KiriPhys: Exploring New Data Physicalization Opportunities

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Fig. 1. Study setup for our exploratory qualitative study of KiriPhys. The left image shows the KiriPhys examples used in the study in the original, flat state. The images in the middle and on the right show the KiriPhys after a participant has started interacting with them.

Abstract— We present KiriPhys, a new type of data physicalization based on kirigami, a traditional Japanese art form that uses paper-cutting. Within the kirigami possibilities, we investigate how different aspects of cutting patterns offer opportunities for mapping data to both independent and dependent physical variables. As a first step towards understanding the data physicalization opportunities in KiriPhys, we conducted a qualitative study in which 12 participants interacted with four KiriPhys examples. Our observations of how people interact with, understand, and respond to KiriPhys suggest that KiriPhys: 1) provides new opportunities for interactive, layered data exploration, 2) introduces elastic expansion as a new sensation that can reveal data, and 3) offers data mapping possibilities while providing a pleasurable experience that stimulates curiosity and engagement.

Index Terms— data visualization, physicalization, kirigami, interaction, visual representation design, art & graphic design, aesthetics.

1 Introduction

We introduce KiriPhys, a type of physicalization that leverages kirigami techniques — a rich, complex Japanese tradition in paper cutting. We explore the opportunities that emerge when mapping data to variables that can be manipulated through kirigami techniques. In teasing apart the opportunities for data representation with KiriPhys, we use Jansen et al.'s definition of physicalizations as "a physical artifact whose geometry or material properties encode data" [24, p. 3228]. Our work is motivated by the growing evidence that people find physicalizations engaging [22, 23], easy to understand [22, 23, 59], and emotionally rewarding [56]. Physicalizations also offers new forms of data externalization [28] that leverage more perceptual capabilities than non-physical visualizations [24]. As such, they can contribute to the data democratization challenge [54] by supporting data interpretability and visualization authorship [22, 59] for diverse people.

With KiriPhys, we tackle two existing challenges with data physicalization: i) the need to discover new physical variables to represent data, and ii) the need to explore what new types of tangible interaction techniques may be possible for physicalizations. Indeed, while a wealth of research has iteratively identified and evaluated visual variables to encode data in 2D visualizations, the space of physical variables to encode data in physicalizations is ripe for more exploration [24]. Similarly, while great attention has been paid to types and styles of interaction with digital visualizations [17], to date, most data physicalizations are static. Researchers are investigating digital and technical ways of including interactions to create dynamic physicalizations [32]. However, these technologies generally depend on sophisticated, often challenging and expensive to build mechanisms [23, 50].

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KiriPhys is a physical data representation that offers a range of exiting opportunities through the use of 2D materials (e.g., paper, fabric and metal sheet) and common cutting tools (e.g., utility knife, scissors and laser cutter). KiriPhys provides a range of design possibilities including: a) a new set of independent and dependant physical variables that can be mapped to data; b) opportunities of non-technical, tangible, slow, and gentle interaction; c) potentially inexpensive, and often portable physicalizations through the use of 2D materials (e.g., paper, fabric and sheet metal) and common cutting tools (e.g., utility knife, scissors and laser cutter); d) representational functionality on a wide range of scales from the very small to large enough to include architectural possibilities; and e) an aesthetically appealing and intriguing media for data engagement.

With 12 participants, we explored people's response to KiriPhys. We were particularly interested in participants' behaviour toward this new data representation technique and their understanding of data through the KiriPhys variables. Our study offers broader insights into how representation and interactions can be designed to enhance engagement and agency and involve people in playful data exploration.

2 Background and Related Work

Here we outline the use of paper, kirigami and its modern applications. Then we summarize the benefits and challenges of data physicalization, mentioning static and interactive physicalization examples.

2.1 Paper as a Design Material

Paper is an accessible, malleable, lightweight, and inexpensive medium that provides rich affordances for different interactions through bending, folding, cutting, writing, and drawing. Leveraging these characteristics, paper has gained attention as a material in interface design in human-computer-interaction (HCI). Researchers have incorporated simple actuation methods to enhance regular paper properties and turn it into moving or shape-changing interfaces such as interactive pop-up books [40, 41]. Accessible paper-based technology has been developed to support novices in making their own low-cost interactive paper-based devices such as Paper Robots, Paper Speakers and Paper Lamps [43]. Accessible paper actuators that people can embed into everyday objects have been developed to enable new types of paper-based, shape-changing interfaces with rich interactions, such as pop-up books and lampshades enhanced with motion [55]. In addition, several computer-aided design (CAD) systems have been developed within HCI research for exploratory construction of paper craft and to facilitate iterative design processes [37,63]. In visualization, to help foster data literacy in education, DIY paper charts were designed to help children explore data through playing and the creative process of making [3]. Similarly, Wun et al. present a Miura-Folded Bar Chart using paper origami in supporting DIY data physicalizations [58].

2.2 The Kirigami Technique and its Applications

For centuries, Kirigami ('kiru', cut; 'kami', paper) has transformed sheets of paper into beautiful and complex two- and three-dimensional structures [2]. Similarly to origami [46], which refers to the folding of paper, kirigami [2] consists of both folding and cutting a thin sheet to create 3D designs [61]. Scientists and designers of many disciplines have leveraged the kirigami technique with a variety of 2D materials to design novel technology. Kirigami's scalability has created structures ranging from the nano to the architectural. In nano-materials, kirigami has been introduced as a novel technique of fabrication to enhance material properties [18,45,57,60]. In robotics, the crawling capability of a soft actuator was significantly enhanced by designing a highly stretchable surface harnessing kirigami principles [42]. Kirigami techniques have been used to create inexpensive and lightweight devices that track solar position, maximizing solar power generation [29]; and, in architecture, to create large-scale, lightweight adaptive spaces [14]. In HCI, kirigami techniques were explored to study the range of haptic feedback delivered by different kirigami designs [62]. Inkjet printed circuits with kirigami structures now allow people to design and fabricate keyboards that can be attached to a touchscreen and customized for individual needs [10]. Although paper-crafting and kirigami techniques have been widely and successfully applied in other fields, they are yet to be applied to the field of (physical) visualization.

2.3 Data Physicalization

Data physicalizations have been shown to have many benefits, for instance, in public spaces they have been used to encourage people to use renewable energy [15,16], and to communicate weather data tangibly to non-scientists [25]. Physicalizations have also fostered self-reflection and self-improvement [7,26,47,52], and when applied to everyday personal data can lead to behaviour change [11,12,51,52].

Static Data Physicalization. Today's availability of fabrication machines like laser cutters and 3D printers enables designers with minimal technical skills to rapidly create physicalizations with inexpensive materials. Laser cutters are often used to create physicalizations (e.g., [23]), and prototype software has been developed to aid this [48]. 3D printing has been used to represent activity data through varying shapes, sizes, and volumes [26,27,47]. These physicalizations can be created relatively simply; however, they lack interactive capabilities.

