Tangible Carbon Blocks: Data Physicalization for Everyday Carbon Emissions

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Abstract

We present *Tangible Carbon Blocks*, a data physicalization toolkit that represents everyday carbon emissions as color-coded, stackable blocks. Daily carbon emissions are often communicated through abstract numerical values, making them difficult for non-experts to understand, compare, and reflect on. While existing carbon-recording tools such as calculators, dashboards, and summary metrics can raise awareness, they provide limited support for intuitive understanding and self-reflection. To elicit design requirements, we first conducted a 7-day formative study with five participants, combining daily carbon-activity recording through our website with post-interviews. Participants perceived carbon emissions as abstract, difficult to compare across activities, and rarely calculated in daily life. Based on these insights, we designed *Tangible Carbon Blocks*, which translate emissions into physical blocks that are gradually removed as emissions accumulate. We then conducted a second 7-day study with the same five participants, who continued recording their activities while using the blocks. Our results showed a descriptive reduction in participants' average daily emissions during block use, though this trend remains preliminary given the small sample and short duration. Open-ended responses further suggest that the blocks made category differences more visible, helped participants perceive emissions more intuitively, and prompted reflection on cumulative everyday consumption. Together, our results suggest that tangible physicalization can be an intuitive and low-cost way to support comparative and reflective engagement with everyday carbon emissions.

Index Terms: Data Physicalization, Carbon Emission, Interaction Design.

1 Introduction

Individual actions may appear fragmented or insignificant in the context of climate change. However, everyday activities, including material consumption and transportation [18], collectively contribute to carbon emissions. A key challenge is helping individuals understand how emissions are distributed across daily activities and recognize which choices contribute disproportionately.

Existing carbon- and energy-feedback tools often rely on aggregated totals, numerical indicators, or summary charts. Although these representations can increase awareness, they may provide limited support for interpreting differences across everyday activities or reasoning about trade-offs. Analogy-based representations can improve the communication of abstract data beyond numerical forms [3], while eco-feedback research has shown that numerical summaries alone may not sufficiently support comparison across categories of consumption [9, 19]. Sustainable HCI research further suggests that resource feedback can remain detached from everyday practices, making consumption difficult to interpret as a limited resource that requires ongoing reflection [2].

Inspired by research on scarcity mindsets, which suggests that perceived limitation can shape attention and decision-making [14], we explore how carbon emissions can be represented as a finite and allocatable budget through interaction design. Our goal is not to improve the precision of carbon accounting, but to support intuitive interpretation, category-level comparison, and reflection on cumulative consumption. We introduce *Tangible Carbon Blocks*, a data physicalization toolkit that represents everyday carbon emissions as color-coded, stackable blocks. Eight material and transportation categories: plastic (PP), paper, wood, car, electric vehicle (EV), metro, bus, and walking are represented using distinct colors. Each block represents a category-specific *interaction unit* calibrated from participants' one-week baseline records rather than a fixed life-cycle emission value. Remaining blocks are carried forward across days and gradually removed as emissions accumulate, making cumulative consumption patterns physically perceptible over time. Through this depletion-based representation, we explore how tangible interaction may support intuitive perception, category-level reflection, and awareness of limited carbon budgets through our proposed physicalization toolkit [17].

Our work has three main contributions: First, we introduce a depletion-based data physicalization approach that represents everyday carbon emissions as the consumption of a finite and tangible carbon budget, rather than as continuously accumulating numerical values. Second, we present *Tangible Carbon Blocks*, a low-cost physical prototype that maps multiple categories of everyday carbon-emitting activities onto removable and stackable blocks to support tangible interaction and cumulative reflection. Third, through a small-scale exploratory deployment with five participants, we provide preliminary insights into how depletion-based physicalization may support intuitive perception, category-level reflection, cumulative awareness, and social discussion. Rather than establishing causal evidence of emission reduction or long-term behavioral change, this work contributes an exploratory design and corresponding considerations for everyday carbon physicalization.

2 Related Work

To contextualize this work, we review prior research on carbon-emission communication, tangible representations of abstract data, and reflective interaction design for sustainability practices. Prior meta-analyses also highlight the growing importance of interaction, communication, and user-centered research in visualization [15].

2.1 Carbon Emissions Feedback

Prior research in sustainable HCI has explored a range of approaches for communicating carbon emissions and sustainability-related information, including carbon footprint calculators, digital dashboards, and environmental labels. Carbon footprint calculators and environmental labeling toolkit are widely used to communicate environmental impact, but users often struggle to relate these numerical values to everyday decision making [25, 26]. Eco-feedback

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toolkit have been shown to increase environmental awareness and influence energy-related behavior by providing users with information about their consumption patterns [9]. These toolkit typically rely on numerical indicators, charts, or summary metrics to represent environmental impact. Prior eco-feedback research shows that consumption feedback can influence user behavior [6, 8].

While eco-feedback toolkit can increase awareness, fewer studies examined how users compared emissions across everyday behavioral categories or reason about trade-offs between them [19]. For example, disaggregated electricity feedback showed limited evidence that numeric breakdowns alone support user-driven comparisons across contexts. Sustainable HCI work further argued that such feedback could frame resource use as an abstract quantity detached from everyday practice, making it difficult to perceive emissions as a bounded resource that requires allocation and prioritization [2]. As a result, most existing toolkit remained screen-based and relied on numerical representations, which may limit embodied understanding of carbon emissions and its distribution across behaviors. **We build on this line by exploring a tangible representation that foregrounds cross-category comparison and resource-allocation reasoning.**

2.2 Tangible Representations of Abstract Data

Human–computer interaction research has shown that tangible and manipulable representations can make abstract data easier to understand, explore, and compare [17]. Tangible and embodied interaction similarly uses physical artifacts to externalize information and support reasoning through direct manipulation [16, 12]. Data physicalization builds on these principles by encoding data through material properties including shape, volume, and spatial arrangement. Recent work has also explored physical representations of affective and abstract information, showing that embodied interaction can support intuitive interpretation and emotional engagement [13].

Prior systems have used physical tokens, stacked forms, bar-like structures, and interactive installations to communicate quantitative relationships beyond numerical displays [17]. Sustainability-oriented physicalizations have further demonstrated the value of tangible representations for self or environmental reflection [32]. Econundrum communicated the climate impact of dietary choices through a shared data sculpture [28]; Edo used participatory physicalization to prompt reflection on food-related environmental impacts [29]; Carbon Scales supported collective sense-making around food-production emissions [21]; and Cairn enabled situated data collection, representation, and analysis in everyday contexts [10]. Together, these systems show how physicalization can make environmental data more experiential, discussable, and socially situated.

