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Thinking Spatially About Data: A Developing Framework to Understand Children's Spatial Reasoning in Data Physicalization

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ABSTRACT

Encoding intangible data variables with visual, spatial, and physical properties demands a high level of spatial reasoning. The ability to reason spatially is widely deemed critical to science, technology, engineering, arts, and mathematics (STEAM) learning. While much research has explored the relationship between learning with visualizations and spatial skills development, little is known about how children use their spatial reasoning in constructing tangible visualizations. This work-in-progress investigates how data physicalization activities, organized within a Design module in primary classrooms in the Netherlands, provide a window to understanding children's spatial reasoning about data. Based on preliminary analysis, we identify six indicators of children's spatial reasoning as observed in their constructing processes and artifacts. Most children in the study used tangible materials of varied sizes, curated meaningful spatial arrangements, and employed different unitizing methods to encode numerical data with spatial properties. Some children adjusted the sizes, units, or spatial arrangement to refine their tangible visualizations, considered the pros and cons of two- and three-dimensional forms of presentation, and made creative use of spatial shapes. In summary, this case study offers insights into children's use of spatial reasoning in data physicalization creation and practical implications for situating data physicalization activities in formal learning environments.

CCS CONCEPTS

• Human-centered computing; **• Visualization**; **• Visualization application domains**; **• Information visualization**;

KEYWORDS

data physicalization, spatial reasoning, spatial thinking, design education, maker education, constructive visualization, tangible user interfaces

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1 INTRODUCTION

The use of two or three-dimensional representations helps externalize our ideas, enhances our understanding of knowledge [3], and makes further visual exploration and manipulation possible [1]. Working with external representations such as graphs, diagrams, and models often requires spatial reasoning skills [4, 5, 26, 56, 57, 62]. Spatial reasoning—meaning "the mental process of representing, analyzing, and drawing inferences from spatial relations between objects or within objects" [6]—develops since early childhood [4, 38] and is critical to the learning of science, technology, engineering, arts, and mathematics (STEAM) [7–10, 40, 42, 43, 45, 60]. Existing studies have leveraged increasingly popular interactive visualization techniques, such as augmented reality and tangible computing, to support children's spatial reasoning [11–13, 62]. Yet less is known about how spatial reasoning contributes to children's creation of data-driven, tangible user interfaces, also known as data physicalization.

Data physicalization refers to "a physical artifact whose geometry or material properties encode data" [14], where abstract information in data variables is metaphorically represented by visual and spatial properties of tangible forms, such as their shapes, sizes, and spatial placements [15]. A salient feature of making or interacting with data physicalizations is the recruitment of our visualization and perceptual exploration skills [14, 19, 28, 29, 46, 47, 54]. Through spatially arranging visual and tangible cues, designers make use of the spatial relations between data variables [1, 47] to highlight meaningful associations [16] or hierarchical information [19]. Viewers, on the other hand, use spatial perception skills to extract information from visual and tangible cues such as shape, volume, and spatial position [14]. Our current study is especially interested in understanding how children use spatial reasoning to create their own data physicalizations.

1.1 Spatial reasoning in data physicalization

Based on the information visualization process model [2, 27], a critical step in transforming abstract data into visual or physical forms of representation is visual mapping, which means assigning "data dimensions to visual variables" to give "an initial visual form" to data [27]. These visual variables can have spatial or graphical properties [2]. Once an initial, abstract form of representation is established, presentation mapping is performed to decide how the physicalization will look like, including applying the visual mapping rule to all data variables or fine-tuning the presentation to facilitate viewers' perception and comprehension [27]. While this model does not describe all the cognitive processes involved in constructing data physicalization, it is evident that visual and spatial reasoning play critical roles.

The complex spatial reasoning involved in constructing or interacting with tangible visualizations has been addressed by multiple studies. For example, people visually estimated how data variables should be arranged by assigning unit meaning to specific dimensions (e.g. lengths) or quantities of tangible objects. Such visual parameters helped people mentally process and externally represent the spatial relations between data variables [19, 28]. Spatial arrangement can be used to depict hierarchical relationships in data using [19] or determine the optimal spatial layout in tangible visualizations [21]. Spatial relationships among tangible objects, on the other hand, helped participants make sense of and organize information [53, 56, 57]. Compared to visualizations displayed on screens, tangible user interfaces provide embodied experiences that facilitate people's perceptual understandings [14, 15, 49, 55, 57] and "enforce thinking about the spatial organization of visual elements and visual mapping" [29]. In other words, data physicalization appears to nudge people to actively reason about ways to encode intangible data using visual and spatial features of tangible materials.