Interactive Data Physicalization. Physicalizations have the intrinsic advantage of affording interaction, and many support non-technological interactions. For example, physicalizations that rely on simple tokens such as Lego blocks and wooden tiles support manual rearrangement and tend to be inexpensive and accessible, especially for novice people [21,30]. Some physicalizations rely on physical mechanisms to support more advanced interactions. For example, Bertin's reorderable matrix [5] – which was later reproduced using laser-cutting technology [39] – consists of separate cells, and a rod mechanism for reordering cells across either rows or columns. Incorporating technologies into data physicalizations,offers new opportunities to create a wide range of interactions, for example: EMERGE, an interactive bar charts offering touch filtering and sorting [49], and Zooid, self-propelled micro-robots [31]. While such technology is moderately scalable, it often relies on relatively expensive technology that is not widely available and may require some expertise to be fabricated. KiriPhys is intrinsically interactive and is designed to be pulled and stretched. In our initial exploration of KiriPhys we focus on its non-technological interactive capabilities.

3 KiriPhys

In this section, we explore the data mappings that can be supported by KiriPhys. We parallel Bertin's approach [4] by considering cuts on a piece of paper as our basis (like Bertin's visual marks) and then explore how data might be mapped to cut variations. KiriPhys variables are particular in that they usually apply to a cut pattern consisting of multiple rather than a single cut. Therefore, we do not discuss single cut variables, although single cut position, thickness, and orientation can be varied. We focus on the design space of cut patterns that are made of multiple cuts, which form cut patterns (see Figure 2). See the accompanying videos for an explanation of the process of creating a KiriPhys.

3.1 Independent KiriPhys Variables

Figure 3 shows the basis of how a cut pattern can be varied. A cut pattern consists of cut lines (formed by alternating cuts and joints) arranged in a concentric or parallel manner. Varying the width of joints will affect the length of the cuts. The rings (for concentric cut lines) or stripes (for parallel cut lines) of solid material between two cut lines are called **loops**, and the width of these loops can be varied. The pattern has an inner loop of a given shape and size, as well as an outer loop that also has a given shape and size. All these variables affect the cut pattern's expansion amount, direction, and texture that are revealed upon interactively pushing or pulling the cut pattern.

Independent KiriPhys variables are those supporting direct data mappings, i.e. quantitative parameters of the cut pattern that can directly encode data values. Note that although cut patterns can be varied using traditional independent visual variables such as colour, position, size and orientation, we do not detail these since they behave similarly to their visual variable counterparts. We identify six independent KiriPhys cut pattern variables (see Figure 2-Independent Variables):

- The *overall shape* of a cut pattern can be regular or irregular. The overall shape depends on the shape of the inner loop and the shape of the outer loop. In-between loops are interpolations between the inner and the outer loop of the cut pattern.
- The *number of joints* of a loop is equal to the number of cuts in that loop. It is countable and can vary between loops.
- The *width of joints* of a loop is the amount of solid material between two consecutive cuts of a loop. It is measurable and can vary both within a loop and between loops.
- The *number of loops* is the number of solid material loops in the cut pattern. It is countable.
- The *width of loops* is the amount of space that separates two consecutive cut lines. It is measurable, and can vary between loops.
- The *position of cut-pattern* is the position on the KiriPhys surface on which the cut-pattern is located.
- The *orientation of cut-pattern* is the alignment of the cut-lines in a cut-pattern.

3.2 Dependent KiriPhys Variables

Dependent KiriPhys variables are varied through changes in the independent variables from the previous section. They can be used to represent data values; however, the mappings are not as straightforward and quantitative as they are with independent variables. We identify seven dependent KiriPhys variables(see Figure 2-Dependent Variables):

- The *size of inner loop* and *size of outer loop* describe the 2D size of the first and last loop of a cut pattern. While data can be assigned to either the inner or outer loop, the other one's size may be influenced by such things as the size and width of the loops.
- The *amount of expansion* captures the height and volume of a cut pattern when fully expanded. This is influenced by the flexibility of the material and the variations in the cut pattern's independent variables: a smaller number of joints and/or narrower joints leads to more expansion, while a smaller number of loops and/or narrower loops leads to less expansion (see Figure 4).
- The *direction of expansion* is the direction in which the cut pattern can expanded. Regular concentric cut patterns can be expanded upward, downward, and to some extent obliquely. The direction

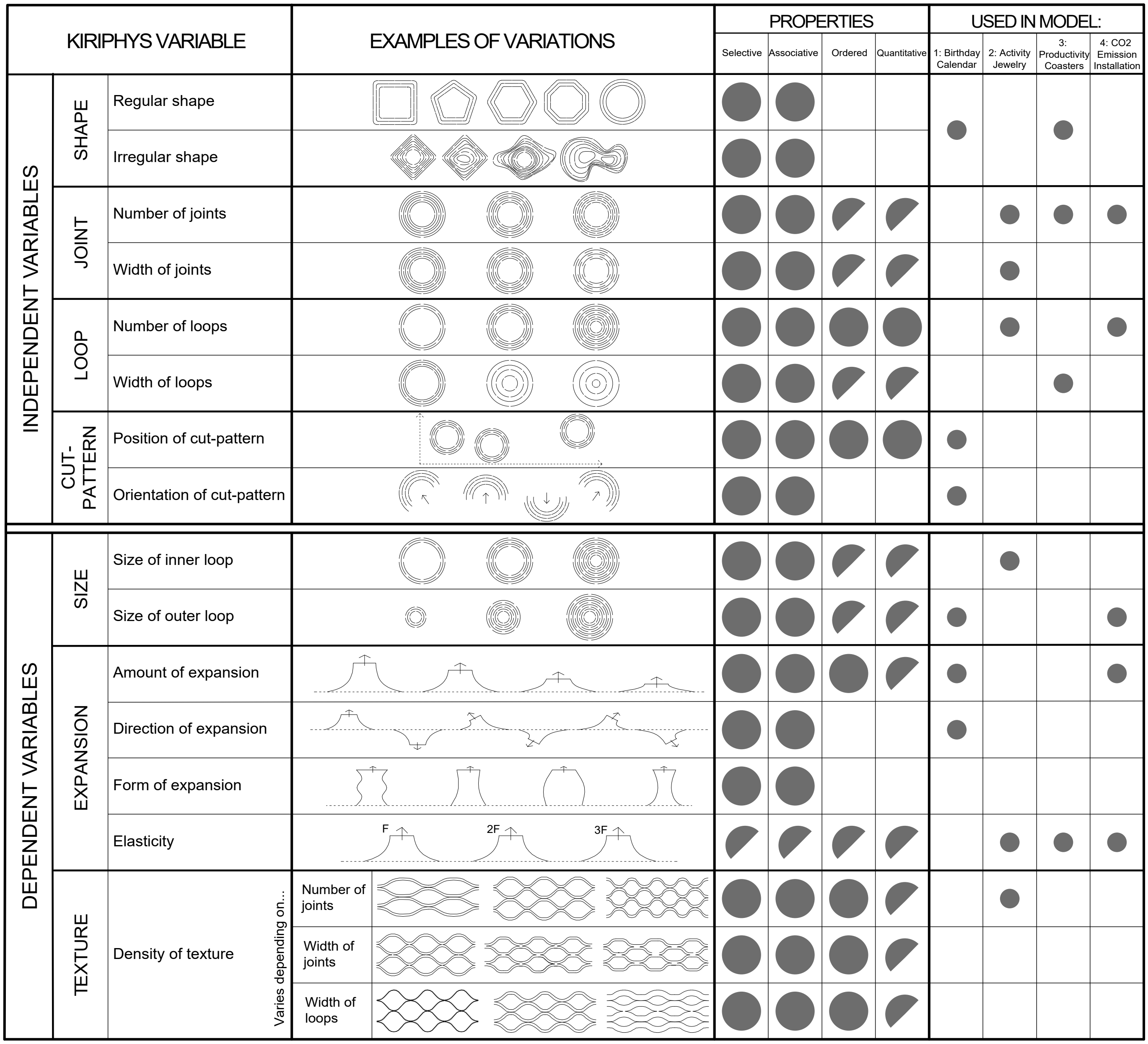

Fig. 2. The KiriPhys variables, grouped vertically in *independent* and *dependent* variables. Each variable is illustrated with a schematic illustration, and we indicate the extent to which we hypothesize each variable to be selective, associative, ordered, and quantitative (an empty cell means unlikely, a full circle means likely, and a half-circle means that making a hypothesis is difficult). The last four columns of the table indicate with a circle, which KiriPhys variables are used in the four examples we utilize in the study.

of expansion of a cut pattern is dependent on the influenced by cut lines and on the width of loops.

