ABSTRACT

Title of Thesis:	TRANSFORMING ENVIRONMENTAL EDUCATION: EXPLORING THE IMPACT OF DATA PHYSICALIZATION ON CHILDREN'S LEARNING Yi Hsieh Lin, Master of Science in Human-Computer Interaction, 2024
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This paper explores the integration of data physicalization in Education for Sustainable Development (ESD), focusing on its potential to enhance the learning experience for young audiences, particularly those aged 7-12. By examining current approaches in ESD and analyzing the impact of tangible data interactions on children's understanding and engagement with sustainability issues, the study underscores the importance of innovative educational methods. Preliminary findings indicate that data physicalization help enhance comprehension, engagement, and active learning among young learners. The research contributes to the discourse on effective ESD practices, advocating for the inclusion of data physicalization techniques in educational curriculums to better prepare youth for addressing global environmental challenges.

TRANSFORMING ENVIRONMENTAL EDUCATION: EXPLORING THE IMPACT OF DATA PHYSICALIZATION ON CHILDREN'S LEARNING

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2024

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Acknowledgements

I would like to express my profound gratitude to Professor Jason Aston, my mentor and chair of my thesis committee. His invaluable guidance and insightful instructions have been fundamental to the completion of this research. The depth of his mentorship has profoundly influenced my academic journey.

Further, I owe a debt of gratitude to Dr. Elizabeth M. Bonsignore for her significant contributions and meticulous feedback, which have greatly influenced both the development and refinement of my work. Her encouragement and support have served as a beacon of inspiration, shaping the trajectory of my research endeavors.

I also extend my thanks to Drs. David Weintrop, Dennis Frezzo, and Zeena Zakharia for their gracious acceptance to serve on my thesis committee. Their expertise and unique viewpoints have greatly enriched my research, providing a comprehensive understanding of my study's scope.

A special note of thanks to my family—my parents and sister—for their relentless support and faith in my abilities, which have been the bedrock of my academic journey. My friends also deserve heartfelt thanks; their unwavering encouragement and belief in me have been sources of immense strength. Lastly, my gratitude extends to all the KidsTeam co-designers and study participants. Their willingness to share their time and experiences has been vital to the success of this research.

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Chapter 1: Introduction

The urgency of addressing global sustainability challenges, such as climate change and biodiversity loss, underscores the vital role of youth in fostering a sustainable future. The 2030 Agenda for Sustainable Development particularly emphasizes youth engagement as crucial for realizing its goals, pointing to the necessity of integrating sustainability education from an early age (Gupta, 2022). Despite its importance, there is a notable research gap on the effectiveness of such education for children aged 7-12. Moreover, the potential of data physicalization as a tool in sustainability education has been underexplored, despite initial findings suggesting its promise in enhancing learner engagement and understanding.

This study aims to extend from past research by exploring the application of data physicalization within Education for Sustainable Development (ESD) for young children. Through tangible interactions with data, the goal is to deepen children's comprehension of key issues, such as climate change, carbon emissions, and sustainable practices, in ways that traditional charts, graphs, or text-based materials may not achieve. This approach also aims to foster critical thinking and problem-solving skills, encouraging children to actively engage with the data and reflect on its real-world implications. By facilitating tangible interactions, this study hopes to bridge the gap between abstract concepts and practical understanding, ultimately equipping young learners with the knowledge and skills needed to make informed, responsible decisions about the environment. Through these methods, the research seeks to empower the next generation with the tools necessary to take meaningful action toward a more sustainable future.

To explore these objectives, the research will focus on the following key questions related to the design and implementation of data physicalization in Education for Sustainable Development (ESD) for young learners:

1. How does the design and implementation of data physicalization in educational settings help youth learn sustainability?

   [1.a] How do youth interact with data physicalization to learn about sustainable development?

   [1.b] How does exposure to data physicalization influence youth's environmental behaviors and attitudes?

   [1.c] How can data physicalization be effectively designed and implemented in educational settings to teach sustainability?

The integration of data physicalization into ESD represents a novel pathway towards more effective sustainability education. By fostering a deeper understanding of environmental challenges through interactive learning experiences, this research contributes to the ongoing conversation about how to best prepare the next generation to take care of our planet.

Chapter 2: Related Work

2.1 Introduction to Education for Sustainable Development (ESD)

ESD is important in addressing today's environmental challenges by instilling values of sustainability, respect for the environment, and responsible use of resources in young people. This approach prepares future generations to solve sustainability issues. The escalating environmental challenges of our era demand a transformative shift in education, steering the youth toward sustainable knowledge and actions. Education for Sustainable Development (ESD) embodies this shift, fostering values of diversity, environmental respect, and the judicious use of planetary resources from a young age. This holistic educational approach is pivotal in preparing a generation to address and solve the complexities of sustainability challenges with insight and innovation.

The concept of sustainability education has evolved significantly since its inception. It was first introduced at the Conference on the Human Environment (UNCHE), also known as the Stockholm Conference, in 1972. At that time, environmental information and education were identified as key tools to raise awareness of environmental problems, with the seventh policy type – environmental information and education – being the most frequently implemented across Europe. Governments used various channels such as press, television, films, posters, and radio to launch public education and information campaigns. In countries like Chad, for instance, films and leaflets were used to inform people about the correct use of pesticides. Alongside these public campaigns, seven countries integrated environmental topics into their school curricula (Joos, 2023).

Since the late 1980s, following the publication of the Brundtland Report by the OECD, which introduced the concept of sustainable development as a critical global issue, the role of education in ensuring global survival has been widely discussed by politicians and researchers. As a result, efforts have been made to incorporate issues such as climate change and natural resource management into teaching and learning practices (Hägglund & Samuelsson, 2009).

Agenda 21 further emphasizes the importance of education in promoting sustainable development. It argues that education is essential for enhancing individuals' capacity to address both environmental and developmental challenges. Education for Sustainable Development (ESD) is thus seen as a crucial element in creating informed and responsible global citizens, capable of addressing sustainability challenges (UNCED, 1992).

2.2 Implementation and Challenges of ESD

Current ESD implementations demonstrate a multifaceted approach, integrating sustainability across curricula while employing transformative pedagogies and promoting participatory learning experiences. At the foundational level, PISA found that "98% of students in OECD countries attend schools in which environmental topics (e.g. pollution, environmental degradation, relationships between organisms, biodiversity and conservation of resources) are taught (UNESCO, 2018). Building upon this curricular integration, educators are adopting transformative approaches: "Transformative pedagogy should draw on the experience of learners and create opportunities for participation and the development of creativity, innovation and the capacity to imagine alternative ways of living" (UNESCO, 2018).

This transformative approach extends to early childhood education, where play-based learning is emphasized: "If children are learning individuals, then in their play, they have to be allowed to apply their perspectives, ideas, and fantasies into whatever the teacher introduces in practice" (Samuelsson & Park, 2017). Translating these principles into action, some schools have implemented "a variety of activities that are generally manifested in conservation activities and ecoliteration development" (Gunansyah et al., 2021). Furthermore, to enhance student engagement and ownership, participatory methods are employed. As noted by Ohlsson et al. (2024), "According to the preschool teachers, there is often a vote on such matters as who they will play with, where they will play and what the theme of the teaching will be, and the ambition on their part is that children's interests should direct the teaching."

Despite these comprehensive implementation efforts, significant gaps remain in ESD, particularly in translating knowledge into action, addressing consumption patterns, and providing practical, engaging content. A fundamental challenge lies in the disconnect between education and behavior change. As Blumstein and Saylan (2007) pointedly observe, "Yet by most objective measures, this money has been wasted, because out of the classroom, people have failed to make the link between their individual actions and the environmental condition."

This disconnect is further exacerbated by a lack of focus on crucial areas such as consumption patterns. The same authors argue that "Changing consumption patterns is not generally a targeted outcome of environmental education, but we believe it is one of the most important lessons that must be taught" (Blumstein & Saylan, 2007). To bridge this gap between knowledge and action, the literature suggests a need for more practical applications. (Hedefalk, Almqvist, & Östman,

2015) propose that "ESD should not only focus on theoretical knowledge but also on practical applications that resonate with children's everyday lives." This emphasis on practicality is closely tied to the need for more engaging content, as the same authors note, "Effective ESD requires educators to adapt content to be more engaging and relevant, ensuring that children can relate to and understand sustainability issues" (Hedefalk, Almqvist, & Östman, 2015) Notably, within the provided literature, there is a conspicuous absence of discussion regarding mathematical content integration in ESD, suggesting another potential gap in current approaches. This omission is particularly significant given the importance of quantitative skills in addressing complex sustainability challenges.

2.3 Data Physicalization in Education: From Theoretical Foundations to Practical Applications

Data physicalization—the practice of mapping data to physical form—sits at the crossroads of various domains, including data visualization, tangible user interaction, and design (Bae, 2022). This approach aligns with Piaget's constructivist theory that "knowledge is only truly acquired when it is used by a particular individual in the process of solving a specific problem" (Wells, 2001), as it transforms abstract concepts into tangible, interactive experiences that learners can physically manipulate and explore.

Building on Papert's constructionist theory, which emphasizes that "constructs that occur in the mind are most effective when supported by overt constructs in the world" (Papert, 1993), data physicalization provides concrete representations that support cognitive development. This is particularly relevant for children in the concrete operational stage, where physical interaction with objects aids understanding. As defined by Jansen(2023) physicalization supports "cognition, communication, learning, problem solving, and decision making" by removing digital constraints and creating tangible data interactions.

The social aspects of data physicalization in sustainability development settings align with Vygotsky's social learning theory and Wells' emphasis on collaborative learning. As Wells argues, "knowledge is constructed and reconstructed between participants in a given situation" (Wells, 2001), and data physicalization projects create opportunities for such collaborative meaning-making. This is evidenced in projects like CoDa (Collaborative Data), where students collectively explore and manipulate data representations (Veldhuis et al., 2020).

However, implementing data physicalization faces certain challenges. While Lave (1991) situated learning theory suggests learning should be embedded in authentic contexts, balancing this with scalability remains difficult. As class sizes increase, maintaining meaningful engagement becomes more challenging. Moreover, there is a risk of oversimplification of complex data through physicalization, which might lead to misconceptions.

To address these challenges, educators must carefully consider both design and implementation. Following López García & Hornecker's (2021) recommendations, physicalization activities should be complemented with discussions that explore deeper complexities, aligning with both constructivist principles of active learning. Success stories in various educational domains demonstrate how this balance can be achieved, from geography teaching with Augmented Reality Sandboxes (Sauvé et al., 2023) to sustainability education through interactive simulations like

EnerCities, which simulates the experience of building a sustainable city, covering environmental, economic, and social sustainability dimensions (Knol & De Vries, 2010).

2.4 The Transformative Potential of Data Physicalization in Sustainability

Data physicalization emerges as a revolutionary force in Education for Sustainable Development (ESD), adeptly surmounting the challenges inherent in both traditional and digital teaching methodologies. By transforming complex sustainability data into tactile, engaging formats, data physicalization not only enriches the educational experience but profoundly deepens student engagement and understanding of critical sustainability issues.

It offers an exciting opportunity for engaging people with physical representations of data that can be examined and manipulated to gain a mental model of a set of variables and their relationships. This is of paramount importance not only for researchers and professionals but also for improving citizens' awareness in different domains, impacting civil society, and pushing behavior change (Pittarello & Semenzato, 2024).

Physicalizations are beneficial as physical interaction with data can increase user engagement, facilitate learning and understanding, and make data more accessible. Active touch also facilitates effective information retrieval from data physicalizations. Finally, physicalizations allow for social interactions around them to facilitate collaboration and shared sense-making.

Yet, the journey of integrating data physicalization into sustainability education is only beginning. The path forward requires thorough and rigorous research to fully explore the potential of this innovative approach. By carefully examining its strengths, limitations, and practical applications, we can gain a deeper understanding of how data physicalization can be effectively integrated. Investigating its application across varied educational settings, experimenting with diverse materials, engaging different participant demographics, and evaluating the long-term effects of data physicalization on learners' attitudes and behaviors towards sustainability represent critical milestones in my quest to refine and validate effective ESD strategies.

Participatory data physicalization offers a way to engage a community with data of personal relevance that otherwise would be intangible. Currently, there is no single clear definition offered yet, hence we refer to PDP as "a physical visualization that allows for a co-located audience to physically participate in the creation of the visualization by directly encoding their data while following predetermined rules" (Sauvé et al., 2023).

The pursuit of this knowledge is not just academic—it is a pivotal step towards realizing a more sustainable and equitable future, making the case for data physicalization in education not merely compelling, but imperative. Making citizens aware of issues related to the environment becomes more and more urgent to involve them in behavioral changes (Pittarello & Semenzato, 2024).

Chapter 3: Methodology

3.1 Research Design

This research employs qualitative methods to investigate how tangible data representations and physical data models can enhance 7–12-year olds' comprehension of sustainability concepts. The study applies Grounded Theory methodology as outlined by Stough & Lee (2021) to analyze participant observations, interview transcripts, and artifact documentation, enabling the identification of recurring patterns in how children interpret and interact with physical data models. The theoretical framework combines Piaget's Constructivist Learning Theory, emphasizing hands-on manipulation of physical objects, with Kolb's Experiential Learning Cycle to structure activities that move from concrete experience to abstract conceptualization. Human-Centered Design methods, including contextual inquiry and iterative prototyping, inform the development of age-appropriate sustainability education toolkits.

The research consists of two distinct design sessions conducted with KidsTeam members aged 7-12 years old. The first session, involved nine children, divided into three groups of three. The session began with a 20-minute Circle Time discussing the Question of the Day about environmental actions, followed by 45 minutes of design activities where students engaged in sustainable meal planning using food cards, carbon emission blocks, and balance scales. The session concluded with journaling completion. These activities generated observational data about students' understanding of environmental impact and their responses to physical data representations.

