Physicalizing Sustainable Development Goals Data: An Example with SDG 7 (Affordable and Clean Energy)

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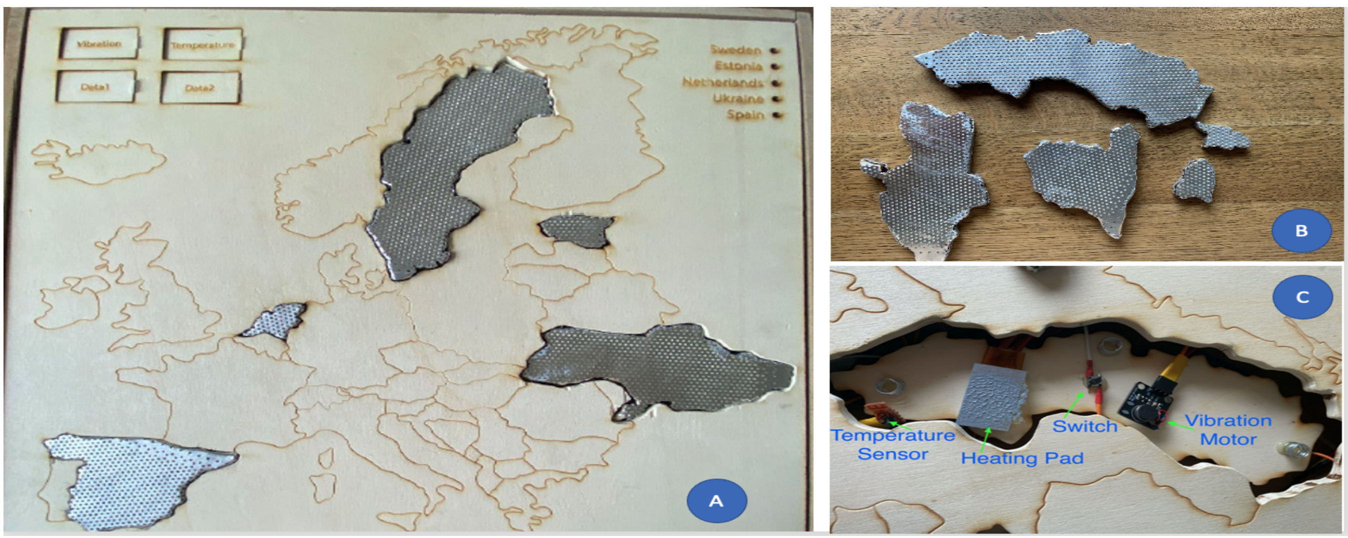


Figure 1: We created a data physicalization that uses vibration and temperature as modalities to convey facts related to SDG 7 (Affordable and Clean Energy). By using vibration and temperature to represent energy data, we aimed to convey abstract data in a more graspable way by minimizing the metaphorical distance between data and the representation (i.e. qualities and properties of the physicalization -were drawn from the qualities and properties of the data). (A) The physicalization that uses temperature (T) and vibration (V) to represent Affordable and Clean Energy data of five countries: Sweden, Estonia, The Netherlands, Ukraine and Spain; (B) Laser cut wooden buttons (representing the geometric shape of the country) wrapped in metal to enable heat conductance; (C) Internal organization (using Sweden as example) of electronics and sensors to enable vibration and temperature output.

ABSTRACT

In 2015, all members of the United Nations adopted the 2030 agenda for Sustainable Development (SD). Seventeen (17) goals (SDGs) were formulated towards peace and prosperity for people and the planet. However, concerns have been raised about whether these sustainable goals can be achieved by 2030. Communicating advances regarding SDGs to citizens in an effective and engaging way is thus crucial, as it can reveal which goals need more attention and prompt them to think about what to do at an individual level to support SDG progress. Physicalizations present an opportunity in this context and the overall goal of this work is to empirically articulate the merits of different strategies to convey SDG data physically. We created a data physicalization that uses vibration and temperature as modalities to convey facts related to SDG 7 (Affordable and Clean Energy). Vibration and temperature was chosen to aim for reducing the metaphorical distance between the data and the representation (i.e. to align the quality of data with quality of representation). In a preliminary evaluation, both modalities were perceived as enjoyable by the participants. The two modalities

CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9156-6/22/04…$15.00
https://doi.org/10.1145/3491101.3519638

were efficient, however, vibration as a modality was more effective. Temperature, despite presenting a lower metaphorical distance, did not appear to be an effective modality to convey SDG information.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; **Interaction techniques**.