- The *form of expansion* is the 3D shape that is formed by the cut pattern when expanded. It is dependent on the width of loops, which can vary along the cut pattern: wider loops make it thicker while narrower loops constrict it.
- The *Elasticity of Expansion* refers to the force one needs to apply to the cut pattern for it to expand to the fullest amount. A cut pattern holding more and thicker joints is harder to expand than one with fewer and narrower joints.
- The *density of texture* of the expanded cut pattern is dependant on the number of joints and the width of joints. More and/or wider joints result in a denser texture, whereas fewer and narrower joints result in a more open pattern.

4 Four KiriPhys Examples

In this section, we introduce KiriPhys variables through four KiriPhys examples, that we also used in the qualitative study presented in Section 5. The last 4 columns in Figure 2 summarize which variable is used in which KiriPhys. KiriPhys combines conventional variables like position and orientation (Birthday Calendar) with KiriPhys variables like elasticity and texture (CO2 emission Installation). These examples are designed to cover different aspects in terms of: 1) representation (through using different variables), 2) interaction possibilities (that range from supporting exploration to data-editing to communication), 3) data sets (that range from personal to worldwide data), 4) purposes (that range from private messaging, to reminiscing, and to educating), and 5) scale (that range from jewelry-size to table-size). This coverage also helped us examine different aspects of KiriPhys while keeping the time of the study session manageable.

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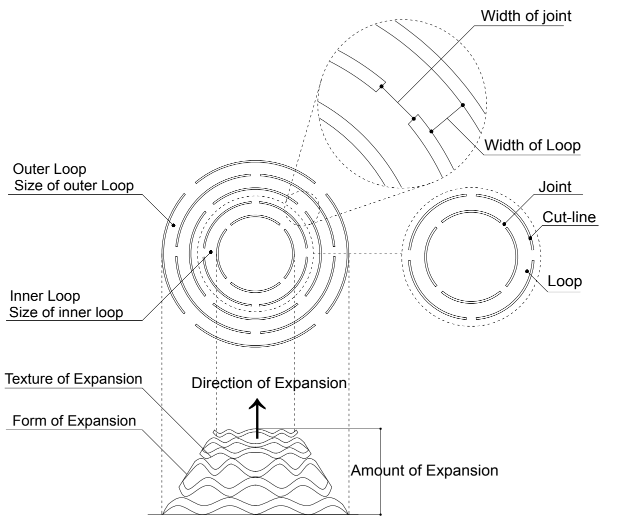

Fig. 3. A simple circular cut pattern and the parameters to consider in a cut pattern. The top diagram is showing the top view of the cut-pattern and the bottom diagram is showing its side view once expanded.

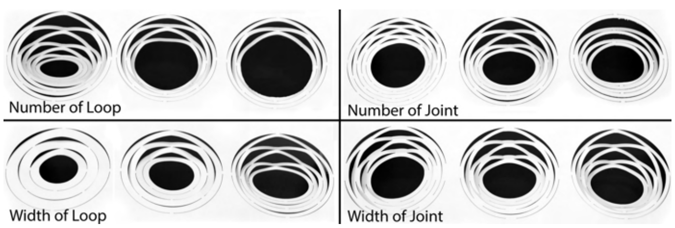

Fig. 4. Variations in loop (left) and joint (right) variables affect expansion variables. Variation numbers are decreasing from left to right.

KiriPhys 1: Birthday Calendar is a medium-scale wall decoration that represents family birthday data, for reminiscing and information-sharing (see Figure 5). The days and months are marked on the right and at the top of the frame. The 2D coordinates of each curved cut pattern correspond to a day and a month, and its orientation represents the gender of the person's birthday. The number of loops of a cut pattern represents the age of the person, with one loop for every four years. The older the family member, the larger the outer shape and the amount of expansion of the cut pattern. The direction of expansion represents the proximity of the person to home: if a person lives close to their family, its corresponding cut pattern expands upward, and if they live far away, it expands backward. The KiriPhys can be updated as time goes by. New loops can be cut to update ages and add family members. The direction of expansion can be inverted if someone moves away or returns to their hometown. A limitation of this design is that there are only two orientation values for two genders. To include non-binary genders, one could use non-binary variables such as shape.

KiriPhys 2: Activity Jewelry is a set of wearables that support comparison and communication of running data (see Figure 6. We designed this KiriPhys because personal visualization research [20] tells us that physicalization can be easily interpretable to their owners as well as the people in their vicinity [33] and can encourage people to reflect on their data and change their behavior [35]. Physicalizations of personal activity data have been used as a way to reward and motivate people after their activities [47] and to promote self-reflection [26, 47]. Wearable physicalizations have been studied in the context of activity data. For example, Patina Engraver [38] engraves patina-like patterns on the wristband of activity trackers; and Loop [44] represents the amount of physical activity per day with wooden loops of varying sizes.

The data is about three friends, Ava, Emma, and Jessica, who recorded their number of runs, their time and distance for a week; they also provided their number of years of running (see Figure 6(A)). An earring, a ring, and a bracelet were then created for each of them.

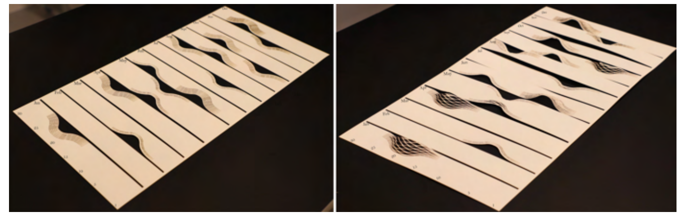

Fig. 5. The Birthday Calendar KiriPhys before and after expansion.

The earrings and the rings are designed using the KiriPhys circular pattern. For both, the number of loops corresponds to the number of runs, the number of joints corresponds to the total hours of running, and the width of joints is inversely proportional to the number of years they have practiced running. The size of the outer loop of the earrings is the same for all earrings, while the size of the inner loop varies. This is achieved by starting from the outer loop and adding one loop inside the cut pattern for each run. A larger number of running hours corresponds to an increased density of expansion.

The bracelets are designed using the KiriPhys linear pattern. The number of loops corresponds to the total hours of running, the number of joints corresponds to the number of runs, and the width of joints is inversely proportional to the number of years they have practiced running. As the person goes for more and longer runs, the KiriPhys gets larger with a denser expansion texture, while on the contrary, fewer and shorter runs lead to an artifact with a thinner cut pattern.