However, tangible feedback for personal carbon emissions across multiple everyday activity categories remains comparatively underexplored. Existing sustainability physicalizations have primarily addressed food, collective interpretation, or situated environmental data, and have tended to present accumulated values or static states rather than progressive depletion. Our work explores this gap by representing personal carbon emissions as a finite physical resource that diminishes over time, supporting category-level reflection and awareness of cumulative consumption.

***Tangible Carbon Blocks* extends prior work in data physicalization by using gradual depletion to make cumulative carbon-emission patterns physically perceptible over time.**

2.3 Designing for Reflection in Sustainable Interaction

Research in sustainable HCI has emphasized designing for reflection by encouraging users to reconsider everyday practices and their environmental consequences [7, 2]. Rather than focusing only on immediate behavioral feedback or performance optimization, reflective approaches seek to make habitual activities visible and reshape how their consequences are understood [30]. Recent visualization research further suggests that affective qualities in data representation may strengthen engagement and support reflection on abstract information [20].

Sustainable interaction design also emphasizes the importance of situating resource feedback in everyday life, enabling users to recognize cumulative patterns and reconsider routine practices [2, 26]. Tangible artifacts may support this process by giving abstract consumption data a persistent presence in users' daily environments.

Although prior reflective systems have employed visualization, persuasive technology, and critical design, less attention has been paid to how hands-on interaction can frame carbon emissions as a finite resource that is gradually consumed over time. **We contribute a tangible interaction framing that supports category-level reflection and the perception of carbon emissions through physical depletion.** This gap motivates our exploration of depletion-based physicalization for interpreting and reflecting on everyday carbon-emission records.

3 Formative Study

Before developing the final *Tangible Carbon Blocks* prototype, we conducted a seven-day formative study to examine how potential users understood everyday carbon emissions and to establish a practical mapping between recorded emission values and physical blocks. The study combined daily activity recording through a web-based questionnaire with post-study semi-structured interviews.

The formative study had two objectives. First, it examined how participants interpreted carbon-emission values, compared everyday activities, and related these values to their daily practices. Second, it collected baseline records to calibrate the category-specific emission units represented by the blocks in the final prototype.

3.1 Participants

We recruited five undergraduate students (3 female & 2 male), aged from 18 to 22, to participate in our seven-day formative study. None of our participants had formal training in carbon accounting or sustainability research.

3.2 Procedure and Apparatus

We developed a web-based questionnaire[1] to collect participants' daily transportation and material-use records before they interacted with *Tangible Carbon Blocks*. During the seven-day formative study, participants completed the questionnaire once per day.

Our questionnaire covered five transportation categories: car, metro, bus, walking, and electric vehicle; and three material categories: PP/plastic, paper, and wood. For transportation activities, the system estimated carbon emissions using the recorded travel distance and the emission factor assigned to each transport mode. For material use, emissions were calculated using the recorded weight and the corresponding emission factor per gram.

Each participant was provided with an electronic scale to measure the daily weight of paper, wood, and plastic. Travel distances were estimated from the origins, destinations, and routes shown in participants' mobile map applications. Participants followed the same measurement and estimation procedures throughout the study to improve consistency across daily records. At the end of each day, they submitted the questionnaire, after which the system generated category-level carbon-emission estimates. The resulting seven-day baseline records are summarized in Table 1.

3.3 Post-interview

After the seven-day recording stage, we conducted semi-structured interviews with the five participants to understand their perceptions

[1] https://frolicking-salmiakki-072098.netlify.app/

Table 1: Total daily carbon emissions of five participants during the formative baseline-recording stage.

Participant	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total	Mean
P1	0.123	0.146	13.544	0.612	2.248	2.135	2.041	20.849	2.978
P2	23.800	12.110	5.542	2.981	5.643	3.462	4.230	57.767	8.252
P3	1.724	5.091	2.408	1.303	1.699	2.456	2.113	16.794	2.399
P4	6.383	9.743	6.236	6.518	4.924	2.177	5.420	41.402	5.915
P5	2.111	3.069	2.167	2.339	3.333	4.031	3.012	20.063	2.866

Note: All carbon-emission values are reported in kg CO_2e[2].

of carbon emissions and the difficulties they experienced when interpreting the recorded results. Each interview lasted 10-15 minutes, varying depending on participants. The questions focused on participants' understanding of carbon emissions, their ability to compare different daily activities, and their engagement with carbon-related calculations. The interview questions and representative responses are summarized in Table 2.

Participants commonly described carbon emissions as abstract and difficult to connect to daily actions. They also expressed uncertainty when comparing the relative impact of different activities, such as transportation and material use. In addition, they rarely engaged in explicit calculation of their own carbon emissions. These findings suggested that a carbon-feedback design should not rely only on numerical information. Instead, it should support intuitive perception, cross-category comparison, and continuous reflection through more accessible forms of representation.

3.4 Block Unit Calibration

Based on the baseline records, we defined a baseline-calibrated unit for each category. This unit specified how much carbon emission one physical block represents. The goal was not precise life-cycle carbon accounting. Instead, we used the unit as a practical interaction scale, helping participants perceive category differences through block addition or removal.

We denote the per-block unit for category c as u_c in kg CO_2e per block. Formally, we calculated the block unit as:

$$u_c = \frac{E_c^{\text{baseline}}}{N_c},$$

where E_c^{baseline} is the baseline weekly total carbon emissions for category c, and N_c is the number of blocks allocated to that category. Emission factors from prior literature were used in the questionnaire to estimate activity-level carbon emissions E, while the baseline records were used to calibrate the physical block units.

We then adjusted the resulting values to keep the interaction manageable and visually perceptible. Material-related categories were assigned smaller per-block units because their daily emissions were generally lower, while transportation-related categories were assigned larger per-block units because they produced higher emissions. This calibration process allowed changes within each activity category to remain visually perceptible while keeping the overall prototype practical for everyday tangible interaction.

The final baseline-calibrated mapping is reported in Section 4.

4 Design of Tangible Carbon Blocks

Based on our formative study, we designed *Tangible Carbon Blocks* as a physical representation of everyday carbon emissions. In this section, we present our design goals, our physical block toolkit, the mapping between carbon emissions and block depletion, and a representative scenario of use.