The second session, included six returning participants, working in two groups of three. Beginning with a 20-minute Circle Time reflection on behavior changes since the previous session, students then spent 40 minutes interacting with an improved wooden toolkit featuring differently sized blocks to represent carbon emissions and compensatory actions. This was followed by 20 minutes of Big Ideas discussion and reflection activities. Using observation and the Big Ideas documentation technique, these sessions evaluated both the effectiveness of the physical toolkit design and students' conceptual understanding of sustainability data. Both sessions focused on how data physicalization can enhance youth comprehension of environmental concepts and influence their attitudes toward sustainable behaviors.

This approach directly addresses the research questions by examining how youth interact with and learn from physical data displays, particularly in understanding complex concepts like carbon emissions and compensation actions. Through the children's engagement with the toolkits and their documented responses in journals and group discussions, the methodology captures both immediate learning outcomes and potential behavioral changes toward sustainability. The progression from initial design activities to more structured data interpretation tasks also provides valuable insights for developing age-appropriate, engaging educational tools for environmental education.

3.2 Participants

Participants in this study were children between the ages of 7 and 12, part of the KidsTeam research group of Human Computer Interaction Lab at The University of Maryland. This specific age group was targeted based on their developmental stage, which is considered crucial for cultivating sustainable mindsets and behaviors, aligning with the principle that recognizing the competencies of young children can significantly inform research ethics and methodology. Ethical considerations were meticulously observed, adhering to stringent guidelines for research involving children. As Danby and Farrell (2005) advocate, children should be viewed as gatekeepers of their own accounts, competent to withhold or share their experiences, and ultimately decide whether or not they wish to participate. This entailed obtaining consent from their parents and informed assent from the children, thus honoring their capacity to engage in decisions about their participation, ensuring the confidentiality of the information provided by participants, and clearly communicating the children's right to withdraw from the study at any time. In this conceptualization of the child, the child is constructed not as a 'child' participant, but as a 'research participant' (Danby and Farrell 2005). In the first session, 9 children participated in the research, referred to as Participants 1 through 9 (P1–P9). In the second session, only 6 children were present: P2, P3, P4, P5, P8, and P9.

3.3 Materials Used

In the design sessions, I employed a wide range of carefully selected materials to create an engaging, hands-on learning experience focused on sustainability. These tools were designed to help children grasp complex environmental concepts in a simple, interactive, and enjoyable manner. In the first session, children interacted with AI-generated food cards, scales, and carbon blocks to visualize and understand the carbon footprints associated with different food items. These tools, combined with reflective journaling, allowed children to document their experience throughout the session, providing valuable feedback with sustainability. The toolkit evolved in the second session, incorporating wooden block sets to simulate carbon emissions and reduction strategies in a tactile and visual way. I also provided large sheets of paper for creatively explore "big ideas" related to sustainability toolkit. By utilizing these materials, I effectively gathered meaningful data to preferences address my research questions.

3.3.1 AI-Generated Food Cards

AI Model Selection: In the development of AI-generated food cards, selecting the appropriate AI models for image generation was crucial. The project aimed to create high-quality, consistent, and visually appealing illustrations. To meet this goal, I utilized two distinct AI technologies: DALL·E for image generation and ChatGPT 4 for content creation. DALL·E, developed by OpenAI, was chosen for its exceptional capability to generate high-quality, detailed images from textual descriptions. This model stood out for its ability to closely align with specific prompts, enabling a high degree of creativity and specificity in the visual content. DALL·E's proficiency in rendering textures, colors, and lighting effects with precision made it the ideal tool for illustrating a wide range of fruits and vegetables. During the development phase, I also experimented with MidJourney, another AI image generation model. Despite its potential, MidJourney faced challenges in maintaining the desired consistency in visual style across the food cards. Even with precise prompts and subsequent refinements, the outputs varied significantly. This inconsistency was a significant obstacle, given the importance of a cohesive visual narrative for educational materials. Ultimately, I favored DALL·E for its superior ability to produce images with greater stylistic consistency through prompt modification.

Content Preparation for AI Generation: In developing the visual foundation for the project, I assembled a mood board using various images from Pinterest, including illustrations by different artists and designers such as Ngân (2023) and Rebombo Estudio and Raquel Jove (2021). These images provided stylistic inspiration and helped shape the overall aesthetic direction. And then, I uploaded the predefined style to ChatGPT, prompting,

"How should I give a prompt to generate the same style of pictures?"

The answer received was detailed and explicit-

"Create a highly detailed and realistic illustration of [desired fruit or vegetable]. The [fruit or vegetable] should be depicted with a lifelike appearance, showcasing natural color gradients, precise reflections, and accurate textures. It is essential to include at least one [fruit or vegetable] sectioned to reveal the interior structure, with visible seeds or pulp. A plain white background is recommended to accentuate the subject, complemented by soft shadows under the [fruit or vegetable] to impart a sense of depth."

This resulted in detailed instructions for creating highly realistic illustrations of fruits and vegetables. Based on ChatGPT's guidance, I developed a standardized prompt structure for DALL·E. The application of these guidelines in DALL·E, however, encountered variability in the consistency of the AI's output. While some illustrations perfectly matched the intended aesthetic, others deviated. This inconsistency necessitated an iterative approach to refinement. In response, I employed a method of feedback loops, where successful illustrations generated by the AI were re-uploaded as benchmarks. This step was instrumental in refining the prompts for subsequent image generation. Specifically, I sought to adjust the initial prompts based on the characteristics of these successful illustrations, thereby informing the AI to produce images that more closely adhered to the desired aesthetic standard. This process of continuous adjustment and re-evaluation exemplifies a dynamic method of leveraging AI capabilities, optimizing the prompts to achieve greater consistency in the visual style of the food cards.

Information on the Cards: These food cards provide a clear visual representation of different food items, offering insight into the carbon footprint of each product from production to consumption. The front of each card showcases the food item itself, designed to catch attention with clean, simple visuals. On the back, the card breaks down the specific stages of the food's production process, detailing how CO_2 emissions accumulate at each step. Each card uses data from carbon emission calculation websites, such as My Emissions (My Emissions, n.d.), and Food carbon emissions calculator (Food carbon emissions calculator, n.d.) to provide specific CO_2 outputs for each stage.

Figure 1: A food card featuring AI-generated visuals - The front displays the food item with its name, while the back illustrates its production process and CO_2 emissions per step and in total.

Purpose and Use in the Study: The food card serves as an educational tool to help children engage with and understand the environmental impact of various food items by connecting them to their associated carbon footprints.

3.3.2 Balance Scale

The scale in the study serves as a tool to physically represent the carbon footprint of different food items, helping children better understand the environmental impact of their choices. After selecting food cards, children place carbon blocks on one side of the scale to visualize the weight of the emissions – signifying a human-caused imbalance in the Earth's carbon cycle. On the other side, they place markers representing sustainable actions, such as recycling or walking, to attempt to balance the scale i.e. balancing the CO_2 generated to sustain our planet earth.

3.3.3 Carbon and Action Blocks – Session 1

In the study, carbon blocks are used to physically represent the carbon footprint of various food items, helping children visualize the environmental impact of their choices. After calculating the food cards, children place carbon blocks on one side of a weighing balance to reflect the carbon emissions associated with the food. They then balance these compensation blocks representing actions that reduce carbon dioxide, such as walking or recycling.

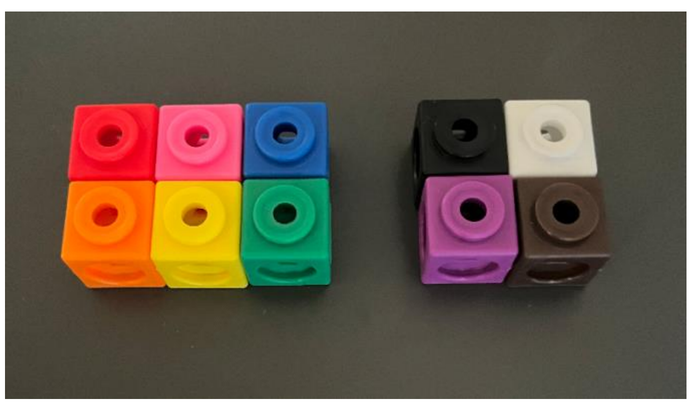

Figure 2: Left-Action Blocks / Right - CO_2 Blocks

3.3.4. Reflective Journals

Reflective journals in this study are designed to allow children to document their thoughts, challenges, and learning experiences related to sustainable development. These journals serve as a tool for personal reflection, helping to deepen their understanding of sustainability and fostering a more thoughtful engagement with the activities.

3.3.5 Wooden Toolkit – Session 2

Material Selection: The goal for the second session was to create a series of wooden blocks that represent various amounts of carbon emissions: 0.1 pounds, 0.2 pounds, 0.3 pounds, 0.5 pounds, and 1 pound. Each food card's carbon emissions can be represented by various combinations of the wooden blocks. For example, to represent 0.7 pounds, you could use a 0.5-pound block together with a 0.2-pound block. Along with creating blocks of the same size that would demonstrate the behavior of carbon offset compensations. These blocks needed to be durable, easy to handle, and visually distinguishable in terms of weight representation. To house the blocks, I designed a wooden box capable of securely containing the blocks while enduring the cumulative weight. This prompted the selection of appropriate materials for both the blocks and the box based on their physical properties and suitability for laser cutting and assembly.

Plywood for Wooden Blocks: For the wooden blocks, I chose plywood due to its structural integrity, dimensional stability, and cost-effectiveness. Plywood is made by gluing together multiple layers of wood veneer, with the grain of each layer running perpendicular to the previous one. This cross-grain construction gives plywood excellent strength and resistance to warping, cracking, or shrinking, which are essential qualities for blocks that will be frequently handled and used for demonstration purposes. Furthermore, plywood provides a uniform and smooth surface that is ideal for laser carving. The precision of laser carving allows me to inscribe the blocks with accurate weight representations, ensuring clear identification of each block's carbon emission value. Plywood's consistent texture also makes it easier to achieve precise cuts using a table saw or band saw, which is particularly important for smaller blocks where accuracy is crucial.

MDF and Plywood Combination for the Box: Initially, I selected MDF (Medium Density Fiberboard) for the wooden box. MDF is composed of wood fibers compressed with resin to form a dense, smooth, and uniform board, making it an affordable and readily available material. The smooth surface of MDF made it a logical choice for laser cutting the precise finger joints that would be used to assemble the box. These finger joints were essential for providing structural stability and creating a seamless assembly without the need for additional fasteners. However, after assembling the box, I encountered an issue with MDF's softness at the edges. To resolve this, I modified the design by incorporating plywood for two opposite sides of the box, while retaining MDF for the other two sides. This adjustment allowed me to combine the strength and durability of plywood with the smooth, customizable surface of MDF, resulting in a box that could endure the weight of the blocks while maintaining a polished finish.

Precision in Production and Cutting Process: The production process required a high level of precision, both in the preparation of the blocks and the assembly of the box. Laser cutting was utilized for the box due to its ability to produce accurate, clean cuts and precise finger joints. For the blocks, the laser carving technique ensured that each block was marked with the correct weight, while the table saw, and band saw were used to cut the blocks to the required dimensions.

The blocks were produced in the following sizes, correlating to the weight they represent:

- 0.1 pounds: 1 inch (W) x 1 inch (H) x 0.5 inches (L)
- 0.2 pounds: 1 inch (W) x 1 inch (H) x 1 inch (L)
- 0.3 pounds: 1 inch (W) x 1 inch (H) x 1.5 inches (L)
- 0.5 pounds: 1 inch (W) x 1 inch (H) x 2.5 inches (L)
- 1 pound: 1 inch (W) x 2 inches (H) x 2.5 inches (L)

The precision of these dimensions was crucial for ensuring that users could easily handle the blocks and that the blocks visually and physically represented the different carbon emission values accurately. Additionally, to ensure the longevity of the blocks and the box, each component was thoroughly sanded to create a smooth, tactile finish. This step was particularly important given that the main users of the toolkit are children. By sanding all edges and surfaces, I minimized the risk of splinters or rough spots that could cause injury during use.

Figure 3: Wooden toolkit with CO_2 and action blocks arranged in a box.

Sustainability Considerations: In addition to functional and practical considerations, sustainability was an important factor in the selection of materials. Plywood is often sourced from fast-growing species of trees, making it a more sustainable option compared to solid hardwoods. Additionally, MDF is made from recycled wood fibers, which helps reduce waste from the production of solid wood products. By using these materials, I was able to minimize the environmental impact of the project while still meeting the requirements for durability and cost-effectiveness.

Design of the Woodblocks: The design of the wood blocks builds upon the observations made using same-sized plastic blocks from the previous section, with adjustments for more accurate representation. Initially, plastic blocks of the same size were used, with different colors representing various food items. However, this approach lacked precision, as some food portions did not weigh exactly 1 pound. To address this, participants were instructed to calculate the weight and place the corresponding number of blocks. For example, if the total meal weighed 2.2 pounds, they would use two blocks, which was an approximation and not entirely accurate. In this new iteration, the design of the wood blocks is based on the actual weight in pounds, with blocks of different sizes corresponding to different weights. This adjustment allows for a more accurate representation of portion sizes and enables easier comparison of various food items simply by looking at the size of the blocks. From a user experience perspective, the focus is on making the process more intuitive and visually clear for users. By varying the sizes of the blocks based on weight, users can better grasp portion differences at a glance without needing to perform additional calculations. Additionally, the design encourages engagement by offering a more tactile and direct way to compare food items, making it simpler and more efficient for users to assess their choices.