These KiriPhys can be reconfigured to convey additional qualitative information. Figure 6(B) shows how the central area of the earring can be tilted and pulled/pushed. The wearer can reconfigure the KiriPhys to communicate private information with a partner, relatives, or their team at work when it is preferable to communicate in non-verbal ways [53]. For example, at a party, the horizontal tilt of the earring could convey *I would like to go home*, or at work, a migraine sufferer could indicate a bad day by slightly pushing the central ring.

KiriPhys 3: Productivity Coasters could be produced weekly to represent the everyday activities of a person (see Figure 7). The coasters, made of paper, are inexpensive and replaceable and can stay on a desk or coffee table, allowing their owner to reflect on their week. The shape of the cut pattern represents the owner's weekly average mood rate (from 1 to 10) (more specifically, the number of edges of the shape represents the average mood). The number of loops represents the number of meetings for that week and the width of each loop the duration of each meeting. Therefore, the size of outer shape represents the time spent in meetings during the week. The number of study hours is mapped to the number of joints, which in turn affects the density of expansion. These KiriPhys can be used as flat and stackable coasters and upon interaction, can be expanded to reveal data about the owner's week for comparison and reflection.

The design of a KiriPhys that might have a utility, like the Productivity Coaster or the Activity Jewelry, limits the designer's choices as it is important to consider the affordance and function of the object. For instance, the width of loops cannot be too thin for the objects to be practical to be worn or used as a coaster.

KiriPhys 4: CO2 Emission Installation shows CO2 emission data for the seven largest CO2 producer "countries" (China, the United States, the EU, India, Japan, Russia, and South Korea [36]); it aims at engaging the public to raise awareness of this dataset. CO2 is the dominant greenhouse gas produced by burning fossil fuels, industrial production, and land-use change. Although China has been emitting the most CO2 since 2006 [8], it also has the world's largest population, and looking at CO2 emission per capita tells a different picture, with the United States showing much higher CO2 emission per capita [36]. Therefore, to demonstrate a comparison of countries' emissions and responsibilities, this KiriPhys conveys both absolute CO2 emission with an independent variable and CO2 emission per capita with a dependent variable. This KiriPhys is shown in Figure 8, where the cut pattern for each country follows the irregular shape of a leaf. The inner loop is an identical leaf for all countries. Then, one loop is added for every 200

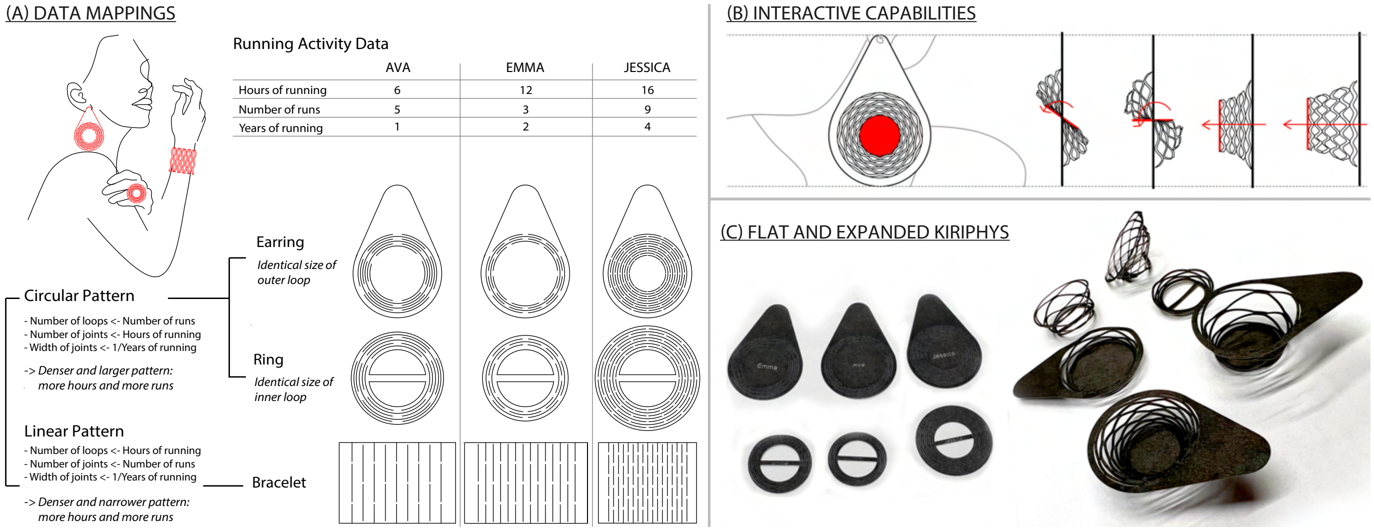

Fig. 6. (A) Data Mappings used to create three sets of KiriPhys jewelry of running activity data (earring, ring, and bracelet). (B) Interactive capabilities of the earring, where mappings can be adjusted by rotating and pulling the deformable structure. (C) Jewelry models used in the study.

Fig. 7. The Productivity Coasters KiriPhys before and after expansion.

tonnes of CO_2 emission. This results in larger cut patterns for countries that emit more CO_2. With these mappings, one can quickly observe and compare the sizes of the outer loops of several countries to get a ballpark estimate of the differences and can also retrieve precise values by counting the number of loops upon closer examination.

The per-capita emission of countries is revealed by interacting with the KiriPhys. The number of joints of a cut pattern is proportional to the population size of the country it represents; therefore, the larger the population, the denser the texture of expansion. As a result, the amount of expansion represents emission per capita. The viewer can expand several cut-patterns simultaneously to compare different countries based on their overall emission, population and per-capita emission. In addition, they can count precisely the population and total emission by counting the number of loops, and joints of cut patterns.

5 Exploratory Qualitative Study of KiriPhys

The previous section presents four KiriPhys that represent various datasets for various contexts and at various scales. In this section, we continue our exploration by studying how people respond to, read, understand, and interact with KiriPhys (REB approval 30000438).

5.1 Participants, Set-up and Materials

We recruited 12 participants (5M, 7F, 19–64 years of age) using word-of-mouth snowballing [6], posts on social media platforms, and mailing lists at a local university. They received a \$20 gift card for their participation. Six participants were working professionals, and six were university students. Their level of education ranged from BA to PhD, and their background varied across Communication & Cultural studies (2), Kinesiology (1), Library studies (2), Interior Design (1), HCI (3), Data Visualization (2) and Mathematics (1). While only 2 had studied data visualization, all had at least minimal experience with software-created visualizations (such as those in Excel).