4.1 Design Goals

Our formative study revealed three design challenges. First, participants found carbon-emission numbers difficult to interpret in everyday terms. Second, they had difficulty comparing the relative

Table 2: Summary of formative interview questions and representative participant responses.

Interview Question	Representative Participant Responses
To what extent do you think carbon emissions affect climate change and the greenhouse effect?	• "I know carbon emissions contribute to climate change, but I don't really understand how big the impact is." • "I'm aware they cause global warming, but it feels quite abstract and distant from my daily life."
How do you usually understand carbon emissions?	• "I know they are important, but the numbers don't really mean much to me." • "It's hard to tell how much impact my daily actions actually have."
Can you compare the carbon impact of different daily activities?	• "I know transportation matters, but I'm not sure how it compares to things like materials or packaging." • "It's difficult to judge which activities contribute more."
Do you ever try to calculate or think about your carbon emissions in daily activities?	• "Not really. I know there are calculators, but I don't use them regularly." • "I sometimes think about it in general terms, but I don't calculate actual numbers."

carbon impact of different activities across categories. Third, they rarely tracked their own emissions continuously over time. These challenges motivated three design goals.

Goal 1: Support intuitive understanding beyond numerical values. The design should reduce users' dependence on abstract numerical metrics and make carbon emissions more directly perceivable. Instead of requiring users to interpret kilograms of CO_2e only as numbers, the toolkit should translate emission information into a physical form that can be seen, touched, and compared. This goal responds to participants' difficulty in understanding what carbon-emission numbers mean in relation to everyday actions.

Goal 2: Enable comparison across everyday activity categories. The design should help users compare the relative impact of different categories, such as plastic use, paper use, car travel, public transport, and walking. Because participants reported uncertainty about which activities contributed more to their carbon footprint, the toolkit should support side-by-side comparison across categories. This goal aims to make differences in carbon intensity more visible through the number and depletion of blocks, rather than relying only on textual or numerical explanations.

Goal 3: Represent carbon emissions as a finite and gradually consumed resource. The design should frame carbon emissions as something that accumulates and consumes a limited budget over time. Since participants rarely engaged in sustained tracking, the toolkit should encourage continuous reflection by showing how everyday choices gradually reduce the available blocks. This goal emphasizes scarcity and depletion, helping users understand that small daily actions can accumulate into noticeable environmental impact over a longer period.

Together, these goals guide the design of *Tangible Carbon Blocks* by shifting carbon feedback from abstract numerical calcu-

Figure 1: Overview of the Tangible Carbon Blocks with eight color-coded emission categories.

lation toward tangible perception, cross-category comparison, and continuous reflection.

4.2 Depletion-based Interaction Rationale

We adopted a subtractive rather than additive representation to frame everyday carbon emissions as the consumption of a limited carbon budget. An additive representation emphasizes how much carbon has already accumulated, whereas the gradual removal of blocks foregrounds the remaining capacity and makes cumulative consumption visible over time. The blocks remaining at the end of one day become the starting point for the next day, preserving a physical trace of previous activities and supporting reflection across multiple days. This depletion metaphor was intended to make the idea of limited resources more perceptible, rather than to induce or measure a specific psychological scarcity effect.

4.3 Design Overview

As shown in Figure 1, *Tangible Carbon Blocks* represents everyday carbon-emission records using color-coded, stackable blocks. The prototype covers eight material and mobility categories: PP/plastic, paper, wood, car, electric vehicle (EV), metro, bus, and walking [1, 24, 27, 31, 5, 11, 23].

Walking was included as a low-emission mobility category because human movement involves metabolic energy expenditure. Within the accounting boundary adopted in the questionnaire, additional physical activity may be associated with additional food intake, whose production generates indirect greenhouse-gas emissions. The assigned walking value therefore reflects an estimated indirect contribution rather than direct emissions from walking. It depends on assumptions about dietary intake and carbon intensity, and walking remains substantially less carbon-intensive than most motorized transport modes. Color was used solely to distinguish activity categories. Because the palette was constrained by the availability of commercially manufactured blocks, it was not intended to communicate carbon intensity, environmental severity, or other semantic meanings. Participants were introduced to the color–category associations before deployment and were provided with consistent labels throughout the study. Nevertheless, differences in hue, saturation, and brightness may have made certain categories more visually prominent. Future designs could adopt a controlled, color-vision-accessible palette and supplement color with labels, icons, shapes, or textures. The modular blocks support repeated removal, stacking, and side-by-side arrangement. Unlike transient screen-based feedback, the remaining blocks persist in the surrounding environment, preserving a visible trace of earlier activities. Their low cost and ease of manipulation also support exploratory use in everyday, educational, and shared contexts.

Table 3: Mapping between block categories, colors, and baseline-calibrated per-block units (u_c).

Category	**Block Color**	**Block Unit u_c (kg CO_2e/block)**
Plastic (PP)	Red	0.05
Paper	Orange	0.002
Wood	Yellow	0.05
Car	Green	1.0
Electric Vehicle (EV)	Cyan	1.0
Metro	Blue	1.0
Bus	Purple	0.5
Walking	Pink	0.2

Each category contains a fixed number of blocks, with each block corresponding to a baseline-calibrated carbon-emission unit, u_c. These units were derived from the formative baseline records described in Section 3.4 and are summarized, together with the color assignments, in Table 3. The resulting mapping functions as a practical interaction scale rather than a precise life-cycle carbon-accounting system.

Since emission ranges varied substantially across activities, material-use categories were assigned smaller per-block units, whereas transportation categories used larger units. This category-specific calibration keeps depletion perceptible within each category while maintaining a manageable number of physical blocks. The design therefore supports observation of category-level depletion and cumulative change over time, rather than direct equivalence between blocks belonging to different categories.

4.4 Interaction and Mapping

To represent everyday carbon-emitting activities, the interaction with *Tangible Carbon Blocks* centers on physically removing blocks. After the user completes the web-based questionnaire, the system estimates emissions. The user then removes a corresponding number of blocks from the relevant category. Specifically, we convert estimated emissions E into an integer block count: $n = \lceil E/u_c \rceil$, where u_c is the per-block unit for category c.

Categories are arranged side by side to support comparison across material and transportation choices. Prior studies on multiple-view visualization suggest that side-by-side arrangements can support comparative reasoning across complex information spaces [4]. Prior work on multimodal and embodied interaction also shows that physical interaction can support intuitive exploration of complex information spaces [33]. The gradual depletion of blocks makes cumulative emissions visible over time and shows the remaining capacity in each category. By comparing the remaining blocks across categories, users can reflect on how everyday actions consume a limited carbon budget.

