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Carbon Scales: Collective Sense-making of Carbon Emissions from Food Production through Physical Data Representation

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ABSTRACT

The climate impact of our food consumption is a key issue to sustainability. Yet understanding the food system and the impact it has can be difficult given its abstract nature. In this paper, we report on a Research through Design project aimed at designing and evaluating a data physicalization for supporting collective sense-making of the climate impact of food. Throughout the design process, we have explored the materiality of CO2 emissions and ways to design with less resource use. The resulting data physicalization, Carbon Scales, was evaluated in a three-week field study with 27 participants. Our findings show that collective sense-making can be enabled through interactive data physicalizations and that this can lead to carbon literacy. We expand on a) sustainability through design by arguing for the value of artifacts that let people *stay in the interaction* as this can support collective sense-making and b) sustainability in design by showcasing the value of designing with an *interaction-first and materials-second* mindset.

CCS CONCEPTS

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

KEYWORDS

Data Physicalization; Materialization; Sense-making; Tangible Computing; Literacy; Sustainability; Data

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1 INTRODUCTION

Environmental data has become a central part of understanding our planet and promoting actions toward more sustainable lifestyles. As many of the impacts of unsustainable lifestyles (e.g., global temperature changes) are invisible to the naked eye, when we think about the environment, we think with and through data. Representations of the concentration of carbon emissions[1] in our atmosphere, air quality in urban spaces, and sea-levels around the world are largely based on scientific data that is collected with a variety of tools (e.g., sensors, meters, scales) and represented in ways that provide insights about these phenomena.

In recent years, it has become clear that the food system of today is a major contributor to carbon emissions through resource intensive and unsustainable agriculture and production, transportation, retail, and consumption [50, 77]. However, the environmental impact of the food system is more or less hidden for people in their everyday lives [70]. Scholars in Human-Computer Interaction (HCI) have sought, both in the food domain and in adjacent domains such as housing and mobility, to use environmental data to steer behavior through increasing knowledge about consumption (e.g., [2, 9, 18, 19, 32, 35, 52, 61, 65, 69, 90, 100]). However, an increase in knowledge does not necessarily influence attitude nor behavior [57]. Research in materialization (i.e., [3, 73, 99]) have shown how engaging people in the abstract concepts of everyday life, for example energy or carbon emissions, has the potential of making such concepts more meaningful and practices around them more sustainable [73]. Additionally, research has recently, based on advances in digital fabrications, micro-controllers, shape-changing interfaces etc. as well as accessibility to data, advocated for the use of data physicalizations to democratize data [15] and increase learning from engaging with data [51]. We see that there is an opportunity for combining materialization (of carbon emissions) and data physicalization to engage people with the environmental footprint of our food system and how emissions are distributed along global value-chains as a means to support more meaningful relations to emissions, food, and data by making these concepts tangible and concrete.

In this paper, we describe a Research through Design (RtD) process [101] in which we worked with sustainability through design and sustainability in design [68]. This entailed an attempt at making emissions from food production more meaningful to people by materializing CO2 into Carbon Bits. The bits became part of an interactive data physicalization titled Carbon Scales that invited people to make sense of carbon emissions, data, and food. In the following, we describe our design process and report on a three-week field study of our data physicalization with a total of 27 participants. Based on the design process and field study, we discuss our

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[1]For the sake for readability, we use CO2/carbon emissions as an umbrella term to encompass the major greenhouse gasses (carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), chlorofluorocarbons (CFCs), and carbon tetrachloride (CCI4)) [93].

effort of working with sustainability in design and stress the value of an *interaction-first and materials-second* mindset in design. In addition, we outline the major contribution of our work which revolves around how collective sense-making can be enabled through *staying in the interaction* with data physicalizations and the ways that this can lead to carbon literacy.