KEYWORDS

sustainable development, data physicalization, vibration, temperature, non-visual feedback

ACM Reference Format:

Rick van Loenhout, Champika Ranasinghe, Auriol Degbelo, and Nacir Bouali. 2022. Physicalizing Sustainable Development Goals Data: An Example with SDG 7 (Affordable and Clean Energy). In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3491101.3519638

1 INTRODUCTION

The Sustainable Development Goals are a set of 17 goals that were adopted in 2015 by the members of the United Nations. They propose an ambitious agenda towards peace and prosperity for people and the planet. An effective communication about these goals (e.g. current trends and achievements within specific countries as well as worldwide) is crucial to take informed actions towards their realization. Recent work along these lines has mainly focused on visualization (e.g. guidelines for mapping SDG datasets effectively through basic principles of map design and use [15], or new visualization types to explore SDG data on mobile devices [7]). Physicalizations could complement visualization work with alternative, playful, and more creative ways of connecting with the data and the sustainability topic. Examples of specific challenges include the choice of the appropriate metaphor to convey SDG data, physicalizations of geographic data, coping with the (often) small magnitude of changes in SDG data, and the time-varying aspects of SDG data.

Data physicalizations represent data using physical means such as physical material, sound, vibration, and temperature. They can convey abstract data in a more graspable manner and thereby make data more understandable, memorable and experienceable. The concept of data physicalization is not new but it emerged as a research field only very recently [10]. Many physicalizations were built/ are being developed (see [6] for a review) using various physical modalities such as acrylic [13], light [18], water [20], sound [9] smell [3] and vibration [11], to name a few. Data physicalizations have a great potential in narrowing the gap between users and data and in making an impact through more immersive data experiences. For example, they have been shown to be effective in engaging users [28], efficient information retrieval [12], improving the memorability of data [27], making data understandable [12, 28], initiating social dialogue about socially relevant phenomena [19], making interaction with data enjoyable [28], promoting self reflection [13, 29] and integrating data to the user's environment [30].

The majority of the existing data physicalizations are based on 3D printed physical material. While they have been shown to be effective in a wide range of aspects, the exploration of other modalities such as vibration and temperature for example can strengthen the effectiveness of data physicalizations and the further development of the field. For example, vibration and temperature are completely non-visual. On the one hand, they can be used to create data physicalizations that can be sensed by visually impaired people. On the other hand, they can be used to create more immersive and multi-sensorial physicalizations through the addition of the haptic sensory modality.

In this research, we explore the use of vibration and temperature to convey abstract data. In particular, we investigate the technical feasibility of realizing data physicalizations based on vibration and temperature, the schematic data encoding (e.g. mapping and transformation functions, perceivable data ranges), their effectiveness and efficiency in conveying data and the user preferences and experiences related to vibration and temperature based data physicalizations. We selected sustainable development goals (SDG) data [22] as our use case. Since there are several SDG goals, there is a need to pick one (or a few) to make SDG-related investigations manageable. In this work, SDG7 was chosen for four reasons: *data availability*; *goal's importance* (according to Asadikia et al. [2], it is one of the most synergetic goals; according to Shneiderman et al. [26], developing user interfaces that encourage resource (i.e. water, energy, and natural resources) conservation is one of the grand challenges for HCI researchers); *use case suitability* (vibrations produce electromagnetic energy, temperature is thermal energy, so both modalities offer - at least theoretically - a low metaphorical distance in the energy context); and *the authors' personal interest.* Our contributions thus are: i) a physicalization that uses vibration and temperature to communicate for SDG7 data (affordable and clean energy) and ii) lessons learned from a preliminary evaluation during a lab-based study (N=16).