4.5 A Scenario of Use

At the beginning of use, the user places all eight categories of color-coded blocks in their initial positions. As daily activities take place, such as using packaging materials or choosing different transportation modes, the user completes the web-based questionnaire to estimate the associated carbon emissions. Based on the calculated results, the user removes the corresponding number of blocks from the relevant category. Over time, differences in the rate of block depletion across categories become visually apparent. By observing these physical changes, users can compare how different everyday behaviors contribute to overall carbon emissions, supporting reflection on the structure and distribution of daily carbon emissions.

5 User Study

To examine how Tangible Carbon Blocks supported users' understanding of everyday carbon emissions, we ran a second 7-day study. The study was designed as an exploratory deployment rather

Table 4: Daily carbon-emission records of five participants during the Tangible Carbon Blocks usage stage.

Participant	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total	Mean
P1	0.119	0.139	12.460	0.520	1.753	1.494	1.265	17.750	2.536
P2	15.844	7.895	3.500	1.739	3.021	1.663	1.801	35.463	5.066
P3	1.672	4.836	2.215	1.108	1.325	1.719	1.310	14.185	2.026
P4	6.192	9.256	5.737	5.540	3.841	1.524	3.360	35.450	5.064
P5	2.048	2.916	1.994	1.988	2.600	2.822	1.867	16.235	2.319

Note: All carbon-emission values are reported in kg CO_2e.

Table 5: Comparison of average daily carbon emissions between the baseline stage and the Tangible Carbon Blocks usage stage.

Participant	Baseline Mean	Condition Mean	Difference ΔE	Change Rate
P1	2.978	2.536	-0.442	-14.85%
P2	8.252	5.066	-3.186	-38.61%
P3	2.399	2.026	-0.373	-15.53%
P4	5.915	5.064	-0.851	-14.38%
P5	2.866	2.319	-0.547	-19.08%
Overall	4.482	3.402	-1.080	-24.09%

Note: All carbon-emission values are reported in kg CO_2e.

than a controlled behavioral intervention. Its purpose was to investigate how participants interpreted, compared, and reflected on everyday carbon emissions through depletion-based physicalization.

5.1 Participants

Since carbon emissions are personal data, to make the data comparable, we asked the same five participants whether they were willing to continue participating in the formal user study. All five participants agreed to take part in the user study.

5.2 Procedure and Apparatus

Our user study lasted for seven days. Before the study began, each participant was provided with a set of Tangible Carbon Blocks. We introduced the meaning of the blocks, the mapping between colors and categories, and the baseline-calibrated unit carbon-emission value u_c for each category.

During the study, participants continued to record their daily activity data using the web-based questionnaire. At the same time, based on the carbon-emission results calculated by the system, they removed the corresponding number of Tangible Carbon Blocks from each category. In this way, carbon emissions generated by daily material use and transportation choices were transformed into visible, touchable, and gradually decreasing physical changes. The participants' blocks after one week of use are shown in Figure 2, and the corresponding seven-day usage-stage carbon-emission records are summarized in Table 4.

5.3 Post-interview

After the seven-day user study, we conducted a post-interview with each participant to understand their subjective perceptions of using Tangible Carbon Blocks. The post-study interviews included five open-ended questions: (1) After using Tangible Carbon Blocks, did you become more aware of which daily activities contributed most to your carbon emissions? (2) Compared with only viewing numerical results on the webpage, did the physical blocks make carbon emissions easier to understand or perceive? (3) During the use of Tangible Carbon Blocks, did you consciously adjust your transportation choices or material-use behaviors? (4) Which category of blocks was depleted more quickly than you expected, and why? (5)Do you think Tangible Carbon Blocks helped you reflect on carbon emissions in everyday life? If so, in what ways?

5.4 Data Analysis

We analyzed both quantitative carbon-emission records and qualitative interview and observation data. The quantitative analysis focused on comparing participants' carbon-emission records before and during the *Tangible Carbon Blocks* usage stage. Specifically, we compared each participant's average daily carbon emissions in the baseline stage with those in the usage stage. We also summarized category-level emissions across eight activity categories: PP/plastic, paper, wood, car, EV, metro, bus, and walking.

To describe the change between the two stages, we used three indicators. First, we calculated each participant's average daily carbon emissions during the baseline stage and the usage stage. Second, we calculated the carbon-emission difference between the two stages: $\Delta E = E_{\text{condition}} - E_{\text{baseline}}$, where E_{baseline} represents the average daily carbon emissions during the baseline stage, and $E_{\text{condition}}$ represents the average daily carbon emissions during the *Tangible Carbon Blocks* usage stage. A negative value of ΔE indicates that the participant's average daily emissions decreased during the usage stage. Third, we calculated the percentage change in carbon emissions: $R = \frac{E_{\text{condition}} - E_{\text{baseline}}}{E_{\text{baseline}}} \times 100\%$.

In addition, we summarized category-level emissions across the eight activity categories and examined individual trajectories rather than conducting confirmatory statistical tests. Given the small sample size and exploratory study design, these values are reported only to describe patterns observed during the study period and should not be interpreted as evidence that the toolkit caused emission reduction or long-term behavioral change.

For the qualitative data, we analyzed participants' answers to interview questions using thematic analysis. We first reviewed responses to the five questions and then grouped recurring responses into broader themes. Representative quotes were selected to illustrate how participants interpreted the tangible blocks, compared categories, reflected on depletion, and discussed possible behavior changes with others. Results are shown in Table 7.

5.5 Results

We first present quantitative results, then the qualitative results.

5.5.1 Quantitative Results

We summarize participants' average daily carbon-emission records across the two study stages in Table 5, and show the corresponding participants' individual carbon emission trajectories in Figure 3:

All five participants had a lower average daily values during the *Tangible Carbon Blocks* usage stage than during baseline recording, although the differences varied across individuals. Across participants, the average daily value decreased from 4.482 kg CO_2e at baseline to 3.402 kg CO_2e during use, a descriptive difference of -1.080 kg CO_2e per participant per day. This pattern should not be interpreted as evidence that the toolkit caused emission reductions. Because the same participants completed both stages in a fixed order without a control group, the difference may reflect self-monitoring, learning or order effects, novelty, schedule or travel changes, and other external factors. At the category level, transportation accounted for most recorded emissions during use, whereas material-use categories contributed smaller amounts. These patterns contextualize participants' reflections on transportation-related depletion but do not demonstrate that the toolkit reduced emissions or sustained behavioral change.

