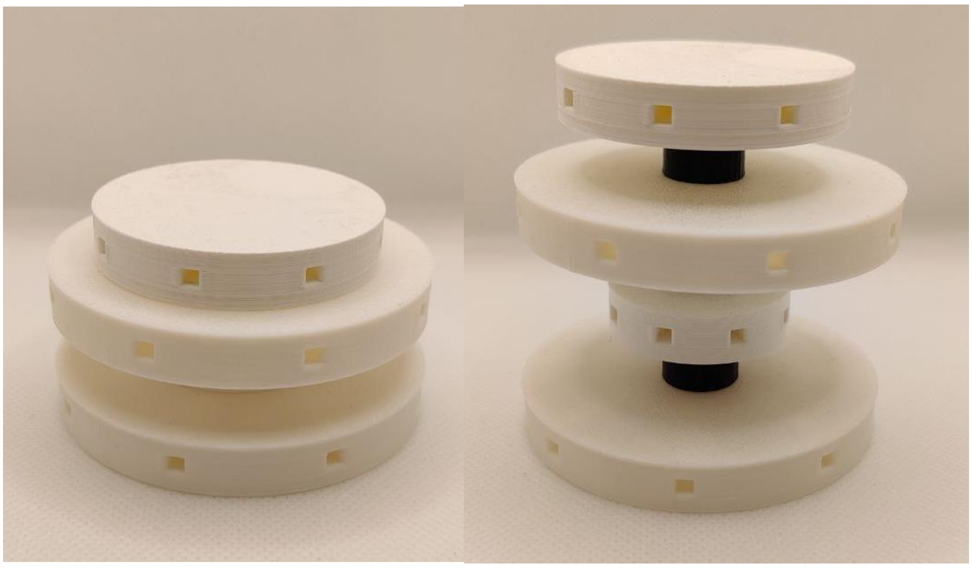


Figure 80. The same stack of tokens without spacers (left) and with spacers (right). Both pictures were taken at the same angle.

To preserve the toolkit's constructive nature and the visualization's structural integrity, the spacers can be outfitted with a small screw to interact with the token's magnets.

Furthermore, the two sizes used for the *map pin* add-ons could potentially cause some ambiguity in their use, as shown in one of the physicalizations created in the workshop. For this reason, future iterations of the toolkit should feature marker add-ons in a single size.

9 Conclusions

This thesis began with the goal of designing a set of building blocks (a toolkit) to support the constructive physicalization of data recorded during a walk and to evaluate its performance. To this end, the growing body of literature focused on the physical representation of information was studied.

Through this study, the many benefits of this type of visualization were analyzed, with the aim of achieving them with the proposed design.

Particular emphasis was given to find optimal strategies to map data to the physical properties of objects and to find how these objects could be arranged to better represent data recorded during a walk.

Furthermore, the *Data Walking* [5][8] experience was used as a very interesting example of workshop meant to involve citizens and study the representation of data recorded while walking. The analysis of the representations proposed by *Data Walking* brought a number of solutions to improve its initial design.

In particular, the physicalization *Data Cylinders* described in the *Data Walking* report [5] was a particularly interesting starting point for the design process. *Data Cylinders* used a stack of circular layers to represent the data points recorded during the walk.

This physicalization presented some features that could be improved, such as:

- An unclear mapping of pictures representing the location on the surface of each token.
- Occlusion problems due to the limited height of the cylinders.
- A limited number of environmental variables mapped to the cylinders.

Furthermore, *Data Walking*'s design needed to be adapted to improve the support to the constructive physicalization paradigm. This was achieved by designing and realizing a set of building blocks that can empower even non-expert users to create their own physicalizations.

After reviewing the literature, a fabrication technology and a material were selected to produce the toolkit, determining specific constraints. The choice fell on 3D printed plastic, a widely used technology with many advantages over traditional manufacturing. The constraints and possibilities of 3D printing were also carefully examined during the design of the proposed toolkit.

To record the data that would have been represented using the toolkit, a data recording device was developed based on a Raspberry Pi featuring an array of sensors. A simple user interface was also designed to operate the device.

The design of the proposed toolkit was then detailed. The toolkit produces a stack-based representation of the walk, with only one type of data mapped to the size of a single main token (i.e. a cylinder). In the workshop realized in the context of this thesis, the token was mapped to a specific environmental variable, the CO2 level, the most significant value recorded by the devices and the one most variable.

With the toolkit proposed in this thesis, additional data types are represented by smaller objects (add-ons) plugged to the curved surface of each token. These add-ons are very important to augment the expressivity of the representation, otherwise limited by the single tokens.

The stack-based structure of the visualization doesn’t represent the shape of the path, but this wasn’t deemed to be particularly significant for many situations. In spite of that, a solution for obtaining a simple representation of the overall shape of the path was considered as a possible improvement.

The structure of the toolkit, composed of tokens and add-ons, allows people involved in the construction process to assemble and modify their own physicalizations, allowing for a high degree of expressivity and personalization.

The proposed toolkit was evaluated by carrying out a workshop focused on the representation of environmental data recorded in three different walks near the Scientific Campus of Ca’ Foscari University of Venice. The workshop participants were then asked to answer a survey where they could give their feedback on the experience and the toolkit.

9.1 Results

The participants enjoyed the visualization they produced using the toolkit and considered the experience engaging and informative. They agreed with most of the design choices that shaped the toolkit but also presented some constructive criticism about how to improve it.

Of particular interest were the occlusion and the importance of the shape of the walk.

The participants highlighted some occlusion issues in their visualization, and some of them considered important the path's shape. Following this feedback, two different solutions that can be integrated with the toolkit were proposed.

The participants were also satisfied with the variety of add-ons in the toolkit, even if they found the shape modifier add-ons to be less interesting.

9.2 Limitations

Due to time constraints and logistical difficulties of hosting a workshop, the sample size was not as large as it should have been.

Furthermore, the 3D printer used in this thesis, while a good indicator of what can be achieved by the vast majority of commercially available printers, is not a state-of-the-art unit. With time, as new technologies become cheaper and more easily available, some of the constraints discussed in this thesis might be overcome.

9.3 Future developments

Following the workshop, two new features were prototyped:

1. A spacer system to improve the optimal viewing angle of the toolkit and limit occlusion issues.
2. A set of add-ons for connecting tokens and visualizing the shape of the walk.

These features were developed starting from the feedback received during the workshop and could undergo further development. The spacer unit could be tuned to ensure a better viewing of the visualization. Connector add-ons could be further refined, for example by providing user-defined angles, to improve the visualization of the environmental variables in relation to the path. The validation of these two new features will be part of future work.

Furthermore, finding ways to represent additional types of data without printing a huge number of tokens could be an interesting development in order to limit waste and improve the sustainability of the solution.

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