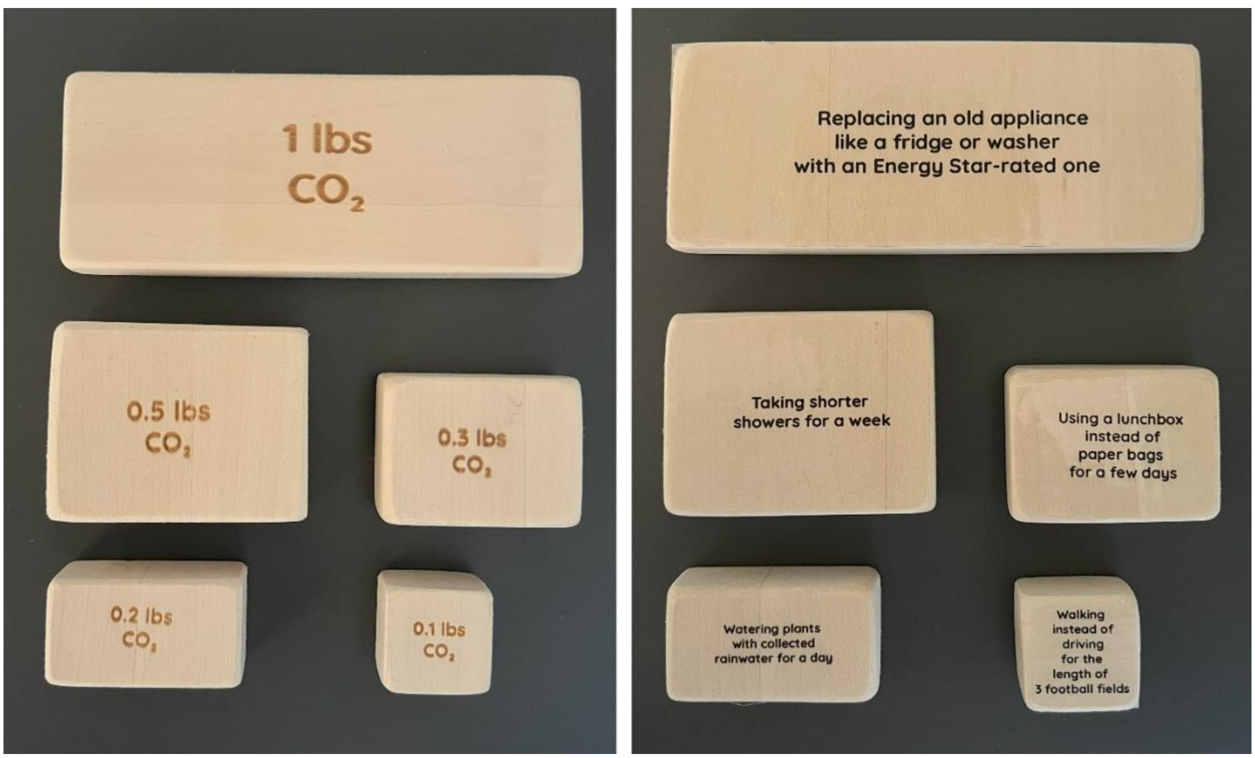

Figure 4:Wooden CO_2 and Action blocks

3.4 Data Collection

3.4.1 Design Session 1

Pre-Session Preparation

Prior to the session, a thorough review was conducted to ensure all preparations were in place for success. This involved gathering all required materials and choosing an engaging Question of the Day to guide discussions on sustainability. Additionally, steps were taken to create a welcoming environment by providing snacks and water, while potential group dynamics were anticipated and addressed to encourage a cohesive and collaborative atmosphere.

Circle Time: The Role of the Question of the Day

I started with the Circle Time, for 20 minutes, marking the formal beginning of the session. This segment was significantly centered around the Question of the Day, a carefully selected query designed to align the children’s thoughts with the sustainability theme of the day.

Question of the Day: “What are the everyday things you do that will help or hurt the Earth?”

The Question of the Day served as a critical tool, enabling facilitators to gauge the children's existing knowledge and perspectives on sustainability, thereby tailoring the session to address and expand upon these views through direct engagement and discussion. Additionally, it fostered an environment where everyone actively participated in conversations about sustainability, creating a setting where the theme was fully integrated and the children were motivated to start working on the activities.

Part 1: Sustainable Meal Planning

In the first part of the activity, the children were divided into three groups of three and given a set of 40 food cards. Together, each group was tasked with selecting meals for a day—breakfast, lunch, and dinner—by choosing the appropriate food cards. After making their meal selections, the children flipped the cards over to learn how each food item is produced and how much CO_2 emissions are generated in the process. They then calculated the total CO_2 emissions for all the food they selected.

In the next step, the children gathered a corresponding number of black and brown blocks to represent the total CO_2 emissions and placed them on one side of a weighing scale. I explained that human activities have increased CO_2 levels in the Earth's atmosphere, creating an imbalance in the natural carbon cycle, and that our actions can help restore this balance. I then showed them an image of different actions that could help, each color-coded. The children chose their preferred actions and selected the matching-colored blocks to place on the other side of the scale, continuing until the scale was balanced or the action blocks outweighed the CO_2 blocks.

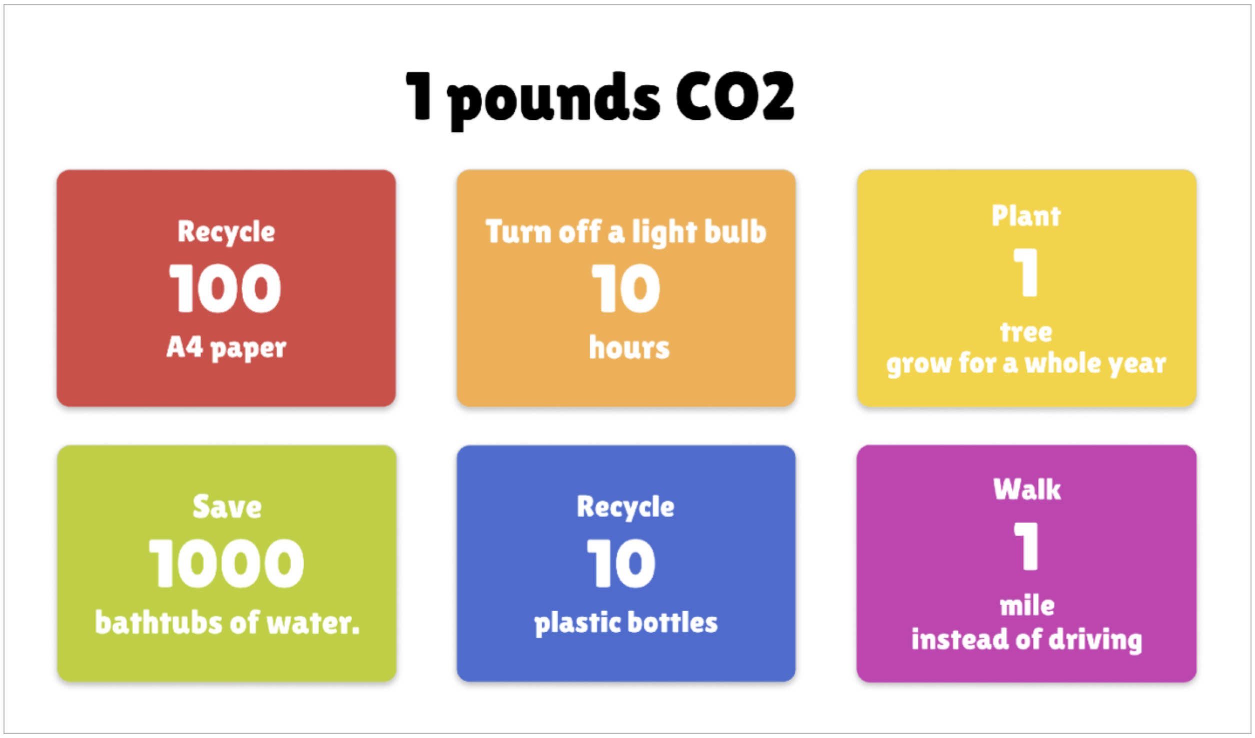

Figure 5: Color coded action statements for using action blocks in design session 1

My design activity draws from the research of Luehr and Smith (2012), which highlights the value of hands-on activities—like gardening, composting, and cooking—for student engagement in sustainability education. They assert that such interactive methods not only enhance engagement but also point to the importance of further research to maximize the effectiveness of these hands-on approaches in learning environments. Embracing this perspective, my methodology extends their research, applying their principles to my context as I explore data physicalization that can advance the methodologies of Education for Sustainable Development (ESD).

Incorporating the concept of carbon offsetting into sustainability education, particularly through activities focused on compensating for the carbon impact of meal choices, highlights the importance of a comprehensive approach to environmental conservation. Galatowitsch (2009), Hyams and Fawcett (2013) support this by stressing the need for rigorous methodologies in assessing carbon offsetting's impact and caution against its potential to serve as a mere alleviation of guilt rather than effectuating real change. By learning to compensate for the carbon footprint of their selected meals, participants gain insight into the broader spectrum of strategies for achieving sustainability goals, highlighting the necessity of not just reducing emissions but also taking actions to balance or offset emissions that cannot be avoided.

Part 2: Carbon Budgeting

For the second part of the activity, I structured it further by giving each group a carbon budget of 13 pounds. The focus shifted to selecting food cards that fit within this carbon budget while planning their meals. To make the activity more organized, I provided pre-printed sheets with placeholders for their selected food cards and a designated space for their CO_2 blocks. The process followed the same steps as in the first activity, but this time, there was a stronger emphasis on collaboration. As the children worked together, it became evident that each child preferred different foods and actions, often reflecting their personal lifestyles and cultural backgrounds.

Figure 6: Participants build meals with food cards and place carbon blocks

This approach was aimed to significantly enhance the depth of the children's involvement with the session's emphasis on sustainability, encouraging them to think critically about the environmental impact of their dietary choices. However, a major challenge emerged as some children began to treat the activity as a competitive game, aiming to select only the food cards with the lowest CO_2 emissions. This resulted in meals consisting mostly of fruits and vegetables, which some children admitted were not appetizing but chose in order to "win." This shift in focus from learning to competition prompted me to re-strategize for the second research session.

The design of the proposed activity is fundamentally inspired by the emerging emphasis on collaborative effort over individualism in addressing environmental sustainability challenges. This approach is grounded in the work of Ardoin et al. (2023), who highlight the critical role of shared responsibility and collective action in overcoming the complexities of climate change and environmental degradation. By engaging groups in planning a sustainable meal, the activity not only mirrors real-world scenarios requiring community cooperation but also aligns with the broader discourse on leveraging collective environmental literacy for a sustainable future.

Ardoin et al. (2023) argue that expanding the scale of engagement and focusing on shared responsibility among different actors at the systems level presents opportunities for a broader contribution to sustainability. This perspective is pivotal in framing sustainability as a shared responsibility, necessitating collective action to foster a sense of community and shared purpose. Furthermore, the emphasis on group-based tasks is designed to encourage participants to engage in meaningful discussions, share diverse perspectives, and collaboratively devise solutions, thereby fostering collective environmental literacy and stewardship. This aligns with the notion that addressing global environmental challenges requires not only the transformation of individual efforts but also a unified approach that inspires and enables communities to work together.

Reflection and Journaling

In the final part of the first session, each child was given a survey sheet to reflect on what they had learned from the activity. The survey included the following questions:

What did you learn today?

What would you like to learn more about?

Did you like or dislike the activity? Why?

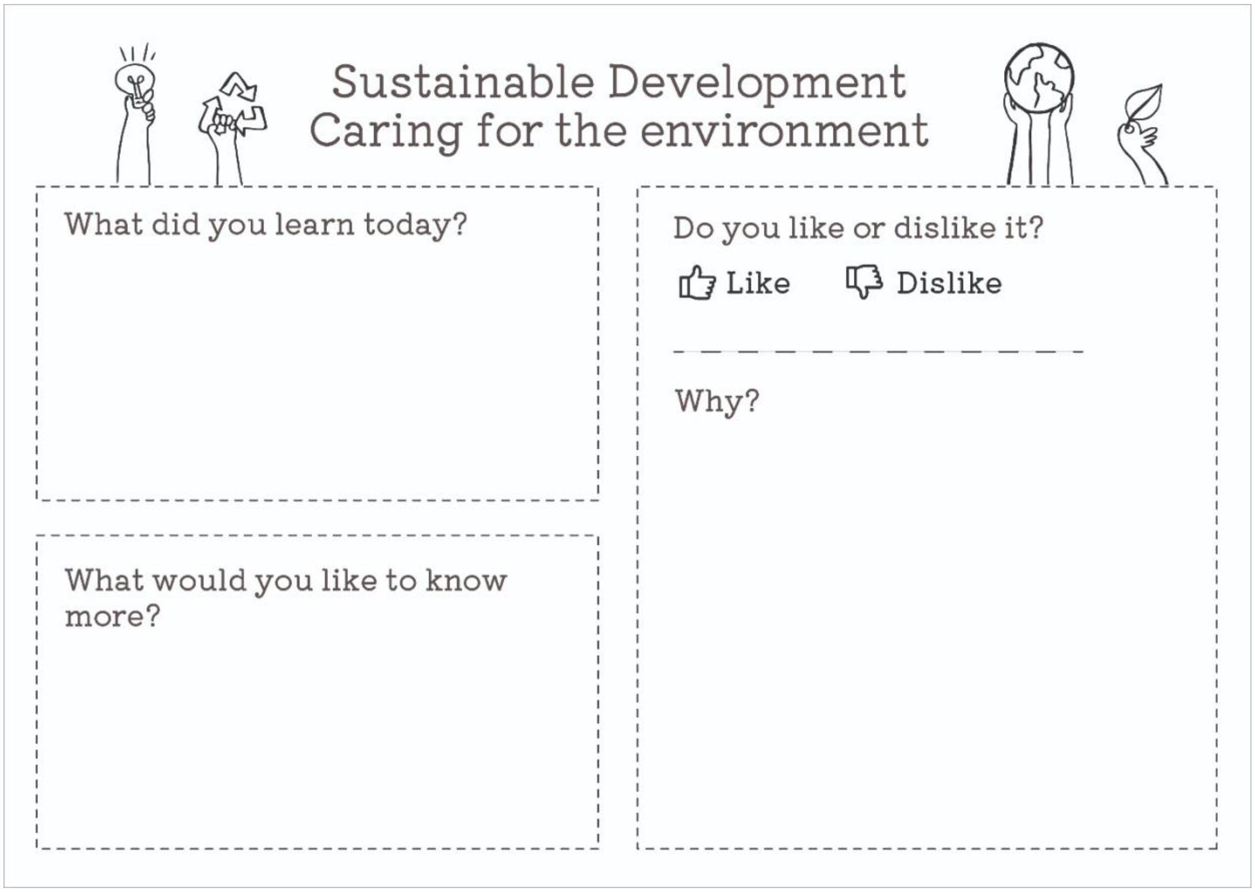

Figure 7: Post-session journaling and survey sheet

The entire session was voice recorded, and photographs, field notes, and post-session debrief notes were collected. These materials documented the children's behavior, their interactions with the food cards, blocks, and weighing scale, as well as their collaboration dynamics. Additionally, observations on their existing notions and knowledge about sustainability along with their rationale for their answers in the journaling activity for the above questions were noted for later data analysis.