Table 6 shows the seven-day category-level carbon emissions during the Tangible Carbon Blocks usage stage. Transportation-related categories, including car, EV, metro, and bus, accounted for a large proportion of the total emissions. However, the distribution varied across participants. P1's emissions were mainly associated with car use, while P2 and P4 showed relatively high and more distributed transportation-related emissions across car, EV, metro, and bus. P3 and P5 showed lower overall emissions, with smaller contributions from car and public transport categories. Paper-related emissions remained very low across all participants,

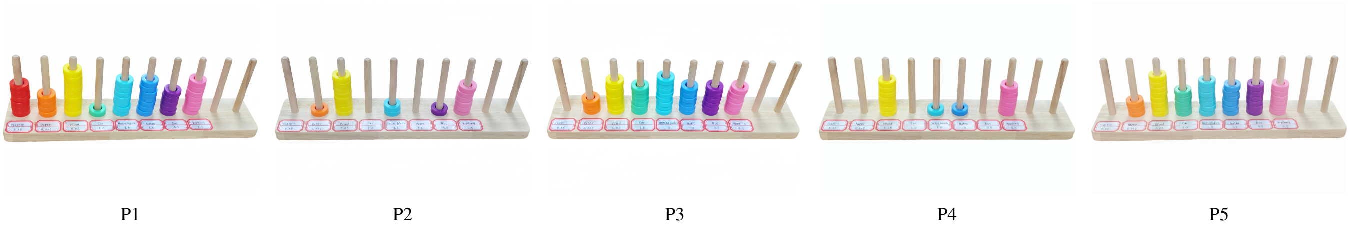

Figure 2: Participants' Tangible Carbon Blocks after one week of use. The remaining blocks visually reflect participants' accumulated carbon-emission patterns across daily activity categories.

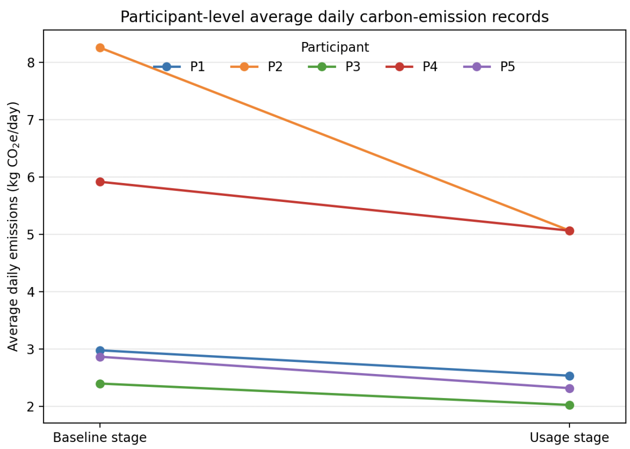

Figure 3: Participant-level average daily carbon-emission records during the baseline-recording and *Tangible Carbon Blocks* usage stages. Each line connects the two stage averages for one participant. The figure presents descriptive individual trajectories and does not imply that the observed differences were caused by the toolkit.

Table 6: Seven-day category-level emissions in the usage stage.

P.	PP	Paper	Wood	Car	EV	Metro	Bus	Walk	Total
P1	0.185	0.012	0.040	8.650	2.350	3.150	2.180	1.183	17.750
P2	0.560	0.018	0.085	9.500	8.200	9.600	4.800	2.700	35.463
P3	0.585	0.015	0.110	4.250	2.050	3.450	1.850	1.875	14.185
P4	0.490	0.020	0.135	9.650	8.790	9.225	4.990	2.150	35.450
P5	0.490	0.014	0.095	4.600	2.260	3.980	2.810	1.986	16.235
Total	2.310	0.079	0.465	36.650	23.650	29.405	16.630	9.894	119.083

Note: P. = Participant; PP = PP/plastic; Walk = walking. Values are reported in kg CO_2e.

while PP/plastic, wood, and walking contributed smaller but still visible portions of the total emissions.

The category-level results show where the recorded emissions came from. Transportation-related categories dominated the usage-stage emissions. In contrast, material-related categories, such as paper, wood, and PP/plastic, contributed much smaller proportions. This pattern helps explain why participants noticed transportation blocks more quickly in the later qualitative reflections.

5.5.2 Qualitative Results and Participant Observations

Our qualitative results (Table 7) are organized around the five guiding interview questions, making the link between interview focus and participant responses explicit.

Q1: Did the blocks help participants become aware of high-emission daily activities? Participants generally reported that Tangible Carbon Blocks helped them identify which daily activities contributed most to their carbon emissions. Transportation-related categories, especially car use, EV, metro, and bus, were repeatedly described as more noticeable because these blocks decreased faster than material-related categories. Several participants mentioned that seeing the transportation blocks arranged side by side made it easier to compare which travel choices contributed more to their overall emissions.

Q2: How were physical blocks perceived differently from numerical carbon results? Participants described the physical blocks as more direct and easier to understand than numerical carbon values on the webpage. Instead of interpreting kg CO_2e as an abstract number, they could look at the remaining blocks and immediately perceive which categories were larger or smaller. This suggests that the tangible representation helped transform numerical carbon-emission data into a more embodied and intuitive form of feedback.

Q3: Did participants report any behavior adjustment during use? Some participants reported that the depletion of blocks created a sense of urgency and encouraged them to consider lower-carbon choices. For example, participants mentioned becoming more willing to choose metro or bus instead of relying on private-car travel when they saw transportation-related blocks decreasing quickly. This does not prove long-term behavior change, but it suggests that the toolkit may support short-term reflection and reduction motivation.

Q4: Which categories were unexpectedly depleted faster? Participants most frequently identified transportation-related categories as being depleted faster than expected. In contrast, paper-related emissions remained almost invisible in comparison. This contrast helped participants recognize differences in carbon intensity across everyday activities. The side-by-side arrangement of categories also supported comparison between high-emission and low-emission behaviors.

Q5: Did the blocks support everyday reflection or discussion? Participants reported that the blocks encouraged continuous reflection because they did not reset each day. The remaining blocks carried over across the week, making cumulative consumption more visible. The side-by-side arrangement also triggered discussion among participants. They compared their remaining blocks, discussed differences in transportation and material use, and shared possible reduction strategies.