2 SUSTAINABILITY IN AND THROUGH DESIGN

Since the introduction of Sustainable Human-Computer Interaction (SHCI) in 2007 [8], researchers have investigated various ways of enabling sustainability *in* design and *through* design [68]. The latter has been a key focus in the community, in particular through explorations of eco-feedback technologies in domestic settings to support sustainable behavior change [12, 25, 39]. However, this strategy rests upon the premise that knowledge about sustainability is a good descriptor for sustainable behavior, a notion that has been rejected multiple times (e.g., [13, 25, 55, 57, 74, 88, 89, 92]). In response to this criticism, research on sustainability through design has expanded to include work that is informed by social practice theory (e.g., [17, 18, 34, 59, 75, 76]), scales of action (e.g., [5, 7, 27, 36, 85]), and more-than-human perspectives [4, 26, 42, 91]. Recently, due to the increased possibility to collect and process environmental data [77], we have also encountered work focused on representations of environmental data that aim to make these more meaningful to non-experts by using narratives, materialization, and data physicalizations (e.g., [23, 64, 66, 83]).

In addition, a recent meta-review by Hansson et al. [39] calls for more research on sustainability in design since this aspect of SHCI to a large degree has been overlooked. Examples of sustainability in design include reducing the carbon footprint of algorithmic processes for online food shopping software [86] and the solar powered website for the low-tech magazine [22] (see also [79]). A way of working with the less prioritized concept of sustainability in design [68] could also be through using low-carbon methods and practices [71]. While Pasek [71] discusses analytic perspectives of low-carbon methods and how research can be done otherwise, such as in relation to academic air travel (e.g., offering regional hubs for international conferences), we adopt a low-carbon approach into design practice by drawing on the principles of *renewal and reuse* as a contrast to *invention and disposal* which has dominated technology development and design [8]. This can be done by not introducing unnecessary consumption into the design process and instead thinking in terms of reusing, up-cycling and salvaging materials for the designed artifacts.

2.1 Materializing environmental data

Considering the above mentioned responses to critiques of SHCI, we outline an opportunity of exploring how environmental data can become more meaningful to collectives of non-experts through materialization and data physicalization. Materialization has been proposed as a possible way forward for sustainability through design based on how it can support a stronger engagement with the environment and the various materials and practices of everyday life [23, 73]. As Pierce and Paulos [73] argue, *"[...] energy engagement could be a powerful way of transforming our relationships with energy in more meaningful and sustainable ways. In terms of materializing energy through engagement with energy devices, designers can aim to design technologies with and through which limiting the availability of energy is not perceived of as increased effort but rather as focal engagement."* [73, p. 121]. In their paper on energy materiality, the idea of limiting availability does not have to lead to discomfort or increased effort but instead make the finite nature of our natural resources an opportunity for meaningful engagement [73]. This is in line with recent research in HCI where we have seen a turn toward materiality (e.g., [28, 37, 78, 95–97]). Wiberg [97, p. 5] states that the material turn aims to articulate a combination of digital and physical materials that has not been emphasized in tradition HCI, shifting toward making immaterial materials tangible and interactive [73]. One example of immaterial materials are carbon emissions as they are a 'waste' product of energy conversion. Data on carbon emissions and their impact has been primarily embedded in expert systems and presented *to* people through data visualizations etc. One possibility for supporting more meaningful engagements and relations with immaterial materials is through data physicalization which aims to present data *with* people using lessons learned from the material turn.

2.2 Fostering engagement through physicalization

Data physicalization draws on aspects from data visualization, tangible computing, data art, data design, data artifacts, data perceptualization, and shape-changing displays [51]. In 1997, Ishii and Ullmer [49] introduced the idea of physical data representations through their work on 'tangible bits' — a concept that aimed to challenge the traditional idea of graphical user interfaces by making user interfaces tangible. This idea of tangible user interfaces informed work on tangible data representations (e.g., [31, 72]) with the formalized name 'data physicalizations'. Jansen et al. [51, p. 3230] define a data physicalization as an artifact that encodes data through its geometry or material properties. Several scholars argue for physicalizing data because it supports embodied learning [15, 43, 44, 51], interactivity [15], ownership over data [15], multiple interaction modalities simultaneously (i.e., intermodality) [15, 45, 51] as well as democratizing data [15, 44, 46], concretizing data [4, 15, 44, 45, 51], and leveraging our diverse perception to a high degree [15, 43, 51]. Buur et al. [15, p. 87] argue that materializing data through a data physicalization affords both manipulation and active engagement which challenge the 'objective' look of numbers and graphs. In addition, Houben et al. [46] show that data physicalizations can bring data into everyday settings in ways that are meaningful, creative, and aesthetic which promotes participation in data representation and thus makes a move toward democratizing data. Data physicalizations can also be used to communicate information on different levels (individual, collective etc.). For this, Sauvé et al. [83] argue that physical data representations should support three layers of information: personal reflection, visualization vocabulary, and a social frame of reference.