3.4.2 Design Session 2

In the first design session, I employed color-coding alongside size to represent compensation activities, but this multi-variable approach proved cognitively demanding for young learners (Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, 2023). I simplified the design in the second iteration to focus primarily on size as the encoding variable for the wooden toolkits, where the size of blocks directly represents quantitative data. This aligns with research showing size to be "one of the most fundamental explicit variables for encoding data" (Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, 2023) and particularly effective for representing quantitative relationships in physical form.

Pre-Session Preparation

As with the first session, thorough preparation was key to ensuring a successful second session. This involved setting up all necessary materials, such as the toolkit with food cards, meal options, carbon emission blocks, action blocks and weighing balance. Additionally, color pencils and journals were prepared for individual reflection activities.

Circle Time: Reflection on Actions

The session began with 20 minutes of Circle Time, focusing on a recap of the first session's activities and outcomes. This was an opportunity to show pictures and discuss what was learned previously.

The Question of the Day,

" Since our last session, what is one thing you have noticed or done differently in your daily life to help take care of our Earth? "

was presented to stimulate reflection and discussion on the practical application of sustainability concepts. I used this as a tool to assess the children's behavior change and awareness since the first session, further shaping the direction of the day's activities. This part of the session was critical for creating a link between learning and real-world action.

Part 1: Meal Planning and Carbon Footprint Calculation

The first design activity expanded on the sustainability concepts introduced in the initial session, guiding participants through a 40-minute, hands-on meal planning task. Although the process was similar to the previous session, the tools used were different. I designed a wooden toolkit that provided a clearer understanding of CO_2 emissions, with larger blocks representing 1 pound of CO_2 and proportionally smaller blocks representing 0.1 pounds of CO_2. The action blocks were similarly designed, where larger blocks represented more impactful actions, such as turning off lights in an empty room for a day, while smaller blocks represented smaller actions, like using a reusable straw for a day.

To place greater emphasis on the learning experience of carbon offsetting and to eliminate the "game" aspect observed in the first session—where children focused on selecting the lowest-emission foods—I provided pre-printed meal sets. Each meal set contained six dishes, and the children were given eight meal sets to choose from. They were divided into two groups of three, with each group selecting one of the four meal sets assigned to them.

Set 5 **Grilled Steak slices** **Avocado slices** **Apple slices** **Grilled Corn** **Cheese cubes** **Water**	**Set 6** **Cucumber slices** **Tomato slices** **Baked Chicken** **Berries** **Milk** **Almonds**	**Set 1** **Cucumber slices** **Carrot sticks** **Grilled Mushrooms** **Berries** **Almonds** **Water**	**Set 2** **Scrambled/Boiled Egg** **Apple slices** **Grilled Pork slices** **Grilled Corn** **Bell pepper slices** **Milk**
Set 7 **Yogurt** **Roasted Bell pepper slices** **Grilled Eggplant** **Cheese cubes** **Carrot sticks** **Water**	**Set 8** **Baked Onion rings** **Chips** **Almonds** **Banana** **Tomato slices** **Water**	**Set 3** **Yogurt** **Chocolate** **Tomato slices** **Cheese cubes** **Banana** **Water**	**Set 4** **Roasted Eggplant** **Lightly Grilled Onion slices** **Fried Chicken** **Avocado slices** **Chips** **Water**

Figure 8: Pre-designed meal set options for each group

This time, I ensured that the children were more involved in calculating the CO_2 emissions themselves, unlike in the previous session where adults assisted with the decimal calculations. This approach aimed to increase their awareness of the numbers and help them better visualize the significance of offsetting emissions when placing the action blocks.

Figure 9: Participants balancing the carbon and action blocks on the balance scale

Part 2: Charting Carbon Emissions

In the second part of the activity, I provided large sheets of paper with pre-drawn X and Y axes and asked the children to map the CO_2 emissions of each dish against the corresponding actions they had taken. This was done to assess whether the children could understand and interpret the physicalized data when presented in a statistical chart, and if this approach could help them learn to read and comprehend graphs through data physicalization methods. This task encouraged collaboration and discussion among the children, allowing them to work together to place blocks on the chart. Through this process, they became more aware of the numbers associated with each food item and the actions they had chosen to offset the emissions, further reinforcing their understanding of the activity.

Part 3: Big Ideas discussion

After completing the charting activity, the children from each group participated in a focus group discussion. They were asked to reflect on the activity and explain their reasoning for selecting specific action blocks and their experience with mapping the blocks onto the graph. The following questions were asked:

What do the blocks represent on the chart?

In your meal options, which food item has the highest carbon number, and which has the lowest?

How did you decide which action blocks to use for each food's carbon emission?

Which action is your favorite to help the Earth, and why?

This discussion provided valuable insights into the children's cognitive abilities to understand sustainability concepts through data physicalization. It also revealed how this approach could help them learn to interpret graphs and comprehend data in a more accessible way. Each group shared their thoughts on how the blocks helped them better grasp sustainability concepts, particularly CO_2 emissions, and their impact.

Reflection and Journaling

The final activity involved giving each child a sheet of paper with a pre-printed question:

"Other ways to show this chart data?"

An empty box was provided for them to draw alternative visualizations they thought might better represent the data they had been working with. This task was designed to explore how children perceive data and to identify ways they might prefer to see it presented for easier understanding, as opposed to more complex charts, graphs, or infographics. This exercise aimed to gain insight into the children's preferences for visualizing data in simpler, more accessible formats.

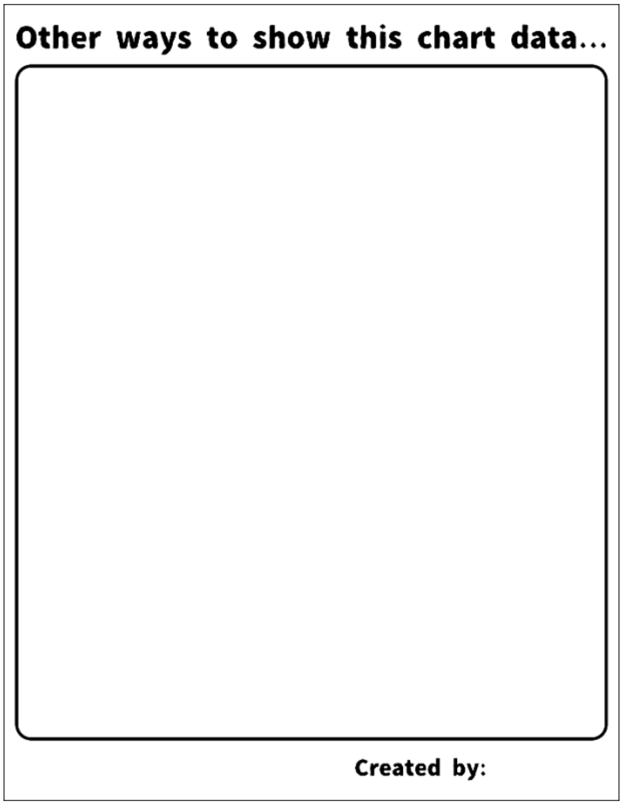

Figure 10: Brainstorming template for how children visualize data

This final activity was designed to consolidate the learning by encouraging participants to express their understanding through writing or drawing. The journaling process allowed for introspection, giving children the opportunity to reflect on how their perception of sustainability had evolved. It also provided a space for them to consider how they could apply the concepts learned to their everyday lives. This reflection period was crucial for reinforcing the key messages of the session, while also highlighting any shifts in the children’s attitudes or behaviors toward sustainable living.

3.5 Data Analysis

The thematic analysis evolved across two KidsTeam sessions, with distinct analytical phases for each session. In the first session, the analysis began with open coding of audio transcripts, reflection journals, and "Question of the Day" responses in NVivo 12. This initial line-by-line coding focused on identifying emerging concepts related to youth's understanding of sustainability and their learning experiences. The open codes were then developed into axial codes that revealed relationships between participants' verbal expressions of sustainability concepts and their learning processes.

Through axial coding in the first session, several key theoretical categories emerged. However, this initial analysis revealed a significant gap in understanding the physical and interactive dimensions of learning through data physicalization. While we could track participants' verbal and written expressions of understanding, we lacked detailed insights into how they physically engaged with data representations and how this interaction influenced their learning process.

Building on these insights, the second session's analysis used the established axial codes as a foundation while introducing new coding categories specifically focused on interaction and design elements. These new codes captured how participants physically engaged with data representations, their collaborative interactions around the physical data, and specific design features that supported or hindered learning.

The second session's enhanced coding framework, supported by video analysis, allowed me to address the previously identified gaps. I maintained the theoretical categories from the first session's axial coding while expanding our understanding of the physical and interactive dimensions of learning. This combined approach revealed how participants' conceptual understanding of sustainability (captured in the first session's coding) was supported and enhanced by their physical interaction with data representations (captured in the second session's additional codes).

This progressive analytical approach showed how the theoretical framework evolved from understanding basic learning processes to capturing the complex interplay between physical interaction, design elements, and sustainability learning. The second session's analysis particularly enriched our understanding of how data physicalization design features influenced learning outcomes, addressing our research questions about effective implementation in educational settings.

Chapter 4: Results

4.1 Design Session 1: Exploring Initial Interactions with Physical Data

The first design session aimed to introduce participants to sustainability concepts through direct interaction with physical data tools, including food cards, colored plastic carbon blocks, and a balance scale. The objective was to transform abstract environmental concepts into concrete, tangible experiences, enabling participants to examine the relationship between their food choices and corresponding carbon emissions. This session yielded valuable insights into the role of physical representations in facilitating environmental learning, while also identifying potential areas for refinement in future toolkit development.

4.1.1 Initial Engagement with Environmental Concept

From the Question of the Day, responses reflected a developing but meaningful understanding of sustainability. Several children mentioned recycling, while others highlighted issues such as pollution and plastic use. For example, one participant noted, "*I help the Earth by not throwing the wrong things in the recycle and trash bin,*" while another pointed out, "*We hurt the Earth by killing insects.*" These responses indicate that children are aware of both individual actions and broader environmental impacts. Notably, some participants touched on larger societal issues, such as one response mentioning "*hurting the Earth by sending nuclear bombs and having wars*," reflecting an awareness of global-scale environmental challenges. This variability in responses underscores the diversity in the children’s current understanding of sustainability education literacy among children aged 7 to 12.

When first introduced to the data physicalization tools, children displayed immediate curiosity and eagerness to engage with the physical representations. "*Where's the yogurt?*" asked one participant, while another excitedly suggested, *"What if we put yogurt and berries and make a parfait?*" These initial questions revealed how the tangible nature of the tools invited immediate interaction and exploration. Unlike traditional learning materials, the physical cards and blocks prompted children to reach out, touch, and begin manipulating the data before any formal instruction was given.

Initial assessments indicated clear differences in understanding across age groups. Younger children (ages 7-9) often concentrated on simple, concrete actions, such as recycling and avoiding littering. One participant mentioned, "*We hurt the Earth by littering and throwing plastic bags in the ocean,*" reflecting a focus on visible, immediate environmental issues. Older participants (ages 10-12), in contrast, demonstrated a broader perspective, recognizing systemic issues like fossil fuels and the impact of consumer choices. For example, one participant highlighted, "*I hurt the earth by playing video games*" indicating an awareness of the environmental impact of energy-intensive activities. These observations suggest that older children are better able to conceptualize the complex, interconnected nature of environmental sustainability, emphasizing the need for age-appropriate instructional strategies that cater to different developmental stages.

4.1.2 Meal Planning and Carbon Discovery

In the initial stage of Design Session 1, participants were tasked with creating a meal plan, an activity that focused primarily on personal preferences without consideration of environmental impact. The children were enthusiastic about crafting elaborate, restaurant-style meals, selecting items like yogurt, berries, and apple to create dishes that appealed to their tastes.

Figure 11: Children create their own meal plans

This enthusiasm shifted when participants were prompted to flip their food cards to reveal the associated carbon emissions. The children were visibly surprised by the numbers displayed. *"I didn't know making food produces so much CO2,"* one participant exclaimed, reflecting a newfound awareness of the environmental consequences of their meal choices. The revelation that foods like meat or chocolate had significantly higher carbon footprints led to expressions of disbelief and discomfort, shifting their focus from taste to the impact of their choices.