2 RELATED WORK

Since vibration and temperature are used in this work, this section briefly reviews previous work that used these two modalities to physicalize data. There exists a couple of data physicalizations that use vibration to encode data. Houben et al. [11] developed PhysiBuzz that uses vibration to encode household ambient data such as ambient air quality (eg. CO_2, NO_2 levels), temperature, humidity, sunlight, and noise pollution sensed using Smart Citizen [5] sensor kit. To encode data, PhysiBuzz uses both vibration amplitude and speed (frequency). For example, it uses either the number of motors (vibration amplitude) or the speed of motors to represent continuous data. They also use the vibration speed to encode relative changes of ambient data (i.e. to signal changing trends in data either in the positive direction or in the negative direction). PhysiBuzz uses a fast pattern of vibrations to indicate trends in the positive direction and a slow pattern of vibrations to indicate trends in the negative direction. No vibration is used when there is no relative change. It also uses the vibration's amplitude to alert when a threshold value (preset by the user) has been reached by buzzing in different intensities from small to huge vibrations. Hogan et al. [9] represented indoor air quality (IAQ) data dynamically measured by the sensors, using vibration. They used eight vibration motors (5 volts each) and encoded air quality data using vibration speed. They compared haptic (using vibration), auditory and visual feedback and found that haptic and auditory feedback stimulated an engaging interpretation of data that involved the whole body whereas visual representations engage through their familiarity, accuracy and easy interpretation [9].

Although not directly for representing data physically, temperature has been studied to communicate information: For example Lee and Lim [16] explored characteristics, values and the potential of thermal expression, i.e. expression delivered by heat. Ranasinghe et al. [21] developed Ambiotherm, a wearable accessory for Head Mounted Displays that provides thermal and wind stimuli to simulate real-world environmental conditions in virtual reality; Halvey et al. [8] investigated how ambient temperature and humidity could affect the usability of thermal feedback; Wilson et al. [31] studied the subjective interpretation of thermal feedback; Di Campli San Vito et al. [4] explored the implications of combining thermal and vibrotactile feedback for in-car notifications via the steering wheel. Although, there exists work like above that focus on using thermal modality as a way of giving some form of feedback, to the best of our knowledge, temperature had not been previously used to physicalize data - to systematically encode data.

3 DATA PHYSICALIZATION

The aim of the data physicalization build during this work is to represent a selected set of SDG [17] data using vibration and temperature. We selected two data sets from SDG Goal 7 data [22]: the share of energy production from renewable energy sources (Dataset 1) and the amount of electricity generated from solar power (Dataset 2). The datasets were downloaded from the SDG Tracker of the ‘Our World in Data’ database (see [23, 24]). To limit the scope of the project, we selected data related to five European countries: Netherlands, Sweden (Northern Europe), Estonia (north-east Europe), Ukraine (Eastern Europe) and Spain (Southern Europe).

Interface. The interface of the data physicalization contains a laser cut wooden map of Europe (Fig. 1, left). On the top left, there are four buttons: two for selecting the two physical modalities (vibration or temperature) and two for selecting the two datasets (Dataset 1 or Dataset 2). The buttons have a wooden interface. On the top right, there is an LED panel to indicate the currently selected country/ies. In the wooden map, the five selected countries (Netherlands, Sweden, Estonia, Ukraine and Spain) appear as pushable wooden buttons wrapped in metal (metal was used to conduct heat (temperature)) (c.f. Fig. 1). The shape of a button and its position on the map represent a country and its relative location in the map of Europe. The buttons were designed to have the shape of the countries to minimize the metaphorical distance between the actual data (country in this case) and its physical representation (shape of a country). If a user wants to sense the amount of electricity generated from solar power in Sweden using temperature, the user has to push the "Temperature" button (top, left, first row, Fig. 1, A)) to select the output modality as temperature, push "Dataset 2" (top, left, second row) to select the dataset about solar energy, and push Sweden shaped button on the map. The user can touch the Sweden button using their palm to feel the temperature. Data (dataset 1 and dataset 2) were encoded using both vibration frequency (realized using vibration motors) and temperature (generated using heat elements attached to the inner surface of the laser cut countries) and were controlled by an Arduino Mega (c.f. Fig. 1 and Fig. 2).