While data physicalizations have a number of benefits when it comes to designing for sustainability, a drawback is that some of them require a lot of materials in construction [51]. As we touched upon before, one of the issues of designing for sustainability is to also make the designed artifacts (in our case, the data physicalization) less resource intensive. Data physicalizations are often comprised of LED lights, sheets of metal, plastic, or wood, wires, actuators, computer hardware etc. to promote certain aesthetic and functional aspects (e.g., visually pleasing, sturdy). However, from a reuse and renewal perspective [8], acquiring high technological components for making a data representation, especially if it is for one-time use, is problematic since it promotes unnecessary consumption. Again, this stresses the importance of finding ways to design physical data representation without introducing unnecessary consumption.

2.3 Sense-making toward carbon literacy

Sense-making is a core part of our human condition; it assumes that humans live in a world of gaps that needs to be connected in certain ways and it is in this process of connecting gaps between the known and the unknown that we make sense [24]. Heidegger [41, p. 15] reflected on how phenomena arise and disappear through his analogy of walking on a trail in the woods: *"Today I am in all clarity at a place from which my entire previous literary output [...] has become alien to me. Alien like a path brought to an impasse, a path overgrown with grass and vegetation - a path which yet retains the fact that it leads to Da-sein as temporality."* As the quote touches upon, phenomena have directedness; they are experienced in time, space, and through movement [41]. Working with sense-making is less about the static and crystallized parts of our knowledge (our known knowns [81]) and more about the step-taking toward new understandings of a given phenomenon (our known unknowns and unknown unknowns [81]). The central idea of sense-making is to explore the steps that people take toward building new knowledge, the situation they are in and what this affords for the step taking, and outcome for the sense-making process [24]. Shotter [87] and Weick [94] reveal sense-making as a kind of 'creative authoring' performed by individuals and groups, in a search for plausibility and coherence, to construct meaning from initially puzzling or even troubling data.

Gabriel et al. [33, p. 2], in their article on narratives in organizational discourse, state that *"facts rarely speak for themselves – and never in isolation. Narratives and stories enable us to make sense of them, to identify their significance, and even, when they are painful or unpleasant, to accept them and live with them."* Thus, it can be argued that it is the narrative surrounding environmental data that allows people to make sense of it (see also [29, 66]). Narratives have long played a prominent role as sense-making devices. Data about abstract and invisible phenomena such as carbon emissions are put into perspective with narratives such as the two degree climate change target [14, 21, 56]. Bolt and Tregidga [10] show how stories and narratives are a means of making sense of ambiguous concepts such as materiality in accounting. While participants struggle to define what materiality is, they are able to tell stories about materiality in action. Fløttum and Gjerstad [30] and Bushell et al. [14] argue that strategic narratives are key to addressing the action gap between dangerous climate change and the current status quo. In our project, we want to investigate how sense-making and narratives around carbon emissions and food production can lead to carbon literacy for food [40]. Hence, it is not solely the outcome (i.e., carbon literacy) but the process toward it (i.e., sense-making) that is important for our research. We define carbon literacy as both the understanding and competencies to assess and argue for how carbon emissions are distributed [47] throughout food production as well as which activities contribute to them.

Based on the related work, we see an opportunity for designing for sustainability by employing the qualities that are offered by physical data representations. Data physicalizations, embedded in narratives, offer both tangibility and enables active engagement that we assume can support sense-making through surprise, estimate/reveal, and embodied interactions. For these reasons, we investigated how data physicalization could support sense-making processes of food sustainability and foster carbon literacy. In the following sections, we will describe the iterative design process which has led to the development of our data physicalization, Carbon Scales, including our materialization of CO2 into Carbon Bits and the study of it.