The task of calculating the total carbon emissions of their selected meals presented further challenges. Younger participants, in particular, found it difficult to add up multiple emission values, which quickly became cumbersome. One participant expressed frustration: *"Can you please help me add all the numbers?"* This difficulty underscored the cognitive challenge inherent in quantifying carbon emissions for young learners and highlighted a need for simplified tools or clearer guidance in the calculation process.

The children were then tasked with balancing the scale using action blocks, each representing an effort to offset carbon emissions. The magnitude of the actions required to balance their meal's carbon emissions was surprising to many. One participant, after adding multiple action blocks, remarked, "*It takes so many actions just to balance one meal!*" This realization prompted a deeper understanding of the relationship between individual food choices and the considerable effort required to mitigate their environmental impact.

They moved from an initial focus on meal aesthetics to an awareness of the environmental costs associated with their food choices. The physical interaction with the carbon blocks and balance scale served as a powerful tool in helping them internalize the scale and implications of their actions.

4.1.3 Carbon Budget Management

During the design session, participants were split to 3 groups of 3 and introduced to the concept of a carbon budget, specifically a 20-pound carbon limit, and were tasked with planning meals that adhered to this constraint. The goal was to encourage strategic decision-making, as participants had to balance their preferences for food variety with the necessity of staying under the carbon limit. The activity revealed varying approaches, showcasing both collaboration and competition among the children.

One of the group adopted a unique strategy to meet the carbon constraint by distributing the responsibility for different meals to each of them. Each participant took charge of planning a specific meal—breakfast, lunch, or dinner—thereby spreading out the carbon emissions across all three meals rather than focusing solely on one. This strategic approach allowed them to evaluate each meal individually and identify opportunities to reduce carbon output while maintaining a balanced diet. One participant noted, *"If I take a low-carbon breakfast, then we have more allowance for dinner,"* illustrating a clear understanding of cumulative impact and strategic allocation.

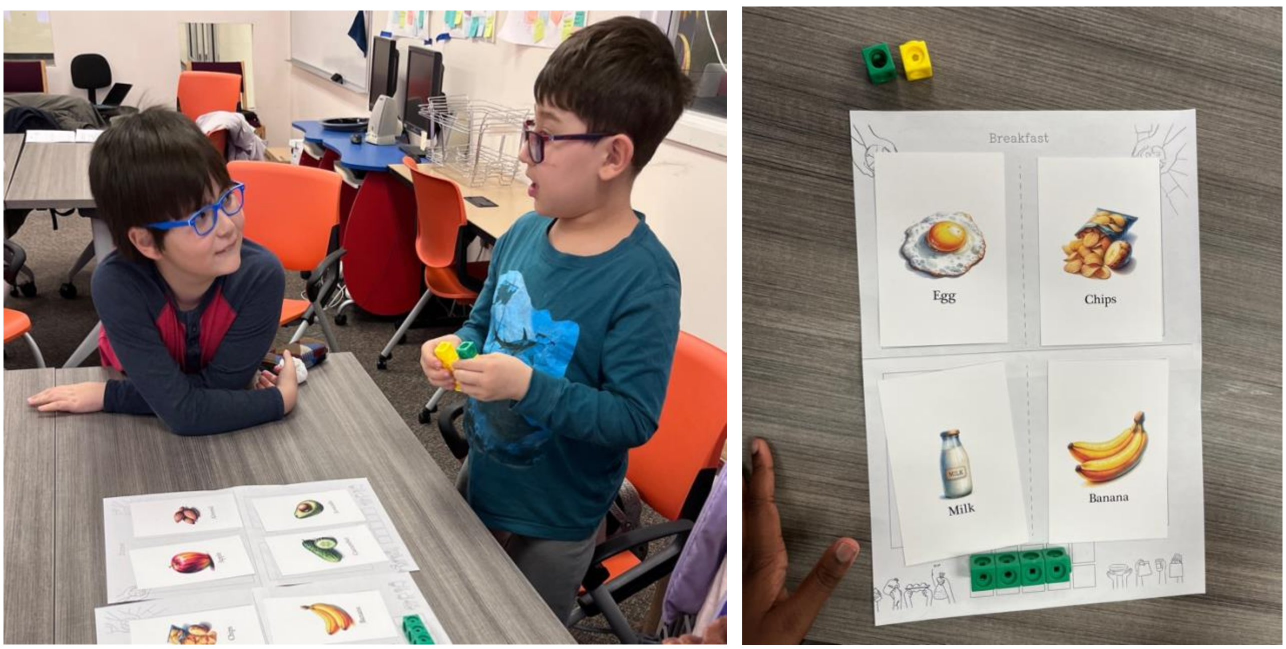

Figure 12: Team collaboration for making meals with a carbon budget

Throughout the session, both competition and collaboration were observed as groups worked towards staying within the carbon budget. In some cases, collaboration emerged naturally as participants pooled their knowledge and worked together to achieve a common goal. One participant asked, "*Do we all agree to do this?"* while discussing meal options, suggesting a cooperative spirit in decision-making. Conversely, there were moments of competition where participants compared their carbon outputs, attempting to outdo each other in achieving the lowest possible total. This competitive element encouraged participants to critically assess their choices, leading some to make bolder decisions to minimize their emissions, such as entirely removing high-carbon foods from their meals.

The process of balancing personal preferences with environmental impact was a core challenge during the activity. Participants had to confront the fact that many of their preferred foods, such as chocolate and meat, carried a high carbon cost. This led to considerable debate within groups, particularly when certain individuals were reluctant to forgo their favorite items. One participant remarked, *"I really want the chocolate, but it makes the carbon go too high,"* highlighting the tension between desire and responsibility. Ultimately, many groups demonstrated a willingness to compromise, opting for lower-emission foods in favor of meeting their carbon goals. This balancing act illustrated the children's developing capacity to weigh short-term desires against long-term sustainability, marking an important step in their understanding of environmental stewardship.

4.1.4 Journaling Activity

The journal entries revealed a deepening understanding among participants about how everyday choices impact the environment. To help them articulate their feelings, we used a line-judging exercise, prompting reflections on their enjoyment or dislike of the activity. Among the nine participants, one expressed a neutral stance due to a lack of optimism about the future, while another conveyed a dislike, viewing the activity as merely a game and expressing no intention to engage in it again.

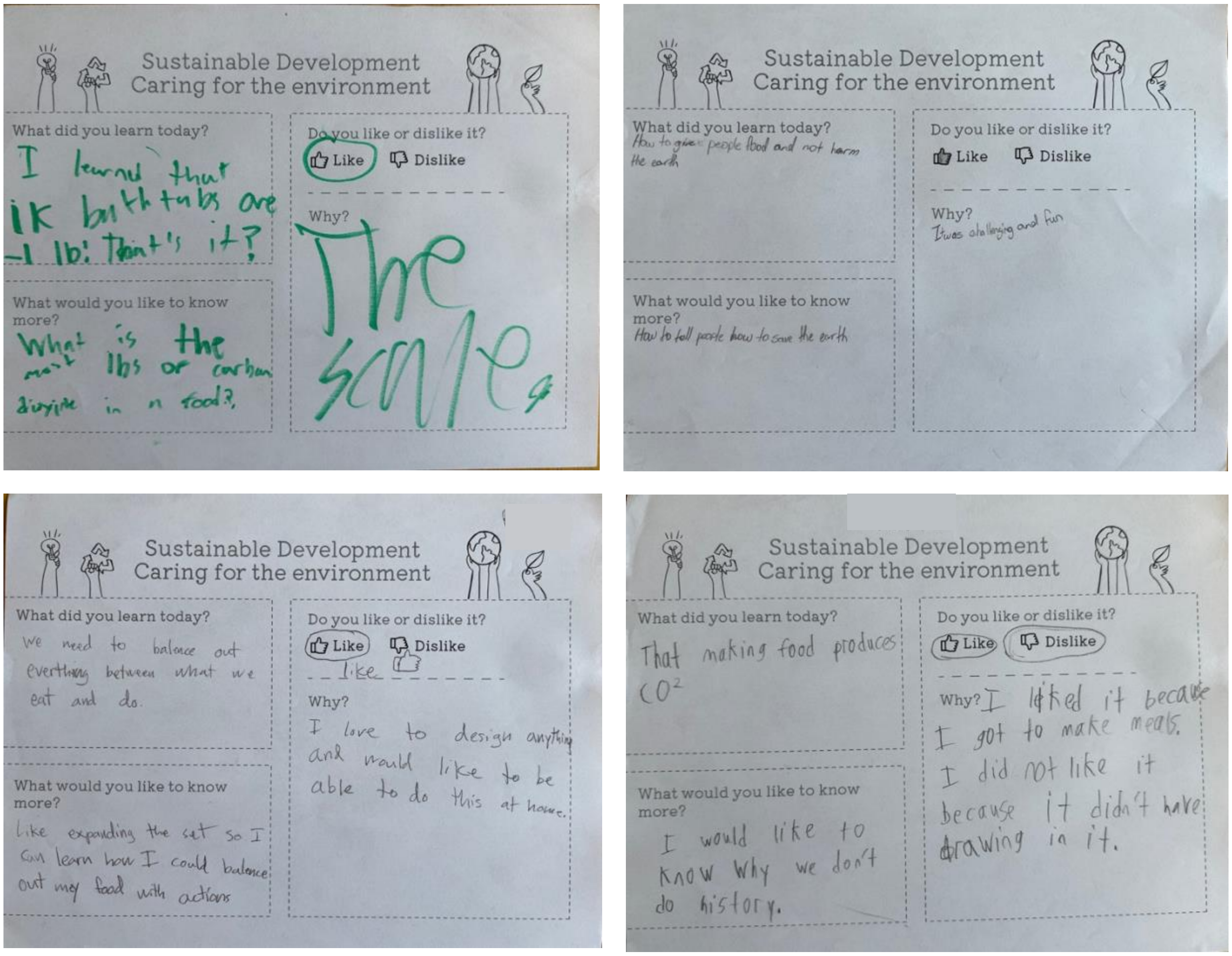

Figure 13: Journaling their reflections after session 1 design activity

In the reflections, some participants demonstrated a budding awareness of carbon emissions associated with various foods. one participant wrote, "*I learned that different foods have different CO_2 waste*," indicating an emerging awareness of the variability in carbon emissions associated with food items. This reflection demonstrated that children were beginning to grasp the concept that not all foods have the same environmental impact, suggesting that the hands-on activities effectively facilitated their understanding of abstract concepts.

The reflections also highlighted specific moments of realization that occurred during the session. One participant noted, "*I didn't know that eating meat makes so much CO2,*" showing surprise at the environmental cost of common dietary choices. Another participant shared, "*I learned that saving 1K bathtub of water will only save 1 pound of CO2, that's it?*" reflecting a broadening of their understanding of sustainability beyond conventional practices. These examples underscore how the activities helped children connect their daily habits to broader environmental consequences.

The journaling activity also provided insights into the questions and curiosities that emerged among participants. Several children expressed interest in understanding how they could further reduce their carbon footprint, with one asking, "*Can I take the cards home? I would like to know the carbon emission of the food I eat every day*." This curiosity suggests that the activities were successful in engaging the children's interest and motivating them to explore additional sustainable actions. Another participant wondered, "*If I have a food I like, but it turns out to have a lot of carbon emission, then should I not eat anything?*" revealing an evolving curiosity about the pervasiveness of carbon emissions and a desire to understand the broader implications of their behavior.

Emotional responses captured in the journals provided further insight into the impact of the activities. Many participants expressed feelings of concern or responsibility after realizing the environmental effects of their actions. One child wrote, "*How to give people food and not harm the earth*" which highlights a positive emotional response and a readiness to take action. These reflections suggest that the journaling activity not only facilitated cognitive learning but also fostered an emotional engagement with sustainability concepts, which is crucial for lasting behavior change.

4.1.5 Challenges

The design session revealed several challenges that impacted the learning experience, including difficulties with mathematical calculations, issues with the physical tools, and group dynamic challenges. These challenges offered valuable insights into areas where improvements could enhance participants' engagement and understanding of sustainability concepts.

One of the main challenges participants faced was related to the mathematical calculations required to determine the total carbon emissions of their meals. Many children found it challenging to add multiple emission values together, especially when the numbers grew larger. As one participant voiced, "*I don't know how to add the dot numbers*" This reliance on adult assistance highlighted the difficulty children had in independently managing the arithmetic involved in quantifying carbon footprints, suggesting that simplifying these calculations or providing more accessible tools could be beneficial.

The use of same-sized blocks differentiated by color to represent different levels of carbon emissions or actions proved confusing for several participants. The blocks' identical sizes made it difficult for children to quickly discern the differences in their meaning, leading to errors in data representation. One participant expressed frustration, noting, "*I want to use pink color for carbon blocks because it is my favorite color*." This feedback suggests that clearer physical differentiation, such as varying block sizes or adding labels, could improve usability and help participants better understand the relationships between different actions and their carbon impact.

Group dynamics presented another challenge, particularly in situations where collaboration was essential for success. Some participants struggled to work together effectively, with conflicts arising over meal choices or the allocation of carbon budget allowances. In one instance, a participant remarked, "*Why do I always have to give up my favorite food?*" , while another group conversation added "*Your meal is not appetizing, who eats chocolate with bell pepper?"* which highlighted a lack of consensus within the group, leading to frustration. These dynamics sometimes hindered the learning process, as group members became more focused on personal preferences rather than the collective goal of minimizing carbon emissions. Improved facilitation strategies that emphasize collaboration and shared responsibility could help mitigate these challenges.