Although participants generally reported positive experiences, some noted that remembering to complete the daily questionnaire and recording material-use information required additional effort. Overall, participants considered Tangible Carbon Blocks to be a more concrete and intuitive way to understand everyday carbon emissions. Their responses suggest that the toolkit supported awareness of high-emission activities, comparison across categories, short-term reflection on behavior, recognition of unexpectedly fast-depleted categories, and shared discussion around everyday carbon choices.

Table 7: Themes, Sub-themes, Representative Quotes, and Participants

Theme	Sub-theme	Representative Quotes	Participants
Embodied Cognition & Comparison	Intuitive perception of relative intensity	"The transportation blocks changed much faster than I expected. Seeing car, EV, metro, and bus blocks side by side made it easier to compare which travel choices contributed more."	P2
		"The paper blocks barely changed, but the plastic and transportation blocks were much more noticeable. This made the differences between categories very clear."	P4
	Beyond numerical understanding	"Compared with numbers on a phone, physical changes are more direct. I do not need to think about units; I can tell which category is larger just by looking at the remaining blocks."	P4, P5
		"This method lets me see what I am actually using in my daily life much more intuitively than mere numerical values."	P3
Sense of Scarcity & Depletion	Perception of finite resources	"Watching the blocks decrease every day made me realize that carbon emissions are more like a limited budget, rather than an invisible number that can increase endlessly."	P2, P4, P5
		"The number of blocks is finite; no matter what I do, I cannot add more. It just keeps decreasing as I make daily choices."	P1, P3
	Loss aversion & reduction motivation	"Seeing only a few blocks left created a sense of urgency. This made me more willing to choose metro or bus instead of relying too much on private-car travel."	P2, P5
		"As the blocks dwindled, I felt a conscious urge to reduce the categories that were used most, especially transportation-related ones."	P3
Continuous Reflection	Cross-temporal awareness of depletion	"Since today's blocks were affected by what remained from yesterday, I began to plan my remaining carbon budget from a longer-term perspective instead of only focusing on a single day."	P1, P4
		"The blocks do not reset; they just stay there. It makes me realize that my emissions do not disappear when a new day starts."	P4
	Deep awareness of lifestyle	"Watching the blocks gradually vanish made me feel for the first time how my ordinary lifestyle could continuously consume environmental resources."	P5
		"The disappearance of the corresponding blocks made me realize that small daily choices, such as transport mode and plastic use, can accumulate over a week."	P1, P2
Social & Shared Reflection	Environment-triggered discussion	"These blocks are arranged side by side as a whole. This layout naturally led us to discuss trade-offs between transportation, diet, and everyday material use."	P2, P3, P4
	Collective sense-making & learning	"When discussing together, we were not just looking at our own blocks; we were also sharing reduction strategies. The atmosphere was very infectious."	P5
		"When comparing differences, seeing others retain more blocks through different choices made me want to imitate those more eco-friendly lifestyles."	P3, P4

5.6 Findings

Below, we summarize our findings from three aspects in which participants experienced and interpreted *Tangible Carbon Blocks*.

F1: Tangible depletion supports intuitive understanding and cross-category comparison. Participants used the depletion of blocks to compare carbon emissions across daily activity categories. Rather than reading each category as an isolated numerical value, they compared the remaining blocks side by side and noticed which categories were consumed more quickly. Transportation-related categories, including car, EV, metro, and bus, were often perceived as more salient because their blocks decreased faster than material-related categories such as paper or wood.

This finding suggests that the physical layout of Tangible Carbon Blocks supported cross-category comparison. The side-by-side arrangement made differences between categories visible at a glance. For example, when participants saw that transportation blocks were depleted more quickly than paper blocks, they could more easily recognize that different everyday activities had very different carbon intensities. In this sense, the blocks did not simply display carbon-emission data; they transformed category-level differences into visible physical changes.

Compared with numerical feedback on the webpage, the tangible representation appeared to reduce the effort needed to interpret relative differences. Participants did not need to compare abstract kg CO_2e values manually. Instead, they could observe differences in the depletion patterns of the categorized blocks and use visual depletion as a direct cue. This supports the design goals of helping users intuitively understand carbon emissions and perform cross-category comparison.

F2: Physical depletion makes emissions feel finite. The gradual removal of blocks helped participants perceive carbon emissions as a finite and consumable resource. In ordinary carbon-feedback toolkit, emissions are often shown as numbers that increase over time. In Tangible Carbon Blocks, however, participants interacted with a limited set of physical blocks that gradually decreased as daily activities were recorded. This changed the format from an abstract accumulated number into a visible process of depletion.

Several participants reported that seeing blocks disappear created a stronger sense of having "used something up." This was especially noticeable when one category decreased faster than expected. The finite number of blocks made the carbon budget feel more concrete because participants could see that the available blocks were limited and could not be immediately restored. This physical loss made the idea of carbon consumption more perceptible than simply seeing a numerical total.

This finding suggests that tangible depletion can support reflection on cumulative consumption over time. Because the blocks did not reset every day, participants could see how small daily choices accumulated during the study. The remaining blocks acted as a physical trace of previous actions. In this way, Tangible Carbon Blocks helped participants reflect on both individual activities and longer-term carbon-emission patterns.

F3: Visible physical artifacts provided a shared reference for discussion and reflection. The side-by-side arrangement of blocks and the collective interaction setting encouraged participants to discuss carbon-emission patterns with others. During the study, participants compared which categories depleted more quickly, discussed why their patterns differed, and considered alternative choices. These discussions were often prompted by visible differences in the remaining blocks rather than numerical values alone.

Our observations suggest that Tangible Carbon Blocks may function not only as an individual feedback toolkit, but also as a shared object for discussion. Because the blocks were visible and physically arranged in the shared environment, participants could easily point to specific categories and compare them with others. For example, transportation-related blocks often became a topic of discussion because they showed more visible depletion. Participants used these visible differences to reason about trade-offs between transportation modes, material use, and everyday routines.

This observation is consistent with prior collaborative visualization research showing that shared visual representations can facilitate discussion, comparison, and collective reasoning [22].In our study, the tangible blocks provided a shared reference point that supported collective sense-making. This led to conversations about alternative choices, such as comparing transportation modes or reducing material consumption. Therefore, Tangible Carbon Blocks may support not only personal reflection, but also social reflection around everyday environmental impact.