3 MAKING CARBON BITS AND CARBON SCALES

Our iterative, 'interaction-first' design process (see section 4.1), resulted in the creation of a data physicalization with two modules — Carbon Bits and Carbon Scales. The data physicalization was created through salvaging, reusing, and upcycling various materials and components.

The Carbon Bits are tangible pieces of CO2, designed to invite participants to physically feel the mass of CO2 that otherwise is ephemeral (see figure 1b). Drawing on previous work, that showcases the interaction and visualization possibilities of stacking pieces on top of each other [6], we explored different ways and materials to do so, until we finally hit a balance between playfulness and disturbance together with stackability. Our focus on sustainability in design resulted in us making the Carbon Bits from reclaimed metal pieces (nuts, bolts, screws etc.), thin sheets of wood, and a binding agent to hold the metal and wood together in a form factor that allows them to be stacked on top of each other. Two weight varieties of the Carbon Bits were made. The heavier variant, measuring 0.8 cm X 4 cm X 3 cm and weighing approximately 100 g was made by sandwiching epoxy resin, mixed with metal pieces in between thin sheets of wood. A black resin coloring pigment was added to both hide the metal pieces and to provide an oily look and feel, intended to evoke ideas of crude oil and pollutants, while the wood was intended to evoke feelings of nature and organic material. The bits were designed to be heavy for their size, so as to explicitly draw attention to their weight. The lighter variant, measuring 0.4 cm X 4 cm X 3 cm and weighing approximately 15 g, was made by sandwiching a 0.3 cm sheet of plywood between two thinner sheets of wood, with wood glue. This was then painted black on the sides to make it look similar to the other Carbon Bits. To feed into the larger narrative around food and carbon emissions, we framed the carbon bits as captured carbon-dioxide from the atmosphere that had been condensed into small blocks.

Carbon Scales is made of reclaimed wood and electronics and consist of four platforms representing the four main phases of food production: agriculture, processing, packaging, and transport (see

(a) (b) (c)

Figure 1: From left to right. The current iteration of Carbon Scales. The finished Carbon Bits. The data physicalization sat up in a local library as part of a public installation.

figure 1a). Each platform represents a distinct stage in the the life-cycle of food products and thereby bringing out the narrative of the journey of the food product from farm-to-table. The platforms each contain a load cell which is embedded in a wooden casing with an acrylic cover which allows for items to be stacked on top of them. Each platform also contains a LED Strip of 8-12 LEDs providing visual feedback. The platforms are connected to an Arduino microcomputer, housed in a wooden box. The Arduino is also connected to a reclaimed plastic button with an embedded micro-switch. When the button is pressed, the Arduino processes the weight on each of the platforms and provides feedback through the LED strips in each platform using colors and the number of LED Strips illuminated. The color of the strips indicates if the weight placed on a platform is near a benchmark value (see figure 4) for that platform which depends on the food product chosen. Benchmark values are calculated based on [20] and [84]. White color indicates the weight on the platform is close to the benchmark value (within a +/- 5% tolerance), blue indicates that it is above the value and orange indicates that it is below the value. The number of LEDs in the strip that light up indicates how close the weight on the platform is to the benchmark value. The lesser the number of LEDs that light up, the further away from the value. Carbon Scales, thus, allows people to weigh a food product against the carbon emissions emitted in producing it.

4 DESIGN PROCESS AND PRINCIPLES

Our data physicalization (Carbon Scales and Carbon Bits) was created through a Research through Design process (RtD) [101] where we adopted an 'interaction-first' [97] approach. This allowed us to design in an iterative manner that, through continuous ideation, critique, and re-framing, provided us with insights that were grounded in reflections from the design process and prior work. This design process was carefully documented through a research diary, imagery, and field notes.

From early on in the process, we were interested in unpacking the 'black box' [60] of the food system (see also figure 2a), i.e. the abstract, hidden dimensions of food consumption beyond what you see in the grocery store. This interest in the food system, as a black box, set us on a path toward data physicalization and explorations of how to make the climate impact of food production more meaningful and understandable to people. Throughout this work, the design have been informed by a number of design principles and concepts, which we describe in more detail below.