While competition initially spurred participants to critically think about reducing carbon emissions, it also led some groups to focus on "gaming" the activity, attempting to achieve the lowest carbon footprint at any cost. One participant declared, "If we just put the lowest carbon foods, we can win!"—a statement that revealed a shift in focus from meaningful engagement with the environmental concepts to simply winning the task. This competitive mindset detracted from the intended learning objectives, indicating the need for a balance between encouraging healthy competition and maintaining focus on the underlying educational goals of environmental responsibility and awareness.

Furthermore, children struggled with understanding the perception of higher or lower values. After calculating the total carbon emissions, some participants mistakenly believed that having the highest number meant winning the activity. One child commented, "*We got the most carbon, so we win!*" to which an elder kid replied, *"No wait, I am confused, so do we have get a lowest number or highest?"* It later had to be explained that the objective was not to achieve the highest value, but rather to minimize carbon emissions, as a lower total required fewer actions to offset. This confusion emphasized the need for clearer instructions and guidance to help children understand the purpose of minimizing emissions rather than viewing it as a competition for the highest score.

4.1.6 First Session Learning Outcomes

The first design session provided insights into the evolution of children's understanding of sustainability through data physicalization. Several changes in environmental awareness and strategic thinking were noted, alongside areas for toolkit improvement and successful engagement strategies.

Initially, the children had a limited understanding of sustainability, primarily centered around recycling. However, by the end of the session, many participants demonstrated a broader awareness of the environmental impact of their dietary choices. The carbon budget activity played a key role in fostering strategic thinking, as participants managed a 13-pound carbon limit. This task encouraged them to think ahead and distribute resources effectively, showing their developing capacity for thoughtful planning. Participants transitioned from selecting foods based solely on preference to considering the associated carbon emissions, which reflected a growing ability to make environmentally informed decisions.

The session employed several engagement strategies that were effective in enhancing participants' learning. Hands-on interactions with the balance scale and carbon blocks allowed children to visualize the impact of their choices, promoting a deeper connection to the concepts being taught. The balance between collaborative tasks and competitive elements helped sustain motivation throughout the activities. However, the competitive aspects require careful moderation to ensure that the focus remains on meaningful engagement rather than merely winning. There is also a need to shift the perception of the experience from a game to a structured challenge that encourages genuine learning and reduces behaviors aimed at just achieving the lowest carbon number.

The session also highlighted several challenges, particularly with the toolkit design. The use of same-sized blocks differentiated only by color caused confusion among participants. Introducing labels or varying block sizes could enhance clarity and improve participants’ understanding of the relationships between actions and their carbon impact. Additionally, simplifying the process of carbon calculations could foster greater independence among the children, reducing their reliance on adult assistance.

Overall, the first design session effectively expanded participants' understanding of sustainability concepts and promoted strategic thinking through data physicalization. Hands-on interactions and a blend of collaboration and competition supported engagement. However, improvements are needed in toolkit design to enhance clarity and independence, and competitive aspects should be moderated to maintain focus on meaningful learning outcomes.

4.2 Design Session 2: Deepening Understanding Through Enhanced Tools

4.2.1 Behavioral Changes Between Sessions

The second design session began with an analysis of the behavioral changes observed among participants following the first session. This analysis was conducted through responses to a follow-up Question of the Day, which focused on the environmental actions children had undertaken at home.

Several children demonstrated a growing commitment to sustainability, citing specific behaviors. One child mentioned, "*I don’t use electricity that much*" reflecting a heightened awareness of energy conservation. Another participant shared, "*I don’t use plastic bottles*" indicating a shift in daily habits inspired by the previous session’s focus on carbon emissions and waste reduction. These reflections highlighted an increased sense of responsibility and application of learned concepts in real-life settings.

The reported behavioral changes extended beyond individual efforts and included activities involving family members. For instance, one participant shared their family sort cardboard at home and reused it, noting, "*I now recycle by playing with trash at home*" These examples show that the impact of the session was not limited to the participants themselves but also influenced their families, suggesting the potential for a ripple effect in promoting environmentally conscious behaviors.

The influence of peer interaction on environmental action recall was also evident in the responses. During discussions, some children admitted, "*I didn't do anything*," but their peers provided examples and reminded them of everyday instances. In response, one child said, "*Yes, I remembered, I close the running tap when brushing my teeth."* This demonstrates how peer support and interaction played a critical role in reinforcing environmental actions learned during the session. Additionally, when one participant mentioned reusing plastic bottles for a school project, others were inspired to recall their own actions, creating a positive feedback loop that promoted shared learning and mutual encouragement. These peer influences underscore the importance of collaborative learning environments in sustaining behavioral changes beyond structured sessions.

4.2.2 Interaction with Improved Wooden Toolkits

The introduction of an improved version of the toolkit, featuring size-differentiated and textured wooden blocks that represented varying levels of carbon emissions and compensatory actions. The improved toolkit aimed to address the challenges identified in the first session, particularly those related to the confusion caused by same-sized blocks and the lack of effective visual differentiation. The toolkit included blocks with different textures: carbon blocks had a natural wooden texture, while action blocks featured a smooth, glossy finish. These textural differences further helped participants distinguish between the types of blocks, enhancing their understanding and interaction with the toolkit. The introduction of these enhanced signifiers provided valuable insights into how physical design improvements could impact children's understanding and interactions.

Another significant change in the second session was the use of pre-prepared meal options. Unlike the first session, where participants had complete freedom to create meals from individual food items, this time participants were given four prepared meal options to choose from. This approach eliminated the "gaming" aspect observed previously, where children attempted to optimize their meals solely to minimize carbon emissions without considering the learning objectives. Although the freedom to create a meal was removed, participants still engaged actively with the toolkit, as they interacted with food cards based on their chosen meal option. This ensured that children remained focused on understanding the environmental impact rather than merely trying to "win" the activity.

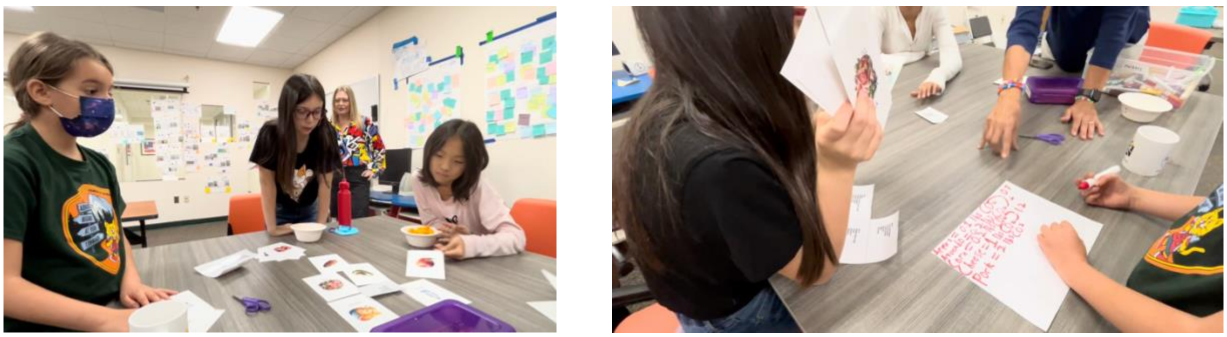

Figure 14: Calculating total carbon emission of their chosen meal plan

The children’s responses to the new size-differentiated and textured blocks were markedly positive. Many participants expressed that the improved blocks made it easier to understand the differences between actions. One participant commented, *"The bigger block means more carbon"* indicating that the different block sizes and textures effectively communicated the relative impact of actions. This differentiation helped participants more easily grasp the concept of proportionality in emissions and compensatory efforts, thereby reducing the confusion seen in the first session.

The improved toolkit appeared to encourage more independent calculation attempts compared to the first session. Children showed greater confidence in managing the carbon data, with several participants attempting to calculate and balance emissions without adult assistance. One child remarked, "*I think we need two more small blocks to balance this*," demonstrating an increased level of comfort with both the numerical and proportional aspects of the task. Also, for children who struggled with the calculation, we observed that they utilized the size of the blocks to aid in comparison and calculation. For instance, they would stack blocks with values like 0.2 lbs and 0.3 lbs, combining two of each to make a whole unit to compare with 1 lbs. This approach showed that the children were intuitively finding ways to offset CO2 with the smallest possible actions, creatively using the physical properties of the blocks to achieve balance. The improved clarity provided by the size-differentiated blocks, distinct textures, and numerical labels (e.g., 0.1 lbs, 0.3 lbs, 0.5 lbs) likely contributed to this boost in confidence, allowing participants to visualize and better comprehend the relationships between emissions and compensatory actions without adult's assistance.

Additionally, the children's interactions with the blocks demonstrated their growing interest, as they continually explored the labels on each block and compared the actions associated with blocks of the same size. Some of them also gathered blocks of identical size to examine and understand the various actions written on them.

Figure 15: Excited interaction with blocks and balance scale

4.2.3 Data Physicalization and Interpretation

The activities that focused on participants' ability to read and interpret charts created through data physicalization. The children worked with physical blocks to create charts, which allowed them to visualize carbon emissions and compensatory actions in a tangible way. This session offered valuable insights into how participants interacted with these visual representations and the challenges they faced in interpreting them.

The activity required participants to place blocks onto a chart to represent their meal's total carbon emissions and their compensatory actions. This physical placement helped some children better grasp the comparative nature of the data. For instance, one participant carefully lined up the blocks and said, *"This row shows all the carbon, and these shows what we did to fix it."* Such examples illustrated that the act of physically placing blocks allowed for a clearer comparison of emissions and actions, aiding in the understanding of balance and proportionality. However, the process also revealed the limitations of physical data in portraying complex information, as many participants struggled to align blocks precisely or correctly interpret the differences between the rows.

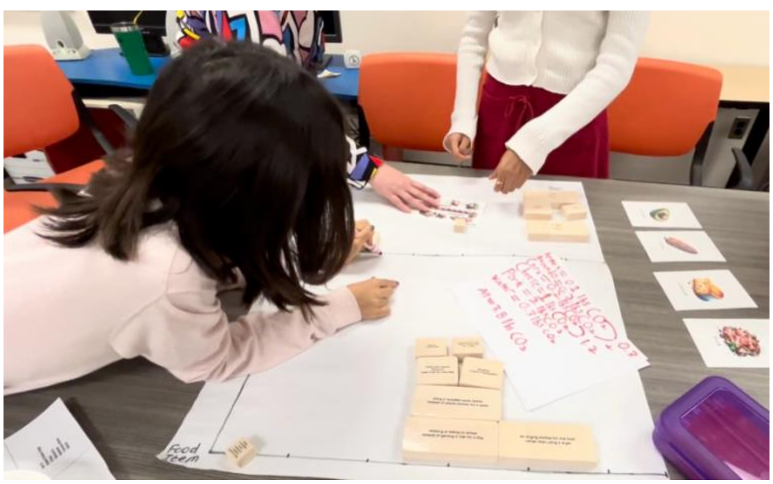

Figure 16: Representing food meal's Carbon emissions and actions on a chart

Participants were tasked with arranging blocks to form charts that represented different carbon footprints associated with various meal choices. For many of the older participants, understanding the chart's overall meaning came relatively easily, as they could connect the visual representation with the numerical data. One child commented, *"More blocks means more carbon in that food—it's like a bar chart."* This ability to make connections between physical and abstract data demonstrated the potential of data physicalization to bridge conceptual gaps, especially for visual learners.

Figure 17: Charts prepared by children based on their meal data

However, despite the progress made in understanding data visualization, challenges with interpreting the X-axis and Y-axis concepts persisted. Some children struggled to grasp the idea of mapping quantities to an axis, with younger participants in particular showing signs of confusion. One child asked, "Which side is for what?" when trying to place blocks on the chart, indicating difficulty in differentiating between the axes. This confusion highlighted an ongoing challenge in helping children understand foundational elements of data representation, suggesting the need for more explicit instructions or visual cues to clarify axis roles.

Age-related differences in comprehension became evident during the data physicalization activities. Older children, typically aged 10-12, were more adept at interpreting the charts and understanding the relationship between carbon emissions and compensatory actions. They demonstrated a higher level of abstraction, with one child remarking, *"If I have fewer blocks here, that means we need fewer actions over there,"* showing their ability to reason about proportionality. Younger participants (ages 7-9), on the other hand, were more likely to view the blocks as individual items without fully understanding the comparative nature of the representation. One younger child expressed confusion, stating, *"I dont know why we need to do this"* These observations indicate that additional support may be required for younger participants to fully understand the abstract concepts being represented, such as negative impacts versus positive actions.

Overall, the use of physical blocks to create charts provided an effective means for most participants to visualize and interact with carbon data. However, challenges related to understanding foundational charting concepts, such as the role of the X and Y axes, and age-specific comprehension limitations, highlighted areas where additional scaffolding could improve the learning experience. Providing further instructions tailored to different age groups could help bridge these gaps and enhance children's ability to interpret environmental data effectively.

4.2.4 Big Ideas

Post activity we conducted focused discussions to deepen participants' understanding of the broader environmental concepts explored through the activities. These discussions centered around children’s reasoning behind their choices and their interpretations of the physical block representations, revealing the emergence of "big ideas" about sustainability and their personal connection to environmental actions.

Many children showed significant growth in understanding, articulating connections between the activity and real-world implications. One participant noted, *"I can tell which food has highest and lowest and what actions to take"* indicating the ability to read the graph they prepared. The focused discussion helped to reinforce key concepts, with participants often referring back to their experiences placing blocks on the chart as evidence for their answers.