We fabricated the four representative KiriPhys we described in Section 4 for each participant. This ensured that all participants had the

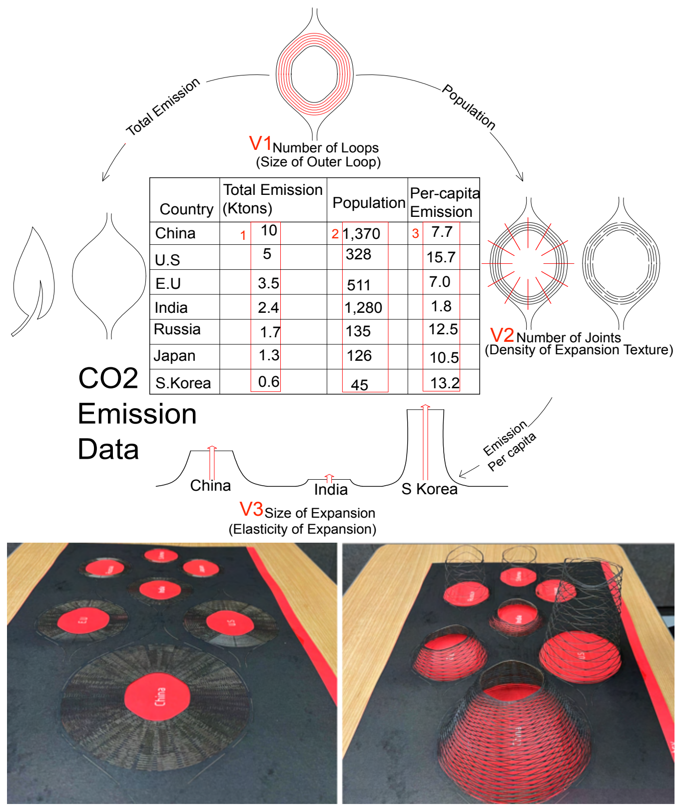

Fig. 8. Data mappings in the CO_2 Emission Installation (top). The KiriPhys before and after expansion (bottom).

opportunity to start from the original flat 2D form. We set up a table large enough to fit all the KiriPhys in a meeting room with good lighting. Figure 1 shows the study setup.

5.2 Procedure

After participants were recruited, we asked them via email to sign up for a time slot. Two days before the study, they were sent the consent form and pre-questionnaire to read and fill out in advance. On the day of the study, we welcomed the participants and asked them if they had any questions about the study or the consent form. Then, we explained the study to the participants describing its different parts and the tasks they will be asked to complete. The experimenter then went through a presentation slide deck to explain the concepts of physicalization and

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	RETRIEVE VALUE	FIND EXTREMUM	SORT
1: BIRTHDAY CALENDAR	Give the parents' birthdays	Find the youngest member of the family	Rank the family members based on their age
2: ACTIVITY JEWELRY	Give the number of hours Emma run this week	Find who ran the most this week	Rank the runners based on their running experience
3: PRODUCTIVITY COASTERS	Give the number of hours they studied in the first week	Find the week during which they had the fewest meetings	Rank the weeks based on this person's mood
4: CO2 EMISSION INSTALLATION	Give the amount of CO2 emission for Japan	Find the country that has the highest CO2 emission	Rank the countries based on CO2 emission per-capita

Fig. 9. The three types of questions participants were asked in order to prompt their exploration of each KiriPhys, with example questions for each.

KiriPhys and participants were encouraged to ask questions.

After participants were familiarized with the whole concept, they were asked to explore the four KiriPhys one after the other. For each KiriPhys, we prompted their exploration of the dataset through a mix of scenarios, explanations, and simple questions to answer. Participants were encouraged to speak their thoughts aloud while manipulating the KiriPhys and ask any questions they might have to the experimenter.

With the first two KiriPhys, **Birthday Calendar** (see Figure 5) and **Activity Jewelry** (see Figure 6(C)), the goal was to observe the participants' first reaction toward KiriPhys. We provided participants with a written scenario explaining the story behind the KiriPhys, and the data dimensions that are being used, but we did not provide any legend or oral explanation of the variables, the data mappings, and the flexibility of the cut patterns. Then we asked participants to tell us what information they think different aspects of the KiriPhys show. To prompt their exploration, we asked them a series of questions in three categories (retrieve a value, find extremum, and sort). Figure 9 shows examples of such questions. After they had described their understanding of the KiriPhys, we walked them through the variables, data mappings, and available interactions of these KiriPhys.

The third KiriPhys they were presented was the **Productivity Coasters** (see Figure 7). They were given a written scenario and an incomplete dataset. This prompted participants to make guesses regarding what mappings were made and what the missing values in the dataset might be. The last KiriPhys was the **CO2 Emission Installation** (see Figure 8), and the complete dataset was provided along with a legend. For both the Productivity Coasters and the CO2 Emission Installation, participants were provided with a question sheet containing tasks such as the ones listed in Figure 9, again to prompt exploration.

Once participants were done exploring the last KiriPhys, they took part in a semi-structured interview in which they were asked about their overall experience interacting with KiriPhys, what they liked and disliked about their experience, which KiriPhys variables were understandable and which were confusing, and if they had any thoughts regarding KiriPhys applications. The study lasted one hour in total.

5.3 Data Collection and Analysis

We collected the pre-study questionnaire responses as well as audio and video recordings of the study sessions. We transcribed the videos using Otter.ai [1] and manually corrected transcription errors. We analyzed the transcripts through iterations of open-coding [9] and meetings with the research team. As a group, we iteratively constructed the emerging themes to capture the perceptions and impressions of the participants. Our initial 25 themes were focused on individual KiriPhys examples, as separate from the interview part. We distilled these to span across examples to arrive at the current grouping. Through our iterative approach (5 times through the whole transcript), we gradually evolved into a full agreement, always keeping the participant words, and in particular, repeated sentiments at the core.

6 Study Results

We present the results under the three overarching themes — interactions, facilitating comprehension, and KiriPhys in context.

6.1 Interactions

The results presented in this section are based on a qualitative analysis of spontaneous reactions and comments from participants. All 12 participants made unsolicited positive remarks, many of which focused on the interaction. All participants appreciated the interactive capabilities of KiriPhys, enjoying the ability to directly manipulate the model. Therefore, when we write that a subset of the participants

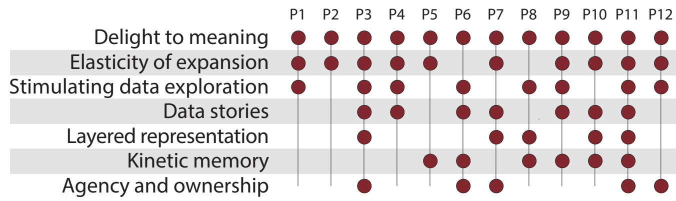

Fig. 10. Spontaneous positive comments by topic and participant.

said something, it does not mean that the remainder said the opposite; just that they did not spontaneously comment on that aspect. Here we tease apart the nuances of their responses to the interaction, by these comments by similarity (See Fig. 11).

Delight leading to Meaning. Without being asked, all participants indicated how their pleasure and appreciation of the KiriPhys interaction encouraged them to discover meaning. For example, they stated that the interactivity *"made [them] want to explore more and dig deeper"* (P9), *"made the process engaging"* (P3), *"made the experience special and memorable"* (P11), *"facilitates learning"* (P7), *"facilitate a deeper connection with data"* (P4), and *"made me touch and feel data"* (P5). P4 summarized this saying *"I have never seen this way of data interaction, it's usually, you know, something on-screen, some bar chart or whatever, but this is just another level of understanding."*

Elasticity of Expansion: New Sensation for Data. 10 participants perceived the elasticity of expansion as a variable and utilized it to analyze the data and compare different cut patterns. They used a variety of different words to describe elasticity: "resistance to expansion" (P10), "springiness" (P11), "elasticity" (P9), and "toughness" (P1). While making comparisons, they used terms such as "easier to pull" (P4, P9) or "harder to pull" (P4), "denser" (P3, P5, P12), and "springier" (P3). Four participants stated that this variable is the most outstanding quality of KiriPhys. For example, P3 described elasticity as being *"a new sensory experience for me"*, P1 stated *"it feels as if something is pulling it down"*, P4 said *"The first thing [...] is just the feeling of expansion. Emma is a lot easier to move than Jessica."* when exploring the Activity Jewelry KiriPhys. Participants relied on elasticity to get an overall impression of the underlying data prior to accurately counting or comparing elements. For example, P5, while exploring the Activity Jewelry KiriPhys, said: *"It's not about thinking about the length or the number of joints. Just the feeling of these two and their difference is telling me the story [...], So maybe Jessica did more runs than Emma because it's [...] loose and flimsy. And then at that point, I start thinking about the structure and connect the fact that Jessica ran more than Emma to variables, why is that? Then I can see the number of the lines are more and the number of joints are more than for Emma."* P10 echoed this while interacting with the Productivity Coasters: *"I had the sense [...] based on the expansion density and resistance, I think the counting just helps to verify my feeling or intuition about it."* Some participants explained that elasticity allowed them to make quick, ballpark comparisons. For example, they said *"This is really amazing. The US is so easy to lift because it has not many joints, so they're not resisting when you pull."* (P10) and, when P4 is exploring the running activity data, *"Eva is good because it's harder to pull."*.