4.1 Interaction-first

In this project we have worked deliberately from an interaction-first principle which suggests that interactions, their form, function, meaning, and ways of presenting themselves, need to be expressed in order for them to be explored through a material lens [97, p. 75-76]. The basic idea was to materialize CO2 and the design challenge, therefore, quickly became about how to do so. As with all materials, CO2 has mass and volume. However, unlike other materials that we encounter on a daily basis, it is both detached from our activities as a waste product hereof and ephemeral in nature since it appears before us only in a certain time frame — at least if experienced at normal temperature and atmospheric pressure. Representing CO2 in both its mass and volume would result in one kg of CO2 (as a sphere) having a diameter of 154 cm. While representing both the volume and mass of CO2 would have certain benefits in relation to comprehensibility of the material, it would also result in limitations concerning space and interactivity and therefore we chose instead to represent solely the mass of CO2. Figure 2b shows a table tennis ball filled with pressurized air and cardboard boxes that we filled with dense materials to give them weight. These were used early in the design process to explore the qualities of mass and/or volume for our materialization of CO2. In order to gain the form of interaction that we sought, namely to impose a constraint in the interaction so to prompt people to *stay in the interaction* for a prolonged period of time, we created the bits in a size where it would be awkward to have more than two or three in one hand at a time (each product required approximately 20 Carbon Bits). The size of the Carbon Bits also allowed us to embed them with weight so that they weighed around 100g without acquiring more dense materials than what was salvageable in the university maker space (see figure 2d).

For the aesthetics of both Carbon Bits and the Carbon Scales, we aimed for a combination of an organic and industrial feel since these are two characteristics that can be attributed to CO2; a clash between nature and culture.

4.2 Peeking into the black box

One of the main goals with the Carbon Scales was to help unpack the carbon emissions of a product across its life cycle, in this case, for food as there is a disconnect between public perception about food, its origins, and carbon emissions in its life cycle [1, 54, 62]. We drew on the analogy of the food system as a black box i.e. a system which internal complexities are obscured by its success [60] in delivering fresh food to the cold counters. By peeking into this black box, we aimed to unfold these opaque farm-to-table life cycle narratives of food products and general public understandings of such narratives. We wanted to portray environmental data about the food system more meaningfully, through materialization and narratives around the data [29, 53]. This was accomplished by revealing the stories, processes, and efforts behind picking up e.g. a bundle of asparagus at the supermarket and make these processes as tangible and interactive as the food product itself. With Carbon Scales, we intended to provoke questions not just relating to how much CO2 different food products emit, but also how and why they emit these specific amounts through eliciting the narrative of the food product and its journey.

4.3 Narratives in the design process

The role of narratives was central to the design process itself. Our cycles of iteration often centred around new expansions, edits, and other changes in the narratives of the data physicalization. The design focused on two main narratives. The first concerns the ability to physically sense the carbon dioxide emitted by food products — *"What would it be like to pick up and feel the weight of the CO2 emitted by this food product, just as we feel the weight of the food product itself?"* This led us to the design explorations with mass and volume, outlined in section 4.1. The second narrative concerns the food system as a black box, where we explored *"How did this food product come to my hand? Where did its journey begin and how did it progress? And how did it come to emit as much CO2 as it does?"* This narrative led to our explorations with the different platforms of Carbon Scales.

As the data physicalization took shape, these narratives also expanded to include those regarding the interactions possible with Carbon Bits and Carbon Scales (more details in section 7.3). For example, our explorations with interactions with Carbon Scales, was guided by the narratives of - *"How can we get participants to stay engaged with the artifact (Stay in the interaction)?, How can we encourage discussions among themselves (Social frames of reference and referent experiences)?* and *How do we get participants not to treat the artifact as a problem to be solved?"*

4.4 Physicalization

A key goal with the Carbon Bits was to not only be a means to visualize an abstract concept such as CO2 emissions but also physicalize the concept in a way that participants could relate to and engage with. In order to serve as a visualization medium, the Carbon Bits therefore were designed to be stackable, so as to create columns and piles. Additionally, our data physicalization (i.e., Carbon Bits and Carbon Scales) draws on three layers of information: personal reflection, visualization vocabulary, and social frame of reference [83] to engage people in collective sense-making around food and emissions.