Data Mapping. As mentioned in Section 1, coping with the small magnitude of changes in SDG data is a challenge. The datasets were mapped to vibration frequency and temperature respectively, that is, the higher the frequency, the higher the data value, and the warmer a country feels, the higher the data value in the dataset. At first, the dataset was mapped to vibration intensities, however this led to difficulties in noticing the differences. We then switched to vibration frequency, which was kept in the end as differences were easier to notice with that modality. Since it is not safe for humans to touch very warm surfaces (they might get burnt) nor is it very pleasant to touch very cold surfaces, the range of temperature values was set to the range [10, 45]. That is, the highest point should not get warmer than 45 degrees Celsius and the lowest data point should not get colder than 10 degrees Celsius.

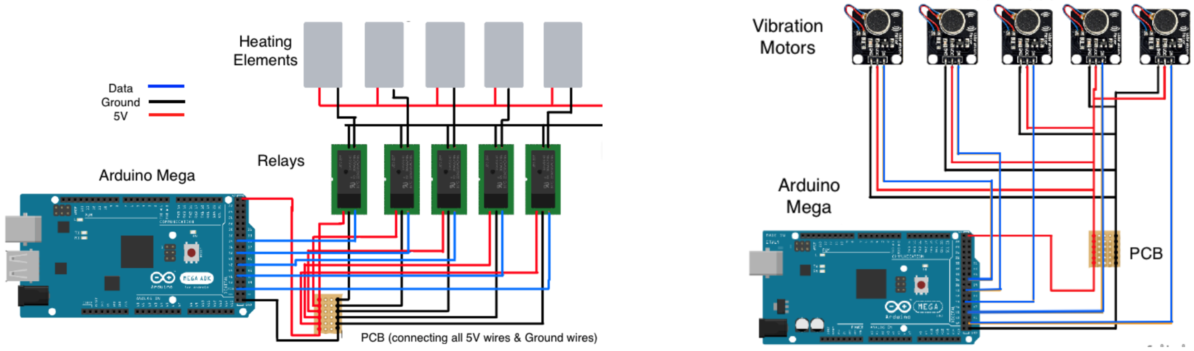
Both vibration and temperature values were produced initially using the default Arduino mapping function [1]. The *map()* function of Arduino performs a linear mapping, similar to d3.scaleLinear(). However, first tests of the prototype led to the observation that vibration/temperature values ended being hardly noticeable. For this reason an alternative mapping strategy was used. First, countries were ranked from highest to lowest, and got a rank from 1 to 5 assigned. The ranks were then assigned discrete vibration and temperature values respectively, e.g. [0 (no delay), 500 (0.5 second delay), 1000 (1 second delay), 1500 (1.5 second delay), 2000 (2 second delay)] for vibration, and [21 degrees, 27 degrees, 33 degrees, 39 degrees, 45 degrees Celsius] for temperature. This strategy led to differences in vibration/temperature values that were more easily noticeable.

4 EVALUATION

The goal of this preliminary evaluation was to assess the performance of the two types of non-visual feedback (vibration and temperature) during information-gathering tasks related to SDG data. We had three types of questions: *maxima* (find the maximum of a set of data points), *minima* (find the minimum of a set of data points), and *cluster* (identify groups of similar data items in a set of data points). Table 1 shows the questions answered during the study and Figure 3 shows efficiency and effectiveness results for the two modalities.

4.1 Variables and Procedure

The independent variables of the study were: the different types of non-visual feedback from the same physicalization (vibration feedback and temperature feedback), the different tasks to perform (i.e. the three types of questions described above), and the datasets (dataset 1 and dataset 2 described above). The dependent variables were: efficiency (the time needed to complete the tasks), effectiveness (number of correct answers) and the subjective preference of one of the two types of feedback. After consenting to participate, the users were given time to familiarize themselves with the installation using a third dataset before starting the study. They then moved on to complete the tasks. The order of the modality, dataset and tasks set was counterbalanced. The participants were shortly



(a) Realizing temperature-based data encoding **(b) Realizing vibration-based data encoding**

Figure 2: Circuit diagrams: Realization of data encoding- Five separate heating elements are used to encode data related to the five countries using temperature (Left); Five separate vibration motors are used to encode data related to the five countries using vibration (Right); Both heating elements and vibration motors are connected to one Arduino Mega.