The children’s understanding of the block representations, including the carbon and action blocks, became a key focus. Several participants articulated their interpretations of what the blocks represented in broader terms. For instance, one child explained, *"The big blocks are like big actions we can do, like planting a lot of trees,"* while another participant reflected, *"The smaller blocks are the little things we can do every day, like turning off lights."* These responses illustrated that the physicality of the blocks made abstract environmental concepts tangible, allowing participants to relate the blocks directly to both large-scale and everyday actions. This understanding demonstrated how the physical toolkit could effectively bridge the gap between data representation and conceptual comprehension.

Participants provided diverse rationales for their action block choices, reflecting their evolving strategic thinking about environmental actions. When asked, *"How did you figure out which action blocks to use for each food's carbon emission?"* Two distinct approaches to using the action blocks for carbon compensation emerged during the session: the "Overcompensation" and the "Minimal Compliance" strategies. The "Overcompensation" group consistently chose the largest available action blocks, aiming to achieve significant reductions quickly. One participant explained, *"I want to make a bigger difference,"* highlighting an inclination towards impactful and decisive actions. This strategy indicated an enthusiasm for exceeding expectations, though it sometimes led to overuse of resources without fully considering the efficiency of the compensation process.

Conversely, the "Minimal Compliance" group selected multiple smaller blocks, choosing to meet the exact requirement with precise effort. A participant from this group stated, *"I think lots of small actions add up to something bigger and they are easier to do"* This approach reflected a nuanced understanding of cumulative impact and a desire to efficiently balance emissions while maintaining a steady, manageable pace. The contrast between these two strategies underscored different interpretations of environmental responsibility and the perceived effectiveness of actions.

The discussion also provided insights into participants' favorite environmental actions and their reasons behind these preferences. One child expressed enthusiasm for reducing plastic use, stating, *"I like not using plastic bags because it's easy to do and helps the ocean,"* indicating a preference for actions that are both achievable and directly impactful. Another participant mentioned, *"Planting trees is my favorite because it helps with the oxygen,"* highlighting an understanding of how larger actions can address environmental issues on a broad scale. These preferences revealed that children were beginning to see the direct impact of their actions on specific environmental outcomes, which fostered a deeper emotional connection to sustainability.

4.2.5 Journaling

The journaling activity in the second session offered participants an opportunity to reflect on their learning experiences, share creative approaches to data visualization, and express how their understanding of environmental concepts had progressed. Through these reflections, children articulated both their challenges and inventive ways to better represent the data they worked with.

The journaling activity revealed that only two of the older participants were able to effectively create their own charts, such as bar graphs, to represent carbon emissions and compensatory actions. One of these participants noted, *"I like numbers, so I added up everything,"* demonstrating an approach focused on numerical data representation. Another participant drew a traditional weighing balance to illustrate the concept of balancing emissions with actions.

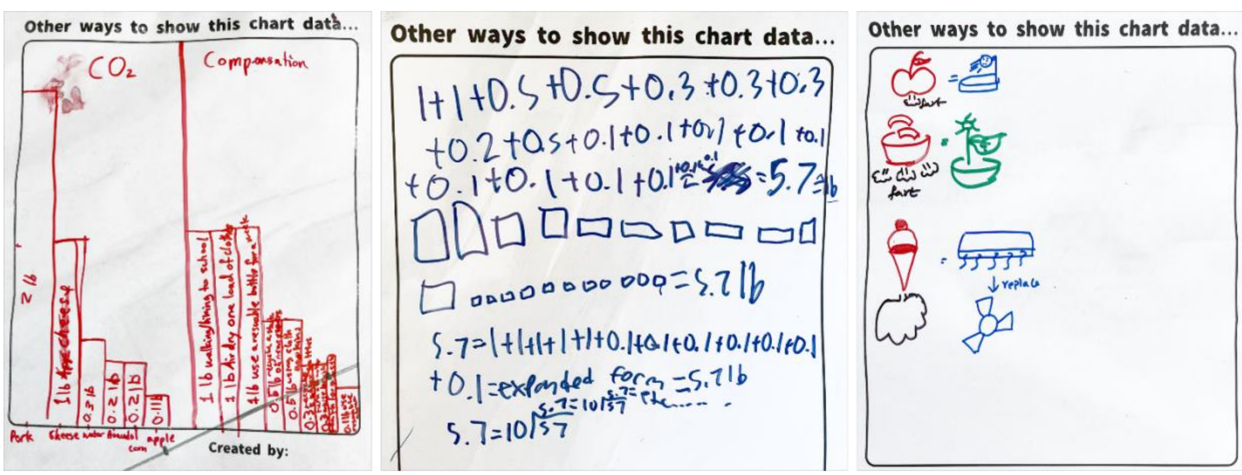

Figure 18: Data interpretation of CO_2 emissions and compensation

However, most of the younger participants found the activity challenging. One child drew a circle to represent different foods and included carbon emissions for each but expressed confusion on how to represent compensatory actions accurately and simply stated, *"I like to draw, so I drew food,"*. The youngest participants struggled significantly, with expressing, *"I don't understand what to do,"* indicating a lack of comprehension of the activity's objective.

Despite these challenges, the activity provided valuable insights into each child's preferred method of engagement—whether numerical, visual, or more abstract. The journaling activity showed that while older participants began to make sense of the data through structured visualizations and arithmetic, younger participants faced more significant challenges in representing abstract concepts effectively. These reflections underscored the need for differentiated support based on age and familiarity with the concepts, as well as the importance of providing multiple ways to engage with complex information.

4.2.6 Second Session Learning Outcome

The second design session revealed substantial growth in participants' understanding of sustainability, improvements in their data literacy, and valuable insights into the effectiveness of the enhanced toolkit. This session built upon the foundation laid during the first session and demonstrated tangible progress in how participants approached and internalized environmental concepts.

Throughout the second session, participants demonstrated notable advancements in their comprehension of sustainability. The introduction of improved data physicalization tools helped facilitate these developments. Compared to the first session, participants were more engaged in balancing carbon emissions against compensatory actions and exhibited greater confidence in using the toolkit. Older children were particularly effective in using the enhanced blocks and charts to make more informed choices about how to offset emissions.

The session also documented enhanced environmental awareness among participants. Children began to articulate a deeper connection between their everyday actions and their environmental impact. For instance, multiple participants reflected on their growing awareness of how simple actions—such as reducing plastic use or turning off lights—could contribute to overall sustainability. This enhanced awareness was further reflected in their responses to the Question of the Day, where children spoke about implementing more sustainable practices at home and influencing family behavior demonstrating a personal commitment to extending their learning beyond the classroom.

The progression in data literacy was mixed but generally positive. I observed children's ability to represent and interpret data when provided with guided, instructional support. With structured guidance, children were able to read data on charts, interpret relationships between different data points, and in some cases, even read between and beyond the data presented. Younger participants, however, still faced challenges in understanding the abstract concepts behind data representation. Some of the youngest participants expressed difficulty in understanding how to visualize the data independently. Despite these challenges, there were instances of collaboration where older children supported the younger ones, fostering a peer-learning environment that helped bridge the gap in understanding. This inter-age collaboration was crucial for helping younger children make sense of the numerical and proportional aspects of carbon emissions.

The effectiveness of the enhanced toolkit was evident in how participants interacted with the new features, such as the size-differentiated and textured blocks labeled with numerical values. The added numbers on the blocks made calculations more accessible, especially when conducted in groups where older participants could assist younger ones with the decimals. This improved accessibility helped maintain engagement across different age groups, allowing participants to work more independently while still relying on collaborative problem-solving. Furthermore, the differentiated textures—smooth for action blocks and natural wooden texture for carbon blocks—enhanced tactile differentiation, reducing confusion between the types of blocks. These improvements contributed to a more intuitive learning experience.

Chapter 5: Discussion

5.1 Balancing Developmental Appropriateness with Scientific Accuracy

Age-appropriate information design emerged as a crucial consideration in the development process. Environmental science education requires careful attention to cognitive developmental stages and appropriate content delivery methods. The challenge lies in maintaining scientific accuracy while ensuring the material remains accessible to young learners. This approach aligns with how "constructive visualizations use simple physical building blocks to democratize making of data representations" (Dumičić, Thoring, Klöckner, & Joost, 2022).

The guidance methodology in environmental education must carefully navigate between scientific precision and cognitive accessibility. The language used to guide learners through these concepts requires particular attention, as it must simultaneously maintain scientific accuracy and remain comprehensible to the target age group. This consideration extends beyond mere vocabulary selection to encompass the entire framework of how environmental concepts are presented and explained. This relates to how "materials communicate, and 'talk' to the creator, indicating how they can be shaped, understood, and interacted with" (Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, 2023).

The research suggests that effective environmental science visualization for young learners depends heavily on the successful integration of concrete representations with abstract concepts. The selection of specific representational forms, such as woodblocks for carbon visualization, must be grounded in both pedagogical theory and practical educational considerations. This builds on how physicalization have been successfully "employed in group educational settings" and can "assist novices" in understanding complex concepts (Dumičić, Thoring, Klöckner, & Joost, 2022). This approach ensures that learning materials effectively bridge the gap between abstract environmental concepts and children's cognitive capabilities while maintaining scientific integrity.

5.2 Design Considerations

5.2.1 Physical Forms for Environmental Data Representation

The visualization of abstract environmental concepts, particularly those lacking definitive physical forms such as carbon dioxide and related climate phenomena, presents significant methodological challenges in educational design. Through this research, the selection of specific representational forms emerged as a critical consideration in developing effective educational materials for environmental science education. This aligns with data physicalization goal of providing "a platform both for a historical overview as well as future exploration of physical data visualizations" (Dumičić, Thoring, Klöckner, & Joost, 2022).

The decision to employ woodblock representations for carbon visualization stems from the fundamental need to make abstract quantities concrete and comprehensible for young learners. This approach is supported by research showing that "making of three-dimensional data artifacts is especially suited for introducing non-experts to data" (Bhargava & D'Ignazio, 2017). The tangible nature of woodblocks provides a clear mechanism for demonstrating environmental imbalances, allowing learners to physically manipulate and understand quantitative relationships that might otherwise remain abstract. This physical interaction benefit is supported by research showing that "the ability to touch 'data' can support cognitive tasks, improve memory of information, generate 'haptic memory'—in particular for extreme items—and result in higher efficiency in retrieving information" (Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, 2023).

5.2.2 Refining Data Physicalization Elements

In the first session, color-coding was tested as a method to denote distinct compensation activities, considering young children's attraction to vibrant colors. However, this approach proved too cognitively demanding for young learners, aligning with findings that while color can be used to encode data (Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, 2023), it may add complexity that impacts interpretation. As Dumičić, Thoring, Klöckner, & Joost, (2022) note in their systematic review, while color is one of the most common encoding variables used in physicalization, the choice of encoding strategy should be carefully considered based on the intended audience and purpose.

In response to this challenge, in the second session, a refined design iteration removed color, emphasizing size as the primary encoding variable, with texture as a secondary element to represent quantitative information in wooden toolkits. I simplified the representation by removing the color elements and focusing on size as the primary variable and texture as a secondary variable for quantification to make the wooden toolkits. This was implemented through carbon blocks and action blocks, where the size of blocks encoded the quantitative data. This aligns with Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, (2023) observation that size is one of the most fundamental explicit variables for encoding data and can be more intuitive to interpret than other variables. Furthermore, as Dumičić, Thoring, Klöckner, & Joost, (2022) point out, geometric shapes and size variations are among the most straightforward ways to represent quantitative data in physicalization.

This transition from multivariable (color and size) to single-variable (size) encoding aligns with guidelines by what Hornecker, Hogan, Hinrichs, & Van Koningsbruggen, (2023) regarding the careful selection of “explicit variables” when designing physicalization for specific user groups. Simplifying design elements according to user cognitive abilities and task goals not only reduced interpretive demands on young learners but also allowed them to engage more directly with the material.

5.2.3 Future Design Suggestions

Based on these insights, future designs of data physicalization aimed at young audiences could prioritize the following:

1. **Data Type and Audience Identification:**

   Explicit Variables*: Direct, intentional encodings such as size, position, or shape, where, for instance, larger blocks denote higher values, and distinct shapes represent different categories. Explicit variables are ideal for clear, accessible cues.*

Implicit Properties*: Elements like material weight or spatial arrangement, which provide subtle context but do not directly encode data values. For example, heavier materials might imply significance, enhancing understanding without adding complexity.*

Consequential Aspects*: Unintended effects, such as shadows or material temperature, that may subtly influence user perception, contributing additional interpretive layers without explicit data encoding.*

2. **Use Simplified Visual Variables:** When designing for young audiences, it is beneficial to focus on minimal and intuitive encoding variables, such as size and texture. These are immediately understandable and provide a straightforward way to represent data without adding cognitive load.

3. **Avoid Overloading with Color:** Although color can be engaging, using it as a primary encoding variable may increase cognitive strain. Instead of complex color schemes, consider simpler, audience-specific strategies to avoid overwhelming young learners who may find it difficult to process multiple data dimensions simultaneously.

4. **Prioritize Material and Physicality:** Physical data representations should use meaningful textures and materials, which support tactile interaction and engagement. Materials like wood or textured surfaces offer sensory cues that maintain interest and help with understanding through direct physical interaction.

5. **Clear Signifiers for Intuitive Interaction**: Incorporate clear signifiers, such as labeled or textured blocks, to guide self-directed interaction with the data. These markers help children differentiate between data elements (e.g., emissions vs. offset actions) and reduce the need for extensive instructions, making the physicalization experience smoother and more intuitive
6. **Design for Sensory Engagement:** Create interactive elements that allow children to manipulate objects. This approach enhances comprehension by supporting haptic and spatial interaction, as the weight or texture of physical objects can aid in data interpretation and spark curiosity.