A Stimulating Data Exploration Experience. 8 participants described their experience of data exploration as a stimulating experience. They used expressions like "triggers my curiosity" (P6), "intriguing data representation" (P9), "more senses involved with KiriPhys" (P11), "it engages my brain fully" (P8), "playful and enjoyable process" (P3),

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"helped me wonder about things" (P1), "engaging exploration" (P5), "fun experience" (P1), and "playful data exploration" (P12). This experience is well described by P9, who said *"I think it's kind of like a puzzle [...] I like doing puzzles and trying to figure things out"*, then *"I feel curious and I can focus on it maybe more easily because I'm trying to figure things out step by step. It feels stimulating."* (P9). Participants frequently talked about the importance of curiosity and playfulness with KiriPhys: *"I think that interaction was giving me curiosity, to see what is there in the data"* (P6); *"This is this is a very fun thing to interact with, like you want to bend it in every other direction and look at it, feel it"* (P4); *"I want to engage with this more and explore more, try pulling this pushing and see what happens?"* (P11); and *"having to figure out what everything means and then make the comparison. It all makes it very engaging. So in a table of numbers, I wouldn't want to ask questions about it. I will be like, oh, yeah, this is a fact. So what? But here, I'm like, all asking questions [...] So it helped me wonder about things. So that was cool"* (P1) (row 2, Fig. 10).

Interactive Form Leading to Data Stories. 7 participants related the KiriPhys appearance or interactive qualities to the underlying data. For instance, while exploring the Birthday Calendar, P4 said: *"the smaller parts are a lot harder to expand. It makes sense. The younger generation are harder to deal with."* With the Activity Jewelry, P11 related the elasticity of expansion to each runner's effort when running, saying: *"it feels like it's so fewer runs and easier expansion. That's an interesting connection. Not lazy, but like, fewer runs less effort. Like she did less exercise I'm doing less effort."* With the CO2 Emission Installation, P3 was impressed by the visual connection of expansion form to CO2 emission data: *"When we think about emissions, we often think about smoke or pollution. And so I think it's like a good metaphor for being able to raise it and see that it corresponds to the emission."*

Layered Representation of Data. 6 participants stated that variables appeared gradually to them. For example, they said *"It is like peeling back layers and saying, oh yeah, here's another way of making a variable physical"* (P11); *"it's kind of like a gradual discovery. like noticing a quality in something and then being curious about what that quality means and then another quality appears"* (P9); and *"they [the variables] are not all at the same level of your awareness, so you don't get confused like oh, too many things going on at the same time. No. There's easy to see ones. And then after you got through those, there are slightly more subtle ones"* (P11). Two participants commented that the reconfigurability of the examples serves as an interaction starter, e.g., *"this sensation and expansion provide a starting point, like, I think often what's in can be a barrier to people not knowing where to start with the data"* (P10). This layered representation of data led to slow and pleasurable data discovery, according to 6/12 participants. They said, for example, *"only when I explore and interact more data becomes apparent to me"* (P5). P8 referred directly to memorability: *"The more time I spend on it, the better I remember [...] because I spend more time on this, to understand it."* (P8).

Kinetic Memory. 5 participants said their physical engagement in forming the physicalization through tangible interactions makes the data more memorable for them. For example, they said *"In my memory, this will always stay because I made it myself my data, I expanded myself."* (P7); *"Without touching and interactions, the learning is not the same, because I remember things physically, which makes the experience richer. Like you push something, and you feel that it was harder to push, as opposed to like you just look at it. [...] Like going to the tactile memory"* (P11); and *"this one, it goes back to my visual and tactile memory, I will remember this. So I remember all the details, but with a bar chart, forget it in a day"* (P8). One participant (P3) used the term "New sensation" to explain this: *"I would like to use the term new sensation. And I think it allows the brain to create stories, or re-experience the event in a way that will resonate more."* P3 then compared this to other ways of representing data: *"let's say I ran X amount of times this week, you hear it doesn't really resonate, if you see it on a graph, it could resonate, but then by holding it and manipulating it, it's like adding a new layer of touch to it, but also remembrance."*

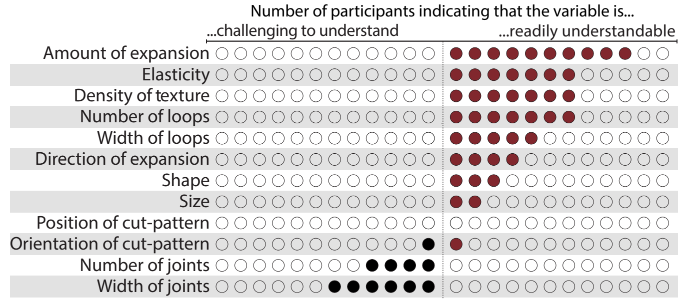

Fig. 11. For each variable, number of participants who commented that it is challenging to understand or readily understandable.

Agency and Ownership. 5 participants specifically described feeling empowered by their sense of agency and ownership. For example, P6's statement: *"When I was trying to do it on my own, I felt I was a part of it and a sense of, okay 'I did that'"* parallels definitions of agency [13]. 3 participants said the interactions make them feel in control; for example, P11 said *"With KiriPhys, I can actually hold things and move them. Other physical visualizations I've seen are pretty much static or they are kinetic, but I don't control them. But here, I like that. I can change things. So I feel more in control."*, and P6 said *"The feeling that I can do anything with that was good."* 2 participants talked about their sense of agency for updating the physicalizations. For example, P12 said *"I think this is very scalable. Like, for the calendar, we can update it as time passes. Not like software, we don't really know when a website updates. And we can also change it [..], if somebody moves away, we can expand it the other way"*, and talked about possible annotation, adding *"I can just write on that. I mean you can add some notes."*

6.2 Facilitating Comprehension

The readability and understandability of KiriPhys are particularly important. We present the participants' first impressions, their decoding of information and their envisioning of data mapping possibilities.