6 Discussion, Limitations, and Future Work

Discussion: *Tangible Carbon Blocks* represents everyday carbon emissions as the depletion of a finite physical budget. Rather than relying solely on numerical totals, the toolkit externalizes cumulative consumption through the gradual removal of blocks, making changes persistent and perceptible in the surrounding environment. This approach relates to affective visualization design, which considers how experiential and emotional qualities of representation may support engagement and reflection [20]. Temporal continuity is central to the design: the blocks remaining at the end of one day become the starting point for the next. This preserves a physical trace of previous activities and allows participants to observe how daily actions accumulate over time. Participants' accounts suggest that gradual depletion made the notion of a limited carbon budget more salient and prompted reflection on cumulative consumption. These observations do not establish a measurable scarcity effect or causal evidence of emission reduction; rather, they indicate that depletion may serve as a useful metaphor for framing carbon emissions as a limited resource. Compared with conventional single-number feedback, the toolkit translates carbon-emission records into persistent physical cues that may help users notice category-specific depletion patterns and reflect on the distribution of their daily emissions. Its contribution therefore lies not in precise carbon accounting or demonstrated behavioral change, but in exploring how tangible depletion may support intuitive perception, cumulative awareness, and reflective engagement [30, 17, 20].

Limitations: Our exploratory findings should be interpreted in light of several limitations. First, the color mapping may have introduced perceptual bias. Because the palette was constrained by commercially available blocks rather than developed through a controlled encoding process, variations in hue, saturation, and brightness may have made some categories more visually salient. Although participants were informed that color denoted category rather than emission intensity or environmental severity, its influence on attention cannot be ruled out. Second, the study relied on manual self-reporting through a web-based questionnaire. Daily estimation of travel distances, weighing of materials, and data entry may have increased burden and introduced omissions, inaccuracies, or inconsistencies. The recorded values should therefore be treated as approximate self-reports rather than exact measurements of personal carbon footprints. Third, the evaluation was limited to five undergraduate participants and a seven-day deployment. The small, homogeneous sample and short duration constrain the broader applicability of the findings. Furthermore, all participants completed the baseline stage before the block-use stage, with no control group or counterbalanced order. Differences between stages may therefore reflect self-monitoring, learning, order, novelty, or contextual influences such as weather, academic schedules, and travel requirements. The results do not provide causal evidence that *Tangible Carbon Blocks* reduced emissions or produced lasting behavioral change. Finally, block units were calibrated from individual baseline records rather than a uniform physical scale or comprehensive Life Cycle Assessment (LCA). Although personalization made within-category changes more visible and kept the prototype physically manageable, it reduced comparability across categories and participants. The toolkit should therefore be viewed as an exploratory medium for reflection and discussion, not as a precise carbon-accounting instrument.

Open Research Opportunities & Future Work: Our work opens several opportunities for future research on tangible carbon feedback. One opportunity is to explore how automated data capture, such as mobile sensing, GPS-based travel recognition, transit records, receipt scanning, or smart-home sensors, can reduce manual entry and support longer-term engagement. Another opportunity is to investigate alternative mapping and encoding strategies. For example, future studies could compare category-specific block units with a uniform carbon unit to better understand the trade-off between physical manageability and cross-category comparability. Researchers could also examine how color-vision-accessible palettes, labels, icons, shapes, or textures can make tangible carbon representations more inclusive.

Future research could further evaluate tangible carbon feedback with larger and more diverse samples, longer deployments, and more rigorous study designs. Controlled or counterbalanced comparisons among physical, digital, and hybrid feedback conditions would help clarify the specific role of tangible representation, apart from self-monitoring, novelty, or order effects. Finally, deployments in households, classrooms, workshops, and public exhibitions offer opportunities to study how physicalized carbon data can support not only individual reflection, but also shared discussion, collective sense-making, and sustainability education [26].

7 Conclusion

We present *Tangible Carbon Blocks*, a tangible data physicalization to support reflection and cross-category comparison of everyday carbon emissions. Through a seven-day formative study and a seven-day user study with five undergraduate participants, we found that the physical blocks helped participants notice relative differences across emission categories, especially between transportation and lower-emission material-use activities, and reflect on how daily choices accumulated over time. Given the small sample size and short duration, our quantitative results are descriptive rather than confirmatory. Instead, our contribution lies in exploring how tangible physicalization can make everyday carbon emissions more perceptible, comparable, and discussable. Future work should involve larger, more diverse samples, longer deployments, and more rigorous carbon accounting methods.

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References

[1] A. Alsabri, F. Tahir, and S. G. Al-Ghamdi. Life-cycle assessment of polypropylene production in the gulf cooperation council (gcc) region. *Polymers*, 13(21):3793, 2021. doi: 10.3390/polym13213793 4

[2] O. Bates, M. Hazas, A. Friday, J. Morley, et al. Towards an holistic view of the energy and environmental impacts of domestic media and IT. In *Proceedings of the Conference on Human Factors in Computing Systems*, pp. 1173–1182, 2014. doi: 10.1145/2556288.2556968 1, 2

[3] Q. Chen, W. Shuai, J. Zhang, Z. Sun, and N. Cao. Beyond numbers: Creating analogies to enhance data comprehension and communication with generative ai. In *Proceedings of the Conference on Human Factors in Computing Systems*, pp. 1–14, 2024. doi: 10.1145/3613904.3642480 1

[4] X. Chen, W. Zeng, Y. Lin, H. M. AI-maneea, J. Roberts, and R. Chang. Composition and configuration patterns in multiple-view visualizations. *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1514–1524, 2020. doi: 10.1109/TVCG.2020.3030338 4

[5] M. V. Chester and A. Horvath. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, 4(2):024008, 2009. doi: 10.1088/1748-9326/4/2/024008 4

[6] S. Darby et al. The effectiveness of feedback on energy consumption. *A Review for DEFRA of the Literature on Metering, Billing and direct Displays*, 486(2006):26, 2006. 2

[7] C. DiSalvo, P. Sengers, and H. Brynjarsdóttir. Mapping the landscape of sustainable HCI. In *Proceedings of the Conference on Human Factors in Computing Systems*, pp. 1975–1984, 2010. doi: 10.1145/1753326.1753625 2

[8] A. Faruqui, S. Sergici, and A. Sharif. The impact of informational feedback on energy consumption—A survey of the experimental evidence. *Energy*, 35(4):1598–1608, 2010. doi: 10.1016/j.energy.2009.07.042 2

[9] J. Froehlich, L. Findlater, and J. Landay. The design of eco-feedback technology. In *Proceedings of the Conference on Human Factors in Computing Systems*, pp. 1999–2008, 2010. doi: 10.1145/1753326.1753629 1, 2