1.2 Data physicalization with children

Unsurprisingly, one fundamental way for children to make sense of and learn about the world is through manipulating physical objects [17, 18]. Hands-on experiences support the learning of abstract concepts [50–52] and the use of tangible materials (e.g. blocks, paper-folding, hand-held models) also appears to benefit spatial reasoning skills development [39–41]. A number of spatial training for children made effective use of hands-on materials to develop spatial skills [40, 41, 60], and that playing with hands-on manipulatives such as puzzles predicted and contributed to children's spatial task performance [58]. A recent meta-analysis revealed that compared to spatial training delivered in digital or paper-pencil formats, spatial training with hands-on manipulatives led to greater improvement in mathematics performance [42], which is desirable since a primary objective of spatial training is to enhance STEM learning outcomes [4, 10, 43, 45].

The physicality of tangible user interfaces affords ample opportunities for spatial interactions and spatial reconfiguration [13, 59], which can help reduce excessive cognitive load required to process all spatial information mentally [59, 61], and may further support children's understanding of the problem space and their idea development [12, 59]. Specifically, low-tech, hands-on materials used in data physicalization allow visualization novices like children to experiment with different ideas and make adjustments handily [19, 20]. Moreover, data physicalization activities are highly engaging [14, 20], spark creativity [21, 22], and enhance the understanding of data [22, 23].

Many data physicalization workshops targeted undergraduate students [21, 23, 30, 31, 44], with relatively fewer studies [e.g. 20, 22] exploring how children create their own tangible visualizations of data. Introducing data physicalization activities to children can add to the ongoing investigation of using hands-on learning experiences to support spatial reasoning skills development. In addition, existing studies that have used visual representations to develop spatial skills have typically relied on ready-made visualizations, such as graphs or diagrams [24–26]. Thus, data physicalization offers a unique opportunity to understand how spatial reasoning is applied when children create their own tangible visualizations. In this case study, we seek to explore, in a formal learning context, how children make use of space and tangible materials to represent abstract meaning and relationships in numerical data, and how spatial reasoning is applied in their construction of data physicalization.

2 METHOD

2.1 Participants

37 children (aged 10-11) from grade seven in an international school in the Netherlands and one classroom teacher participated in the data physicalization activities. We focused on the primary school level because of its relatively open curriculum and emphasis on hands-on learning, and also because it marks an important stage of children's development of statistical literacy [37]. All participants provided consent to be part of this study.

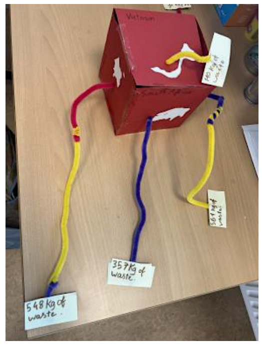
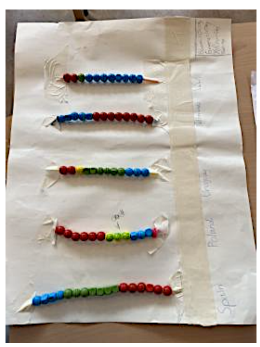
2.2 Materials

We prepared two types of materials for data physicalization construction: data sheets and making materials. We curated the data tables in a way that they fit the design theme and available materials, using units of measurement that were appropriate for this age group (e.g. kilograms or percentages). Data tables were non-ordered and contained only the essential information to highlight the goal of the task [32]. Children chose from data tables of (1) the percentages of five types of waste produced at their school in 2020, (2) the percentages of five types of waste produced in their home countries, or (3) the amount of solid waste produced per capita in five different countries based on the World Bank Database [33]. We provided a variety of making materials (e.g. playdough, elastic bands, paper straws, yarn, beads, balloons) that allowed for a range of operations [34], such as molding, bending, tying, and stacking. To reduce the psychological barrier to constructing [20], we only included materials that children of this age group were already familiar with.

2.3 Procedure

The data physicalization activities were organized in the Designing for Circular Economy course unit, allowing children to explore data related to waste and form a basic understanding of the design problem. The children were instructed to think of creative and easy-to-understand ways to make their tangible data visualizations. They had, on average, 15 minutes to read data tables about waste, make plans, and select materials, 40 minutes to construct tangible visualizations of data, and 15 minutes to present their works to the whole class. The children were free to choose to work in pairs or individually to authentically reflect how they usually work in design projects. Their overall experience in the project was documented in self-report surveys. Brief, semi-structured interviews were conducted upon completion of the surveys with children who had given consent for interviews.