Personal reflection. Our intention was to design the data physicalization as a way to support personal reflection through fostering individual (as well as collective) sense-making about the food system as a whole; the participants' personal dietary choices; and their values around food and sustainability. The Carbon Bits were also thought of as a means for personal and embodied reflection about the connection between the abstract notion of CO2 in the atmosphere and the very concrete and tangible understanding that the Carbon Bits offered.

Visualization vocabulary. The visualization vocabulary was built up by modeling our food system into a simplified version — Carbon Scales. While this 'miniature food system' is based on generalizations and simplifications, it serves the purpose of giving people a common understanding of the parts of the system that contribute to the whole; thus, creating a vocabulary to talk about something as complex as the globalized food system of today. In addition, the Carbon Bits also sought to simplify and concretize carbon emission data from food production by embedding this into playful and uniform bits that people better can grasp and interact with — echoing the constructive visualization agenda [48].

Social frame of reference. Through supporting personal reflection and creating a visualization vocabulary, the aim was to create a social frame of reference where people would be able to reflect on presumptions about food and carbon emissions. For this reason, we designed our data physicalization in such a way as to allow for multiple people to interact with it at the same time. Additionally, the intention of creating a social frame of reference also led us consider the context for the data physicalization. Koskinen et al. [58] outline three main types of contexts for RtD artifacts: lab, field, showroom. Since the aim was to enable sense-making among people in a playful and interactive manner, we drew on the strengths of the showroom (i.e., making Carbon Scales part of a public installation that was inviting to people) and field context (i.e., placing it in peoples' lived environment to foster sense-making among peers with varying knowledge and attitude toward sustainable food production and consumption) when designing our data physicalization.

4.5 Designing with materials at hand

A central issue of the design process was how to design our data physicalization without introducing unnecessary consumption. In contrast to other interaction design projects, where designers comes up with an idea for a design and then acquire the necessary materials, the ideas and designs generated in our design process were shaped by the materials we had access to. This meant that the materials that we were able to salvage, reuse or upcycle determined the course of the design process. Several components of both the Carbon Scales and Carbon Bits, such as micro-controllers, wiring, switches, the thermal printer, wood, LED strips, etc. were salvaged and repurposed from earlier projects in the maker-space where the artifacts were made. Initial prototypes of the Carbon Bits were

(a) (b) (c) (d)

Figure 2: Images taken throughout our design process. Figure 2a shows an early sketch that focused on visualizing the idea of the food system as a black box and the journey of a product. Early explorations of interactions with CO2 as a material using table tennis balls, boxes filled with screws and bolts, and lo-fi prototype can be seen in figure 2b and figure 2c. Figure 2d illustrates the inside of a Carbon Bits before mounting wood on top

crafted from the materials we were able to scavenge (see figure 2b and figure 2c). We might have had an idea that our data physicalization should be made from specific materials or have a certain shape. However, through scavenging for materials, this sometimes meant that we had to go back and iterate the design to accommodate the materials that we could find. This resulted in both opportunities and challenges during the design process which will be discussed in section 7.2.

5 FIELD STUDY

To investigate if and how our data physicalization supports sense-making around the climate impact of food, we conducted an exploratory, three-week long field study. The aim was to validate the prototype and collect initial impressions and experiences of interacting with it. The field study was conducted in the form of a public installation at a teaching facility around sustainability for adolescents and young adults and at a public library as part of a sustainability exhibition. The goal was to recruit a convenience sample of 20-25 participants in the age-range of 18-65, with a focus on young adults (18-35). The focus on young adults was decided upon since they are in the initial phases of forming habits around consumption due to leaving home, buying their first home etc. and therefore would be an interesting group for studying sense-making around carbon emissions of consumption.