[10] P. Gourlet and T. Dassé. Cairn: A tangible apparatus for situated data collection, visualization and analysis. In *Proceedings of the Conference on Designing Interactive Systems*, pp. 247–258, 2017. doi: 10.1145/3064663.3064794 2

[11] T. R. Hawkins, B. Singh, G. Majeau-Bettez, and A. H. Strømman. Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of industrial ecology*, 17(1):53–64, 2013. doi: 10.1111/j.1530-9290.2012.00532.x 4

[12] T. Hogan, E. Hornecker, S. Stusak, Y. Jansen, J. Alexander, A. V. Moere, et al. Tangible data, explorations in data physicalization. In *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction*, pp. 753–756, 2016. doi: 10.1145/2839462.2854112 2

[13] X. Huang, Y. Liu, and L. Yu. Emotionvis: Affective visualization with physical devices. In *Proceedings of the International Symposium on Visual Information Communication and Interaction*, pp. 1–5, 2023. doi: 10.1145/3615522.3615525 2

[14] I. Huijsmans, I. Mac, L. Micheli, C. Civai, M. Stallen, and A. G. Sanfey. A scarcity mindset alters neural processing underlying consumer decision making. *Proceedings of the National Academy of Sciences*, 116(24):11699–11704, 2019. doi: 10.1073/pnas.1818572116 1

[15] P. Isenberg, T. Isenberg, M. Sedlmair, J. Chen, and T. Möller. Toward a deeper understanding of visualization through keyword analysis. *arXiv preprint arXiv:1408.3297*, 2014. doi: 10.48550/arXiv.1408.3297 1

[16] H. Ishii and B. Ullmer. Tangible bits: Towards seamless interfaces between people, bits and atoms. In *Proceedings of the Conference on Human Factors in Computing Systems*, pp. 234–241, 1997. doi: 10.1145/258549.258715 2

[17] Y. Jansen, P. Dragicevic, P. Isenberg, J. Alexander, A. Karnik, J. Kildal, S. Subramanian, and K. Hornbæk. Opportunities and challenges for data physicalization. In *Proceedings of the Conference on Human Factors in Computing Systems*, pp. 3227–3236, 2015. doi: 10.1145/2702123.2702180 1, 2, 8

[18] P. Jaramillo, S. K. Ribeiro, P. Newman, S. Dhar, E. O. Diemuodeke, T. Kajino, D. S. Lee, et al. Transport (chapter 10). In *Climate Change - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 1049–1160. Cambridge University Press, 2023. doi: 10.1017/9781009157926.012 1

[19] J. Kelly and W. Knottenbelt. Does disaggregated electricity feedback reduce domestic electricity consumption? A systematic review of the literature. *arXiv preprint arXiv:1605.00962*, 2016. 1, 2

[20] X. Lan, Y. Wu, and N. Cao. Affective visualization design: Leveraging the emotional impact of data. *IEEE Transactions on Visualization and Computer Graphics*, 30(1):1–11, 2023. doi: 10.1109/TVCG.2023.3327385 2, 8

[21] M. V. A. Lindrup, A. R. Menon, and A. Biørn-Hansen. Carbon scales: Collective sense-making of carbon emissions from food production through physical data representation. In *Proceedings of the Designing Interactive Systems Conference*, pp. 1515–1530, 2023. doi: 10.1145/3563657.3596043 2

[22] Y. Liu and P. Craig. A multiple view approach to support data exploration in co-located and synchronous collaboration. In *Proceedings of the International Conference on Computer Supported Cooperative Work in Design*, pp. 1298–1303, 2021. doi: 10.1109/CSCWD49262.2021.9437845 8

[23] A. Mizdrak, L. J. Cobiac, C. L. Cleghorn, et al. Fuelling walking and cycling: Human powered locomotion is associated with non-negligible greenhouse gas emissions. *Scientific reports*, 10(1):9196, 2020. doi: 10.1038/s41598-020-66170-y 4

[24] A. L. Mourad, H. L. G. da Silva, and J. C. B. Nogueira. Life cycle assessment of cellulose packaging materials production: Folding box board and kraftliner paper. *The International Journal of Life Cycle Assessment*, 19:968–976, 2014. doi: 10.1007/s11367-013-0690-1 4

[25] D. Pandey, M. Agrawal, and J. S. Pandey. Carbon footprint: Current methods of estimation. *Environmental Monitoring and Assessment*, 178(1):135–160, 2011. doi: 10.1007/s10661-010-1678-y 1

[26] D. Perera, N. V. Dias, J. Gwilliam, and P. Eslambolchilar. Exploring household preferences for visualising consumption data: Towards data physicalizations to promote sustainable practices. *Interacting with Computers*, 37(5):481–496, 2025. doi: 10.1093/iwc/iwae054 1, 2, 8

[27] K. Sahoo, R. Bergman, and T. Runge. Life-cycle assessment of redwood lumber products in the us. *International Journal of Life Cycle Assessment*, 26:1702–1720, 2021. doi: 10.1007/s11367-021-01937-7 4

[28] K. Sauvé, S. Bakker, and S. Houben. Econundrum: Visualizing the climate impact of dietary choice through a shared data sculpture. In *Proceedings of the Designing Interactive Systems Conference*, pp. 1287–1300, 2020. doi: 10.1145/3357236.3395509 2

[29] K. Sauvé, P. Dragicevic, and Y. Jansen. Edo: A participatory data physicalization on the climate impact of dietary choices. In *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction*, pp. 1–13, 2023. doi: 10.1145/3569009.3572807 2

[30] P. Sengers, K. Boehner, S. David, and J. Kaye. Reflective design. In *Proceedings of the Decennial Conference on Critical Computing: Between Sense and Sensibility*, pp. 49–58, 2005. doi: 10.1145/1094562.1094569 2, 8

[31] J. Xie, Y. Xu, and H. Li. Environmental impact of express food delivery in China: The role of personal consumption choice. *Environment, Development and Sustainability*, 23(6):8234–8251, 2021. doi: 10.1007/s10668-020-00961-1 4

[32] L. Yao, Y. Zhang, and Y. Liu. Input Physicalization in Practice: An Instructional Walkthrough with Visualization Novices. In *IEEE VIS Workshop on Input Visualization*. Vienna, Austria, Nov. 2025. 2

[33] Z. Yuan, S. He, Y. Liu, and L. Yu. MEinVR: Multimodal interaction techniques in immersive exploration. *Visual Informatics*, 7(3):37–48, 2023. doi: 10.1016/j.visinf.2023.06.001 4