Table 1: Understanding children's spatial reasoning from data physicalization constructing processes and artifacts

Category	Definition	Artifact example	Explanation
		Visual Mapping	
Size Variation (N = 21)	Representing the value differences in numerical data by varying the size (e.g. length, width, height, volume) of the tangible materials		This pair of children varied the length of pipe cleaners to represent the respective amounts of waste produced per capita in five different countries. To begin, they established a rule to unitize the materials they chose, where 100 kg = 9 cm, 10 kg = 1 cm, 5 kg = 0.5 cm, and 1 kg = 0.1 cm. Next, they mapped kilograms of waste per capita onto the respective centimeters of length on pipe cleaners. For example, they measured 67.8 cm of pipe cleaner to represent 548 kg of solid waste per capita produced in France. By transforming numerical data into tangible materials with varying lengths, these children effectively conveyed the differences in data through visual and spatial properties.
Spatial Arrangement (N = 9)	Representing the value differences, hierarchical relationships, or geographic information in numerical data values by arranging, positioning, and orienting the tangible materials in certain ways		This child spatially arranged the five "hot air balloons" to represent the waste produced per capita in five different countries. Viewing from left to right, the spatial position of balloons indicated that they were ranked from light to heavy, which analogically represented ranking the kilograms of waste per capita in five countries from lightest to heaviest. The different positions of the balloon were achieved by varying the lengths of the yarn attached to the balloons. This child not only assigned visual and spatial properties to non-ordered, numerical data visual but also re-ordered the data to reflect specific spatial relations and effectively utilized space to facilitate viewers' understanding of the data.
Unitizing (N = 9)	Setting visual parameters by assigning units of measurement to a certain quantity or amount of materials		This pair of children represented waste produced per capita in five different countries using a combination of colored beads strung together by plastic straws. They unitized beads by color, with blue = 100 kg, green = 10 kg, yellow = 5 kg, and red = 1 kg. To represent the 508 kg of waste produced per capita in the Netherlands, they used five blue beads and eight red beads. By assigning visual and spatial properties to intangible, numerical data to set visual parameters, these children demonstrated their spatial reasoning of a flexible concept of quantity.
		Presentation Mapping	
Making creative forms (N = 11)	Creating static or dynamic novel forms by combining or modifying available materials		This pair of children devised an interactive, movable pie chart using two plates and a pin. They connected the two plates at the center using a bendable pin and made cuts on both plates. As they rotated the plates, data regarding waste produced per capita in different countries would be revealed one by one. To convert the data in kilograms to a presentation format suitable for a round plate, they calculated the percentage of waste per capita in each country when five countries' waste per capita amounts were combined to make 100 percent of the plate's area. They then mapped the countries onto the plate based on their respective areas on the plate. For example, the U.S.A. was assigned an estimated area corresponding to 25 percent of the plate's area. Spatial reasoning can be seen from the creation of this unique form that supports dynamic spatial transformations and allows for viewer interaction, as well as the transformation from numerical data values into spatial information that corresponds to areas on tangible materials.

<table>
<tr><td>Adjusting sizes, units, or spatial arrangement (N = 9)</td><td>Revising or refining the size differences in materials used, the unit values, or the arrangement methods before the final form of presentation is determined</td><td></td><td>This pair of children represented the percentage of five types of waste produced at their school using five paper cups filled with different volumes of materials. They assigned a value of 100 percent to filling one cup and estimated the volume of materials based on their respective percentages. They then combined all materials from the five cups into one to check if they would fit in one cup. In this process, they noticed an overestimation and realized that it was difficult, due to different material properties, to make the paper pieces representing 14% of wasted paper have an equal volume of the plastic caps representing 14% of wasted plastic. They set out to adjust the approximate volume of these two materials. Such adjustment processes involved observing, comparing, gauging, and measuring, all of which recruited children's spatial reasoning skills.</td></tr>
<tr><td>Deciding between 2D and 3D forms of presentation (N = 5)</td><td>Reasoning about the pros and cons of making representations in 2D or 3D formats</td><td>
</td><td>The majority of the artifacts utilized three-dimensionality, while some were two-dimensional, such as those on paper. We observed that children put active reasoning into their choices. For example, this child initially thought of making a pyramid shape to represent the differences in data by varying the lengths of its edges. He eventually decided on making a simple 2D collage with colored papers of varied side lengths. He reasoned that the 2D collage was easy to understand and effective enough to represent the data. The reasoning behind the use of two and three-dimensional space reflected children's exploration of different properties of space in their minds.</td></tr>
</table>