First Impressions. On engaging with their first KiriPhys, all participants spontaneously expressed positive reactions, such as *"Very cool expansion texture, the contrast between background and foreground in expanded mode makes it beautiful"* (P2); and expressing joy *"oh, this is really beautiful"* (P11). However, while 5 participants started to manipulate immediately, 7 participants hesitated to interact because of the KiriPhys' **"delicacy"**. They said, for example, *"Wow, it's been done with such care. So I'm feeling like, what if I tear?"* (P11); and *"if it wasn't paper, we could be more adventurous with manipulation"* (P5). After they were encouraged to interact, they realized that the paper is quite strong, e.g., *"I felt like I was going to break it, but now I can see that this isn't going to break it's really tough"* (P2). Although 3 participants were still afraid to "expand the model too far" with the second KiriPhys, by the third model all participants had assimilated the relative robustness of KiriPhys. 4 participants were positively surprised by the use of paper, saying for example *"I am surprised because initially, I thought they were fragile. They're not, I was surprised that they're quite robust"* (P1), and *"I think it's fun and pretty. It's definitely something that I did not expect with just paper"* (P5).

Readability of KiriPhys Variables. This study allowed us to observe how people read KiriPhys variables. Five participants explained that understanding KiriPhys variables ***required initial explanations*** and learning (e.g., P8 said *"The variables are easy to see. However, it needs explanation."*), but that once learned, the variables were all well understandable. For example, P1 said *"They're kind of easy to understand once you get the mapping right"* and P12 said *"I think with a full explanation, variables are easy to understand."* As participants were exposed to many KiriPhys variables, we directly asked them to name the variables they found challenging to understand, and the ones they found were readily understandable. While Figure 11 quantifies this information, qualitative observations provide a more subtle view of KiriPhys variables' readability.

The ***number of loops***, for example, was often listed as being challenging to understand (7 participants). Actually all participants successfully extracted the number of meetings in Productivity Coasters and ranked the countries in the CO2 Installation by reading the number of loops. However, only 7 participants could correctly give the CO2 emission of Japan when asked about it. While the number of loops does give a general idea of the quantitative value, it might be more appropriate to ordinal to than quantitative data. P11 summarized this, saying *"the number of loops [...] you can just look very quickly, and you get a sense, like, oh, yeah, lots of loops, or not too many loops."*

Many participants said that the amount (10), elasticity (7), density (7) and direction (4) of expansion (that all relate to the elastic property of KiriPhys) were readily understandable. For example, P3 said *"That's [amount of expansion] what resonates the most for me, because [...] this is like a new sensation."*. P10 said *"Through the interaction, I had a sense of the weeks based on the expansion density and resistance. I think because it's a very new thing, counting helped me to verify my feeling or intuition about it through interacting with it"* (P10).

When asked about variables that are challenging to understand, participants mentioned that the **width of joints** is hardly noticeable, that comparing different widths of joints is difficult, and that it is not intuitive that it would communicate data in itself (P3: *"the joints they only acquire meaning once they're pointed out; it wasn't something I thought to intuitively look at."*), Participants also found that the *number of joints* is hard to count, saying for example, *"I physically can feel the difference in the number of joints. However, when it comes to counting the joints, that has to be very exact. That becomes a little hard for me to do."* (P5). Four participants suggested showing large numbers on a more precise, complimentary medium. For example, P4 said *"[...] I feel this (KiriPhys) draws a lot more attention than if you have a bar chart. But then after you get them engaged with the data, they can look at the digital visualization for more precision."*.

4 participants spontaneously discussed the value of reflecting relations in data through the relations of variables in KiriPhys. With the CO2 Emission Installation, they liked how the per-capita emission was represented through the amount of expansion that is dependent on both the number of joints and the number of loop. They said, for example, *"How the different parts of the data that relate to one another can be related to one another in KiriPhys and how it's structured, that's really neat"* (P10); and *"If you have a lot of emissions but you have a fairly low density of population, then the expansion becomes very slinging which means you have a high per-capita"* (P5).

While the spontaneous comments were largely positive, there were also 6 participants who offered negative comments. For example, the same person who said *"It's actually fun!"*, *"Oh, wow cool"* and *"They are robust despite the delicate look"* also shared their confusion about the different look of variables before and after expansion (P3 and P8), and the difficulty in comparing the number of rings in in different countries in the last example due to the similarity of the values (P4, P12). 2 participants (P2, P12) also found it challenging to make comparisons between the U.S and India based on their density of texture, since the values are similar and numbers are too large to count.

Design and Mapping Possibilities. Overall, participants readily understood the concept of KiriPhys and the KiriPhys variables, which allowed them to take a step back and discuss the KiriPhys design space. 5 participants noted the variety of possibilities KiriPhys provides for data representation, saying for example *It's interesting to see how many things KiriPhys can represent, like, mood, running, CO2, even birthday. So that's something that is surprising to me but in a good way* (P5). 2 participants appreciated the possibility to map different aspects of data to one object. P6 said *it is giving me everything in one go. You won't usually see four variables in one thing, right?"* and P7 *"In most visualizations everything is separate [...] you have to understand each data and relate. Whereas this and this [two countries in CO2 emission example], the grid tells me the difference, the height, the depth, the density of the knots, everything tells me the difference like in one go."*

Four participants indicated that the inherent aesthetics and abstract nature of KiriPhys made it a potential object to possess, carry and decorate their spaces with, without necessarily needing to explain the underlying data to others. For example, P2 said *"It is a dual-purpose object that is both jewelry and data-driven. The data-driven aspect is not very distinguishable when you see this"*; and P10 said *" Yeah, it's a nice object, like, you can tell somebody did some modern art, and they don't know the data behind it. Looks like art to me."*

6.3 KiriPhys in Context

Potential KiriPhys Applications. Participants to our study suggested many alternative data mappings and interactions. They suggested tracking their data that is often lost like leisure activities and physicalizing their important data about their families in the form of a decoration. When prompted about possible applications and usage of KiriPhys, they alluded to their potential as ornaments in the form of situated data physicalization in domestic spaces. For example, P6 suggested that *"in India, people have Diwali ornaments, similar to KiriPhys. So, it is already there, and besides being a design, it can capture some data related to home"*, and P1 said *"if I'm really proud of something, then I would want to make it into something like KiriPhys and put it on display. Something like a reward."* Others were excited about the idea to create small-scale KiriPhys gifts for friends and family. P3 said *"I think you can definitely have art creations with your friends and give it to them as a gift"*; and P12 *"We can record our data and send it to each other. It can fit in an envelope."* Two participants talked about the potential of KiriPhys for education. P11 talked about teaching data to school-aged children, saying *"This is a great thing for younger people, like in school, because they can manipulate it, they can play and learn about it."* Participants often emphasized that KiriPhys are engaging visualizations. For example, P3, while interacting with the Activity Jewelry, saw potential for self-reflection and motivation, saying *"if I had this on my desk, and if I had done good work the week before, and then I had this made, it would help me to continue that process and have one similar"*. Five participants spontaneously expressed that the CO2 Emission installation is an impactful way of showing CO2 emissions, saying for example *"it's such real data, and has a real impact in the world that I think it seems like it would be much more powerful this way than it would be seeing it on a screen"* (P9).

KiriPhys and Digital Visualizations: When asked to compare KiriPhys to on-screen representations, 6 participants said the KiriPhys was more fun, playful and rich, and 2 participants mentioned that they *"feel more connected to data"* (P4, P6). 3 commented that *"We already have too much screen time"* and that on-screen visualizations are *"easy to ignore"* (P9) and were *"boring reminders"* (P6) that they *"tend to skip"* (P10). The reasons why participants preferred KiriPhys are varied, 2 participants liked its "3-Dimensional quality". Others said that that with KiriPhys one can *"represent all aspects of data in one go"* (P6, P3), and *"depict the relations in data"* (P9). P5 stressed the benefits of not being given the data in a fully digested form already: *"the bar chart is sorted, like by population, then I just look at what is the highest one? and lowest one? This [KiriPhys] will involve me in trying everything out."* 2 participants appreciated the that KiriPhys *"is always on"* (P12) and can *"exhibit my data to me as well as other people"* (P6).