7. **Limit Variables to Core Functions:** For users with limited data interpretation skills, employing single-variable physicalization—such as using size or volume—is effective. Single dimension encoding helps keep attention focused on the main message and simplifies interpretation, which is particularly useful in educational contexts for younger audiences.

8. **Incorporate Metaphorical Elements Thoughtfully**: Use cultural or material metaphors (e.g., wood for nature data) to reinforce the data theme. This can help children intuitively connect with the subject matter. Choose materials and shapes that support the data's story, allowing for natural associations and enhancing both emotional and cognitive engagement.

9. **Think about the Physical Setting and Scale:** Physicalization should be designed to fit the environment in which they will be used. Consider factors like size, portability, and arrangement based on the space where children will interact with the elements. Large, walkable displays might be ideal in open spaces, while smaller, handheld physicalization work well in classrooms.

These findings reinforce the role of well-designed data physicalization in conveying environmental science concepts to young learners. Transforming abstract data into physical, interactive toolkits allowed children to develop critical understanding of complex environmental issues. Hands-on activities, like using food cards, balance scales, and wooden toolkits, bridged abstract concepts with practical application, helping learners progress from curiosity to more informed decision-making on topics like sustainable practices. Data physicalization also fostered peer interaction, self-guided learning, and a collaborative educational experience.

Challenges encountered, such as difficulty in interpreting more complex representations or multitiered data charts, underscore the importance of clear signifiers and gradual introduction of complex ideas. Simplifying vocabulary and breaking down abstract concepts into manageable parts can further improve comprehension. These results highlight data physicalization potential for broad application in scientific education, particularly as a means of translating abstract concepts into tangible, accessible learning experiences for younger audiences.

5.3 Limitations

While this research offers valuable insights into the potential of data physicalization for enhancing sustainability education, certain limitations should be noted.

5.3.1 Limit Sample Size

Firstly, the scope of this study was constrained by a limited sample size and participant homogeneity. Participants were drawn from a specific educational context, potentially limiting the diversity of learning styles, cultural backgrounds, and accessibility needs represented in the study. This suggests that future research should encompass a more diverse participant pool, ensuring findings are generalizable across a broader range of educational settings.

5.3.2 Narrow Focus on Data Physicalization Tools

Secondly, the study's focus on specific data physicalization tools and activities may not fully represent the variety of available methods for teaching sustainability. By concentrating on a narrow set of tools, the study may have inadvertently excluded other approaches or innovations that could be equally or more effective for sustainability education. Broadening the research to encompass a wider array of data physicalization techniques would provide a more holistic view of how these tools support varied educational goals.

5.3.3 Influence of External Variables

Finally, the study did not account for external factors that could influence the effectiveness of data physicalization, such as students' prior knowledge of sustainability, parental influence, or concurrent educational programs. These factors may have impacted the results and should be considered in future research to more accurately isolate the effects of data physicalization on learning outcomes.

5.4 Future work

Future research must explore innovative ways to help children understand and use data in their daily lives. For example, we could create learning kits that let children discover how data connects to their world. Instead of just showing them charts about environmental changes, they could collect their own measurements using simple tools, helping them see how numbers relate to real things they care about.

Using STEM education models, we need to carefully check how well children learn from these tools. When children work with data, we should watch three key things. First, do they truly understand what they are measuring? Can they explain in their own words what the numbers mean and why they matter? Second, can they use the tools correctly and create their own ways to show what they found? Third, and most importantly, can they use this knowledge to solve real problems in their school or home?

Interactive features could make these tools even more powerful. Our current research shows that children engage well with physical blocks and cards, but we could add elements that respond to their actions. For instance, when children build physical graphs about energy use, displays could show immediate connections to environmental impact. This immediate feedback could help them better understand cause and effect in environmental systems.

These tools need to be adaptable for different ages and abilities. In our sessions, we noticed that younger children preferred simpler, more tactile ways of showing data, while older students wanted to explore more complex relationships. Future tools should grow with the children, starting with basic concepts and building toward more sophisticated understanding.

We found that combining physical and digital tools offers unique advantages. While hands-on materials help children grasp basic concepts, digital tools let them explore bigger questions and see broader patterns. For instance, after using physical blocks to understand their own environmental impact, children could use digital tools to see how their actions connect to larger community efforts.

The way we test these ideas in classrooms needs careful thought. We should start with small groups and really watch how both teachers and students use these tools. Does having physical data representations help children remember concepts longer? Do they start thinking differently about environmental issues? Long-term studies would help us see if these methods create lasting changes in how children think about and use data.

Different children learn in different ways - we saw this clearly in our research. Some students learn best by physically moving things around, others by drawing or discussing. Future tools should support all these learning styles, giving children multiple ways to explore and understand data. This flexibility is crucial for making sure all children can learn effectively.

What works in one school might not work in another. Future research should test these approaches in various settings - urban and rural schools, different grade levels, and diverse communities. The goal is to develop tools and methods that can be adapted to work anywhere while still teaching core concepts about data and sustainability.

By carefully studying these areas and building on what we have learned, we can create better ways to teach children about both data and environmental responsibility. The goal isn't just to teach children how to read numbers and charts – it is to help them become people who can understand and use data to make informed decisions about their world.

Chapter 6: Conclusion

6.1 Research Summary

The study revealed key insights about data physicalization role in sustainability education:

Regarding youth interaction with data physicalization, the research found that physical representations enabled direct, hands-on engagement with environmental concepts. Children initially interacted with the tools based on personal interests, such as creating preferred meal combinations, before transitioning to understanding environmental implications. The physical nature of the tools, particularly the improved blocks with size differentiation and texture variation, helped children visualize abstract concepts like carbon emissions through tangible manipulation.

Concerning environmental behaviors and attitudes, exposure to data physicalization led to observable behavioral changes. After the sessions, participants reported implementing specific environmental practices at home, such as reducing electricity usage and plastic consumption. The physical representation of carbon emissions through blocks and scales prompted shifts in decision-making, as children began considering environmental impact alongside personal preferences. Two distinct approaches to environmental action emerged: "Overcompensation" with large-scale actions and "Minimal Compliance" through multiple smaller actions, indicating varied interpretations of environmental responsibility.

For effective design and implementation, the research identified several critical factors. Size-differentiated blocks with distinct textures proved more effective than color-coded same-sized blocks, enhancing understanding of proportional relationships. Pre-prepared meal options helped maintain focus on learning objectives rather than "gaming" the system. Age-appropriate scaffolding was essential - older children could interpret complex charts and data relationships, while younger children required additional support with mathematical calculations and abstract concepts. The study also found that collaborative learning environments, where older children naturally assisted younger ones, effectively supported comprehension of complex sustainability concepts.

These findings demonstrate how data physicalization, when thoughtfully designed and implemented, can support sustainability education by making abstract environmental concepts tangible and actionable for young learners.

6.2 Research Contributions

This research contributes to the intersection of Human-Computer Interaction (HCI) and education by showcasing the transformative potential of data physicalization in learning environments. It advances the discourse on interactive, user-centered learning by introducing new methods of data representation that cater specifically to younger learners. The integration of physical and tangible user interfaces in educational settings offers a novel approach to teaching complex subjects like sustainability, demonstrating how children can benefit from multi-sensory, active learning experiences.

These contributions hold particular significance in regions with intensive technological manufacturing, such as Taiwan, where the intersection of industrial development and environmental sustainability presents unique challenges. The study provides valuable insights into how data physicalization can enhance understanding of complex environmental impacts, particularly in contexts where industrial energy consumption significantly affects national resources. For instance, Taiwan's semiconductor industry, specifically TSMC, requires energy equivalent to one-quarter of Taiwan's total population consumption, highlighting the urgent need for effective educational approaches that can help future generations understand and address such environmental challenges.

The research also addresses the emerging environmental implications of artificial intelligence (AI) technology. Studies indicate that a single AI chatbot query consumes electricity equivalent to powering a lightbulb for 20 minutes—more than ten times the energy required for a conventional Google search. This finding demonstrates the critical importance of developing educational tools that can effectively communicate the hidden environmental costs of modern technological advancement.

This research also lays the groundwork for future studies that seek to expand the role of HCI in educational frameworks, particularly those focusing on participatory and experiential learning. The findings underscore the potential of data physicalization to revolutionize sustainability education by making abstract concepts more tangible and accessible to young learners. While challenges remain in terms of interpreting complex data, the hands-on, interactive approach has shown promise in fostering deeper engagement and critical thinking.

Future work should continue to refine these methods, integrating both physical and digital tools to provide a holistic, scalable approach to environmental education that empowers the next generation to make informed, sustainable choices. This is particularly crucial in contexts like Taiwan, where the balance between technological advancement and environmental sustainability requires careful consideration. The research thus marks a critical step toward bridging the gap between abstract data and practical, real-world learning, offering valuable contributions to the fields of HCI and education.

Appendices

Appendix A: KidsTeam Participatory Design Session 1 Plan

Sustainable Meal Planning: Exploring Carbon Budgeting with Data Physicalization

Date: 07 December 2023

Place: KidsTeam Research Lab, HCIL, University of Maryland

Format: In-Person

No. of participants: 9

Background: Children are accustomed to participatory and co-design sessions and have previous exposure to using AI tools.

Materials: Food Cards, Blocks, Balance, Infographics, Journal Sheets, Pencils, Phone for recordings

Goal for the session: Explore how children understand and engage with the concept of sustainable development through data physicalization. Investigate how this approach influences their behavior towards environmental sustainability.

4:00 – 4:10: "Snack" – getting ready

Snack // Hanging out // "reducing power dynamic; building relationships/trust.

4:10 – 4:30: Circle Time

Question of The Day

The question of the day helps us all think about the content area of the day's session before the design activities.

Q: What are the everyday things you do that will help or hurt the Earth?

4:30 – 5:15: Design Activity Part 1

Each group is responsible for planning a sustainable meal, and uses the weighing balance to check the carbon impact of their choices.

Objective: Use food examples to show that everyday items have hidden emissions. To give kids an understanding of carbon dioxide emission balance through data physicalization: explaining the amount generated and how it can be compensated.

4:30-4:40 (10min):

Choose the meal

4:40-5:00 (20min):

Each group 10 minutes for weighing the balance

5:00-5:15 (15min): Design activity Part 2

Each group is responsible for planning a sustainable meal for a school day

breakfast, lunch, and dinner), this time you will be confined to 20 carbon blocks, representing your carbon budget for a day. Each group must plan meals without exceeding their carbon budget.

Objective: Develop skills in carbon budgeting and sustainable meal planning by using a tangible representation of carbon emissions.

Prompts for adults to ask children

How did you feel about using carbon blocks to plan the meal?

What do you feel about switching this [food item] with that one?

What challenges did you face while trying to stay within the carbon budget?

What creative solutions did you come up with to make our meal plan more sustainable without exceeding the carbon budget?

Looking at our meal plan, can you identify which items are more environmentally friendly?

Why do you think this [food item] is a better choice?

Are there any foods you would have liked to include but couldn't because of our carbon budget?

What makes these foods less sustainable?

Do you think you will make different food choices after participating in this activity? Why or why not?

5:15-5:28 (13min): Journaling & Survey

Sheets will be provided for journaling and survey

	Group 1	Group 2	Group 3
Kid Partners:			
Adult Partner(s):			
Floating			

Assign Kids and adults into groups with necessary floaters

Appendix B: KidsTeam Participatory Design Session 2 Plan

<u>Carbon compensation and Data Charts</u>

Date: 03 October 2024

Place: KidsTeam Research Lab, HCIL, University of Maryland

Format: In-Person

No. of participants: 6

Background: Children are accustomed to participatory and co-design sessions and have previous exposure to using AI tools.

Materials: Toolkit (Food Cards, Meal Options, Carbon Emission Blocks, Save Planet Blocks, Weighing Balance, Notepad), paper and colored pencils for drawings

Goal for the session:

- Evaluate children's perception or behavior change after the previous section
- Gather feedback on the toolkit's effectiveness in teaching about carbon emissions and sustainable actions
- Observe how children engage with the different components of the toolkit

3:30/3:45 - 4:00pm Pre-Session Setup

- Table1: Set up toolkit components: balance and wood blocks
- Table2&3: Each table should have: one scissor, set of color pencils and pencils, Sharpie, meal set option sticker, food cards, journals
- Table4: Set up snack area,

- Table5: 2 big papers each with chart draw

4:20 – 4:40: Circle Time

Recap **(**5 minutes):

Briefly show some pictures and talk about what we did in the previous section

Question of the Day (10 minutes): *"Since our last session, what is one thing you have noticed or done differently in your daily life to help take care of our Earth?"*

4:40 – 5:20: Design Activity

a. Instructions for groups

1. (5mins) Choose one meal that the group likes best. (which is the set 1,2,3,4 for group a/set 5,6,7,8 for group b) <u>(Notes for Adult partners: Groups can modify their meal slightly by switching one or two items if they can't reach a consensus.)</u>

2. (10mins) Let children use Food Cards to represent their chosen meal items <u>(Notes for Adult Partners: Assist the children to calculate the backside of the carbon but ensure that the children still participate in the calculations themselves.)</u>

b. Data Charts(25mins)

Weight the balance and make a ingredients data chart with the blocks they just weight, start from the group who finishes first and then the next group.

5:20 – 5:40: Big Ideas (20 minutes):

We will present the kids with the charts they created and engage them in a discussion about the data they have gathered.

Prompt questions

- What do the blocks represent on the chart?
- Can you tell me in your meal options which food item has a higher carbon number and which one is the lowest?
- How did you figure out which action blocks to use for each food's carbon emission?
- Tell me which one is your favorite action to compensate and help the Earth and why?
- Can you think of another way to show this chart data?

	Group 1	Group 2	Group 3
Kid Partners:			
Adult Partner(s):			
Floating			

Assign Kids and adults into groups with necessary floaters

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