3 PRELIMINARY FINDINGS

3.1 Using spatial properties to encode data variables: children's making processes and artifacts

A total of 23 data physicalization artifacts were created by children either in pairs or individually. We conducted an initial round of thematic analysis [48] of their artifacts and their making processes to identify evidence of using spatial properties to encode data variables, including varying the sizes [2, 15, 28, 35, 46], spatial arrangement [2, 15, 28, 35], assigning unit values [19, 28], and making meaningful selections or combinations of shapes and materials [14, 28, 47]. While these properties have been widely employed in existing data physicalization artifacts by experts or non-experts, they have not been explicitly regarded as potential indicators of spatial reasoning.

We summed up our preliminary findings on children's use of spatial properties and spatial forms of presentation in the six categories in Table 1, along with the number of artifacts falling into each category. Each artifact example satisfied more than one category. The categories, *size variation*, *spatial arrangement*, and *unitizing* are part of visual mapping, during which the rule of how data is mapped to visual variables is defined. *Making creative forms*, adjusting sizes, units, or spatial arrangement, and *deciding between 2D and 3D forms of presentation* are part of presentation mapping, which is one step after the initial visual mapping and define how the final form of presentation looks like.

Based on classroom observations, semi-structured interviews with children, and children's self-reports, it appeared that a majority of the children could confidently explain the meaning of data to others using their data physicalizations. Many of the children reported gaining a better understanding of data related to waste as well as the different possible ways of data visualization. Furthermore, some of the children indicated that they became more aware of the importance of taking action to reduce waste and developed more ideas pertaining to the Circular Economy design theme.

4 DISCUSSION

The preliminary analysis of children's artifacts and making processes revealed that children carried out visual mapping and presentation mapping [2, 19, 27] widely and frequently to assign visual and spatial properties to numerical data that was not inherently spatial. Making meaningful use of sizes, spatial arrangement, and unit values to encode data, making adjustments to sizes, units, or spatial arrangement to refine their tangible visualizations, as well as making creative use of spatial shapes, dynamic spatial transformation, and two or three-dimensional presentation formats all reflected children's active use of spatial reasoning.

Among these six potential indicators of children's spatial reasoning during data physicalization construction, most of the children produced spatial configurations that used size differences and spatial arrangement to convey data hierarchy. This seems to align with prior research on how tangible user interfaces allowed individuals to notice, explore, and make creative use of visuo-spatial features and spatial relations [19, 28, 57]. Unitizing, another effective strategy adopted by some children to visually map numbers to tangible materials, is in fact also an important cognitive strategy in mathematics that contributes to children's understanding of quantities and proportional reasoning [63], which are inherently spatial. Moreover, the making of novel spatial shapes, particularly those that can be spatially transformed, demonstrates that data physicalization activities are not only open enough for children to express and experiment but also potentially helpful for children to connect the concepts of shapes and numbers and view common shapes in non-rigid spatial ways [64].

Despite the examples given above, some children created tangible visualizations that resembled standard data charts, such as bar graphs and pie charts. While these might seem less creative, they were effective representations of data and also necessitated spatial reasoning. From the perspective of encouraging children to think spatially about data, creating symbolic representations of information is inherently spatial [5] and almost always requires children to reason spatially in order to map numerical data onto visual and tangible forms.

The contribution of this work-in-progress is two-fold. Firstly, while many existing data physicalization artifacts make use of spatial elements, the role of spatial reasoning in data physicalization construction, especially with children, has not been explicitly explored. The six indicators of spatial reasoning in children's creation of data physicalization serve as the stepping-stones for a developing framework to further understand how spatial reasoning—one of the most-studied human cognitive factors [36]—may influence data physicalization construction, and how data physicalization activities can be leveraged to support children's spatial skills development. A thorough analysis of indications found in children's verbal expressions, actions, gestures, and artifacts in this case study is needed before drawing further inferences.

Secondly, it is worth noting that we organized the data physicalization activities not in a vacuum but within a design course unit as an intermediary step for children to gain a deeper understanding of a design problem. Based on the positive feedback from both children and teachers, we reckon that data physicalization activities have the potential to facilitate subject knowledge learning in classrooms [23]. For example, some of the current hands-on learning activities used in the primary curriculum may be purposefully restructured into data physicalization activities that emphasize exploration, visual mapping, and hands-on making. Future studies are needed to explore how data physicalization practices can be integrated into various classroom contexts to support both knowledge learning and spatial skills development.

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