7 Discussion - A Wealth of Design Opportunities

The study results highlight a range of design opportunities for KiriPhys – and more generally physicalization – research and design. In this section, we discuss the selection of KiriPhys variables, general physicalization design considerations, and KiriPhys futures.

7.1 Selection of KiriPhys Variables

Beyond the KiriPhys variables in our study, conventional visual variables like position, orientation, colour, and shape can be used to encode data. For instance, one participant suggested that the colour of loops in the Activity Jewelry could represent the calories burnt or the heart rate for each run. Since KiriPhys variables coexist with conventional variables, the number of possible data mappings is expanded, and therefore more dimensions of a complex dataset can be shown.

However, all KiriPhys variables are not equally appropriate for representing all data types. Some worked well for reading quantities and some were perceived more qualitatively. Apparently, the ***number of loops*** has great potential as a quantitative variable, the ***amount, elasticity, and density of expansion*** have potential as ordinal variables, while the ***orientation of cut pattern*** and the ***direction of expansion*** have potential as qualitative variables. We also found that despite being exactly countable, the ***number of joints*** is difficult to rely on in practice; and that the ***width of joints*** is a poor variable to represent quantitative information. This frees these variables to be manipulated to affect dependant variables, which in turn represent data values.

7.2 Physicalization Design Considerations

The design of a physicalization, as always, depends on specific needs, context, audience and dataset. However, our study results suggest a series of design considerations (**DC1–5**) for researchers and designers interested in working with KiriPhys.

DC1: Consider the Elasticity Variable. We found that participants can intuitively feel the elasticity of expansion as a variable and engage in data exploration through it. Stretching the models and feeling their resistance to expansion not only helped them make sense of data quickly but also made the experience more engaging and playful. They explicitly mentioned how it triggered their kinetic memory. This new sensation in data representation is not limited to KiriPhys structures, but can be found in many different materials and be used as a tangible variable and new form of interactivity in physicalizations.

DC2: Consider Scale of KiriPhys for Interactions. In terms of the size of KiriPhys, while people compared jewelry pieces of different people very well using the elasticity and amount of expansion, some found them too small to count data details. Based on their feedback, one optimum size of the KiriPhys is coaster size that is not too big to make it hard to take with one hand and manipulate with the other hand and not too small to make the counting challenging. Other optimum sizes may occur at other scales, such as architectural scale.

DC3: Leverage KiriPhys Affordances. We observed that KiriPhys affordances are essential factors in initiating interactions. For instance, with the earrings, having the solid parts in the middle and at the top, successfully suggested to the participants how to hold and stretch the KiriPhys. Similarly, in the calendar, the curved part of the cut-pattern edge gave participants a hint of where to start the manipulation. Therefore, affordances are factors in the discoverability of possible manipulations and the resulting discovery of meaning. Participants also had an enthusiasm for linking the form and the KiriPhys interactions with the story behind the data. This added to their experience and encouraged exploration. Therefore, we should consider including by design relationships between dependent and independent data dimensions.

DC4: Consider Construction in Design. We saw that the participants' interactions with the form of the data representation play an important role in developing agency and establishing a deeper connection to the data. The manipulation and shaping of the artifact with their actions gave them enthusiasm to explore and allowed them to decide how to reconfigure it from a flat version. Like previous studies [19], our results suggest involving viewers in the active construction of data physicalizations, and KiriPhys in particular.

7.3 Limitations and Future Work

Methodological Limitations: In this work, we aimed to understand how people behave while exploring data through this new way of representing data in a qualitative study. This has allowed us to generate many hypotheses regarding the effectiveness of KiriPhys variables to encode data that warrant many subsequent quantitative, controlled task-based studies. In particular, through our work, it became evident that KiriPhys variables are not interpreted in isolation, and this should be considered in such studies. In our study, we also only looked at people's reading and interactions with ready-to-use KiriPhys. More research is needed to understand other aspects of KiriPhys, such as authoring practices (how might people create their own KiriPhys?), and how broader audiences in public contexts might interact with KiriPhys (e.g., in an art installation or a museum).

KiriPhys Intrinsic Limitations: The accessibility of the material and inherent aesthetics of KiriPhys make the technique well-suited to casual information visualization (e.g. personal data set, ambient infovis, artistic visualization) and for informal educational settings like museums. KiriPhys also suits data sets with relationships in values, since this interdependence can be illustrated through the dependant and independent variables (e.g. Co2 total/population = emission per capita). However, there are cases where using KiriPhys might not be appropriate. While participants counted the loops and joints effortlessly when their cardinalities were small, they found counting these variables "tedious" and "time-taking" with the CO2 Emission Installation that features larger numbers of loops and joints. This makes it particularly challenging to use these variables to encode data dimensions with high variance and large values. The number of joints and the number of loops can also only represent natural numbers, which might result in having to round quantitative data values and lose precision. Perhaps the major limitation of KiriPhys right now is the amount of time it requires from a designer to draw patterns for large, complex data sets. Existing tools (either manual with pens and scissors or general-purpose vector graphics software) are not designed to accelerate the processes of creating KiriPhys. We see plenty of exciting future research in the space of creativity-enabling digital tools that would support the process(es) of creating KiriPhys.

Alternate Manipulation and Material Possibilities: In this paper, we only provided examples that required manual interactions for reconfiguration. However, KiriPhys can also support the creation of flexible structures, whose malleability can support technology-based dynamic and interactive updates, thus relating more directly to other technologically dynamic physicalizations (e.g., [16, 32, 34, 44]). For example, a KiriPhys can respond to dynamic or streaming data, most explicitly using direction and amount of expansion. In addition, while we only utilized paper, KiriPhys can be created with any cuttable flat material, including more resilient and longer-lasting materials such as metals, opening the way for incorporating data into architectural structures.

Supporting creativity in making custom representations. With KiriPhys, a broad range of shapes, patterns, configurations, and reconfigurations can be created depending on purpose and context. Making paper-based KiriPhys can be relatively inexpensive, eco-friendly and fast with a laser cutter, and only demand basic knowledge in digital fabrication. With KiriPhys **deployability** it is also possible to produce large-scale flat structures that can be moved and expanded laterin varied places. Combining paper with electronics can further enable designers to create physicalization pop-up books that embed physicalizations to be expanded and by their readers.

8 Conclusions

We have presented KiriPhys, a new type of data physicalization based on the traditional Japanese paper-cutting art, Kirigami. We described how variations in cut patterns offer many opportunities for data representation, including mapping data to independent variables such as: 1) shapes and sizes of the inner and outer loops, 2) the number and width of loops, 3) the number and size of the joints between cuts, and 4) the position, orientation, and spatial organization of the pattern. These in turn help reveal data through dependent variables such as elasticity, texture, amount, direction, and form of the expansion. These KiriPhys possibilities, along with a wide range of choices of material and scale, provide a broad design space for creating data physicalizations, and introduce possibilities for non-technical, direct, and slow data exploration. We hope that this work will inspire future tangible data representation. Ultimately, reflecting on our findings, design considerations and future directions may contribute to the design of more delightful, and intriguing interactive data physicalizations.

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