Table 1: Questions answered by the participants during the study

ID	Type	Question
Q1	Maxima	What is the country with the highest share of electricity production from renewables?
Q2	Cluster	What country/countries has/have a higher share of electricity production than the Netherlands?
Q3	Minima	What country has the lowest share of electricity production from renewables?
Q4	Maxima	What country generated the most energy from solar power?
Q5	Cluster	What country/countries generated more electricity from solar power than the Netherlands?
Q6	Minima	What country generated the least amount of electricity from solar energy?

interviewed after the user study. The study was video-recorded and approved by the institutional ethics board.

4.2 Results

16 users (13 Male, 3 Female) participated in the study. Most of them (N = 13) reported that they have interacted with at least one physicalization before the study. The effect of this prior experience with physicalizations on the results was not significant, nor was the effect of gender. The statistical analysis was done using the bootES R package from [14].

Efficiency. The participants took on average 55 seconds (sd: 30s) in the temperature condition and 49 seconds (sd: 19s) in the vibration condition for maxima questions. They took about 21 seconds (sd: 11s) in the temperature condition and 29 seconds (sd: 12s) in the vibration condition for minima questions. Finally, they needed about 48 seconds (sd: 22s) in the temperature condition and 47 seconds (sd: 14s) in the vibration condition for cluster questions. The two modalities seem thus comparable when it comes to efficiency.

Effectiveness. The accuracy values were about 13% in the temperature condition and 100% in the vibration condition for maxima questions. For minima questions, the participants were accurate in their answers at about 25% in the temperature condition and 69% in the vibration condition. The accuracy rates for cluster questions were 52% and 97% in the temperature condition and the vibration condition respectively. Thus, vibration has a slight advantage over temperature, and the advantage is more pronounced for maxima and cluster questions. The temperature condition appeared quite unreliable, with at most 52% responses (i.e. one out of two answers) given being correct.

Enjoyability. Enjoyability ratings were collected using a 5-point Likert scale (1 lowest value, 5 highest value) immediately after the participants finished a set of tasks using a modality. Vibration got higher ratings on average (mean: 4.2, sd: 0.5) than temperature (mean: 3.9, sd: 0.8), but the differences were not statistically significant.

Qualitative feedback. To get more insight into the interaction experience, the users were asked nine questions during a follow-up interview shortly after completing the tasks. Q1: Have you ever used a physicalization before? Q2: Have you ever been interacting with data like this? Q3: Which modality did you like most in general? (follow-up question to this: why?) Q4: What did you like most about the physicalization? Q5: Was there something you missed while using the physicalization? Q6: Where would you like to see something like this? Q7: Do you think you know how these countries compared to each other by using the physicalization? Q8: Would you use such a physicalization again? (follow-up questions to this: why(not)?) Q9: Do you have any other comments or remarks about the study of the prototype? Since the study is exploratory at this stage, and the nature of the interview questions made it possible to have more or less clear episodes during the interviews,

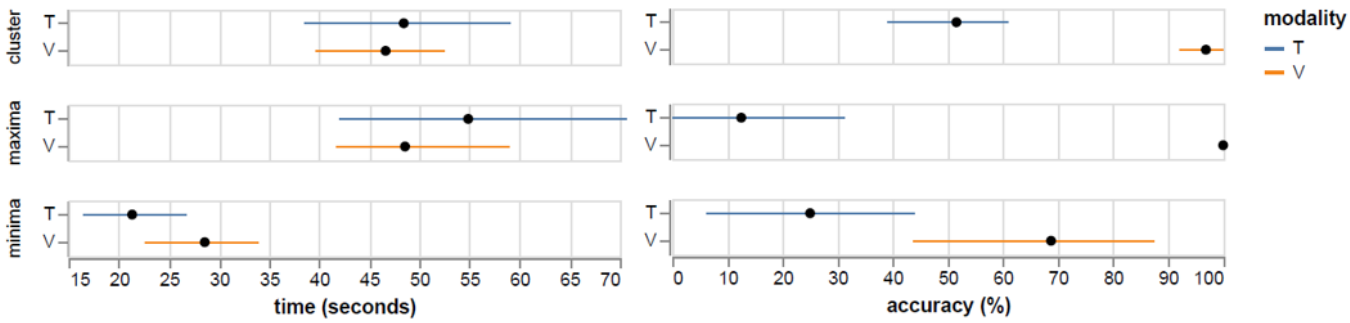


Figure 3: Efficiency and effectiveness results per question type for the two modalities: temperature (T) and vibration (V).

the qualitative data were analyzed using holistic coding, i.e. the assignment of codes to refer to broad topic areas in the data (see [25]).

As said above, the majority of participants have interacted with at least one physicalization before the study (Q1). While they were familiar with physicalizations in general, none of them was familiar with the datasets used during the experiment (Q2). The majority (12/16) reported preferring vibration, mostly because it helped notice differences better. The phrasings were pretty similar, e.g. 'Small differences were easier to distinguish with vibration' (P4); 'Vibration was a bit easier. Especially when the temperature is a bit similar, it's difficult to distinguish.' (P8); 'Personally, I could feel vibration easier than temperature.' (P11); 'You could immediately hear and feel it more. For temperature, I really had to my best to feel differences' (P15). The remaining four reported preferring temperature and did so for different reasons: 'Temperature, because it's very new.' (P2); 'Temperature, it's more absolutely scaled, as in, one is warmer than the other. For vibration, the pattern or intensity could change.' (P5); 'I found temperature more fun, as you had to search and feel what was happening. It's of course just something new, something I don't know yet. This physicalization lends itself more for temperature, also because you hear the vibration more than you can feel it.' (P9); 'Temperature was the most fun. It is something new. It was also subtle, so you really had to feel and think about it.' (P12).

The fact that you can feel something (as opposed to just seeing) was highlighted by the participants more often regarding what they liked about the physicalization (Q4), e.g.: 'You really had to feel, it is more interaction than when you only see the difference.' (P2); 'To actually compare the countries, so touching two countries and actually feel a difference between the two.' (P16). Another positive aspect highlighted was the playfulness, e.g.: 'Looks nice, playful interaction. A table would be quicker to transfer data, but would be less playful.' (P4); 'Playful way to compare. Temperature was nice to feel.' (P6). As regards what they missed (Q5), participants gave a few comments that could be used to improve the work: a hint at which country is currently selected (P1, P2, P12, P14), e.g. using light in the top-right corner of the installation (P2, see Figure 1). Another comment was about improving the ability of temperature (and also vibration) to communicate differences (P5, P7, P10, P11). P6 and P15 missed indications about the topic of the datasets: 'Kind of forgot about the data, or at least what dataset 1 and 2 were.' (P6). P8 missed an overview of the data, and the possibility to compare more countries at the same time; P4 wished exact values and more information about the countries (after the question was answered); P9 suggested better indications about whether or not a button is pushed; and some participants said that they did not miss anything (P3, P13, P16).

There were a broad range of suggestions from the users about where/when a physicalization of this type could be deployed (Q6: where would you like to see something like this?). As to *where*, the answers included: city hall, (tech/science/interactive) museum, a company (power plant for example), at the entrance of a EU building, information points, and elementary/high schools. As to *when*, the answers included: conference or events about SDGs, exposition/presentations about this topic, a conference about global warming, and open days. In general, the majority of users were confident about the differences between the countries (Q7). The majority also reported that they would use this type of physicalization again when given the opportunity (Q8). Finally, they did not have any new comment/suggestion in Q9, except that sometimes the sound made by the motors for the vibration modality might 'fool people' (P3).

5 DISCUSSION

It follows from both the quantitative and the qualitative feedback, the use of vibration and temperature to communicate SDG7 data holds promise. The users seemed to have enjoyed interactions mediated by the two modalities (see enjoyability ratings). The type of modality did not have any impact on the efficiency during the information-gathering tasks, but the temperature did not appear suitable in this study from the accuracy point of view. We now briefly document lessons learned from the study with respect to the requirements for physicalizations of SDG 7 and the effect of metaphorical distance on user performance, before commenting on some limitations of the work.

Requirements for SDG 7 physicalizations. The comments about what the users missed are useful to better pinpoint requirements for SDG physicalization in the future. In particular, the comment from a participant asking for exact values suggests in some situations, documenting the provenance of the physicalization might be needed/wished by users. In the case of visualizations, provenance can be easily documented by attaching the original data to the visualization (e.g. adding a link to the dataset's web page). In the case of physicalization, provenance documentation at the moment is an underexplored but potentially an exciting research area.

Metaphorical distance and user performance. As discussed in [32], data physicalization involves the expression of abstract data in physical representation through the process of data mapping (a.k.a embodiement). Data mapping in turn necessitates the choice of a metaphor. There are two types of metaphorical distances in the context of data physicalization: the metaphorical distance from data (i.e. how close the form of the physicalization is to the original data) and the metaphorical distance from reality (i.e. how the metaphor reflects an audience's knowledge and experiences about the real world). By encoding energy data using electromagnetic energy and thermal energy, the metaphorical distance from data in the study was relatively small. The two metaphors are also quite close to reality. Arguably the metaphor of energy as heat has a lower distance to data than the metaphor of energy as vibration frequency. An assumption in the literature is that 'different modes of embodiment determined by different metaphorical distances can affect the informative value of physicalizations' [32]. Relating to this, the preliminary results of this work suggest that lower metaphorical distance to the data does not always positively correlate with user performance and enjoyability.

Insights related to technical and practical realization. The design choice to have the countries in their original size brought challenges for the use of temperature. As the countries were covered in metal, the size of the country was connected to the size of the metal surface of the country. Thus, for the bigger countries, the heating element had a bigger surface that needed to be warmed up. This resulted in the bigger countries needing more time to heat up. In general, this suggests that physicalization of SDG data needs strategies to provide users with a more or less similar 'surface experience' for all countries before they can make statements on their values. This could happen for example by normalizing the areas of smaller countries to the area of the biggest country in the comparison set (while maintaining the outlines of the smaller countries' shapes).

Vibration or temperature (or haptic feedback in general) might not be the best modalities if the dataset contains a large no of data points due to two reasons: (i) there is a limit to the number of different vibration patterns/ amplitudes or temperatures that can be distinctly perceived by humans, (ii) there is a limit to the number of different vibration patterns/ amplitudes that can be technically realized or temperatures that are safe to touch. Furthermore, Vibration or temperature might not be a good modality if the dataset consists of values that are close to each other - the difference between such points is difficult to perceive via human haptic senses. vibration motors sometimes make noise and in practical settings, it can't be expected that all the motors make the noise in the same way. This can negatively impact the interpretation of data. For example, if a motor attached to a country with a lower data value makes large noise compared to a motor attached to a higher data value, there is a chance that a user associate sound (noise from the motor) to the data it represents - perceive a lower value when the motor is less noisy.

6 CONCLUSION

Through awareness-raising for a wider audience (which could then lead possibly to self-reflection and behaviour change), physicalizations could provide a valuable contribution on the road towards achieving the Sustainable Development Goals (SDGs). In this paper, we explored data physicalization as a means for communication of SDG data in an effective and engaging way. We used vibration and temperature as physical modalities and compared their efficiency, effectiveness and enjoyability. Both modalities were considered enjoyable by the users and were efficient. However, vibration as a modality was more effective compared to temperature. The type of data we used is floating point (real numbers). In the future, we plan to explore further on using vibration, temperature and other physical modalities for physicalizing different types of SDG data (categorical, time variant, discrete, etc.) and to investigate the types of physical modalities (and their physical variables) that fits for different types of data. We also plan to study the persuasive potential of physicalizations in conveying SDG data.

ACKNOWLEDGMENTS

Auriol Degbelo gratefully acknowledges funding from the European Social Fund and the Ministry of Economic Affairs, Innovation, Digitalization and Energy of the State of North Rhine-Westphalia through the SmartLandMaps 2.0 project (EFRE-0400389).

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