In preparation for deployment, a pilot study was conducted with seven participants (two 2-person groups and one 3-person group) to gain initial insights about possible interactions and to test study protocols. The participants were university students in the interaction design domain and were 20-30 years old. Based on results from the pilot study, we iterated the prompts for the participants to make these spark curiosity and to be more engaging (e.g., 'We want to challenge your understanding of food and carbon emissions!' instead of 'Do you want to participate in a study about people's understanding of food and carbon emissions?'). Additionally, we iterated the process in which we revealed the data physicalization for the participants. As the physicalization consists of multiple elements, e.g. Carbon Bits, Carbon Scales, food products, introducing all of these elements at the same time was confusing for the participants. Therefore, we chose to reveal in a step-wise manner (first revealing Carbon Bits, then Carbon Scales and so forth) before presenting the overall challenge for the participants. Comments made by participants during the pilot study also resulted in refinements of the interactions with Carbon Scales, including adjusting the color feedback and adding the receipt module that would print a receipt with information to the participants on how many tries they used for estimation and a short story about the journey of the food product.

Following the pilot test, we conducted the main study with participants at the teaching facility and the library (see figure 1c) in two northern European countries. Recruitment was done through inviting people who approached the installation by themselves to take part in the study or by walking around the venue and inviting people to participate. Most commonly, groups of two-three participants were recruited for each session. The study protocol was structured as follows: First, an introductory interview was conducted which aimed to capture the participants' demographics, knowledge, attitude, and behavior in relation to carbon emissions and food. Thereafter, the participants were invited to estimate carbon emissions of one or more of three products using the Carbon Bits and Carbon Scales. For this, we brought an 80g hamburger from a fast-food restaurant, a 200g bundle of asparagus produced in Peru, and 200g cheese sourced from regional diary production. These food products were chosen because of their ability to spark discussions due to the nature of their carbon footprints (their commonplace nature, high carbon emissions per gram of food product, emissions not related to agriculture, equivalent emissions from non CO2 gases, etc). During the participants' interactions with the prototype, the facilitator asked probing questions. Both during and after the interactions, we also noted down observations, logged estimates, and took pictures of interactions. After completing estimations, we conducted a follow-up interview that revolved around the participants' experiences of interacting with the prototype including their interaction with each other and their estimates of the carbon emissions.

5.1 Data collection and analysis

Throughout the field study, we collected data from multiple sources. The interviews were audio recorded and transcribed verbatim. The interactions among participants and with the prototype were documented with field notes and pictures. Participants' estimates of quantity and distribution of emissions were logged. Data analysis was done iteratively through open coding and inductive thematic analysis [16]. Initially, all authors coded one transcript in collaboration, resulting in 34 codes. To validate the codes, two authors coded two additional transcripts to see if the codes covered the data sufficiently (20 more codes were added which resulted in 54 codes). This initial set of codes was then refined by all authors through reviewing their content and collapsing codes that overlapped (resulting in a total of 38 refined codes — our coding set). With this set of codes, all transcripts and field notes were (re-)coded (12 transcripts and 13 field note documents). To construct themes, the authors read the coded material and discussed fitting themes. To guide this process, we also drew on the technique for identifying themes by Ryan and Bernard [82] including looking for repetitions, indigenous categories, differences, and metaphors. This step resulted in three main themes with several sub-themes. The identified themes were carefully reiterated to make sure they are unique and help answer our research question. In the following, we lay out our findings.

6 RESULTS

In this section we will describe the results from the thematic analysis, starting with a description of the participants to situate our findings before presenting our three main themes: materiality of and tangible interactions with carbon emission data; collective sense-making about carbon emissions and food production; and how the social interactions and interactions with the data physicalization challenges preconceptions toward carbon literacy.

6.1 Who are the participants?

The 27 participants were a diverse group of young adults between 20 and 35 years old, with a slightly skewed distribution in gender (W: 19, M: 11). We included one participant outside of the target group of young adults, P5, who was a teacher that was interested in participating. This was accounted for when analyzing the data from G2 by comparing their statements with other groups. See table 1 for an overview of the participants.

In terms of knowledge about food and sustainability, the group of participants displayed varying degrees of insight into the food system and its climate impact. For instance, several groups had a general awareness of the large impact agriculture has in terms of CO2 emissions (G1, G3, G10-11), while other groups had specific insights into e.g. the climate impact from production and use of plastic packaging in food (G12). This diversity of knowledge reflected the participants' interest in (food) sustainability, with many explicitly stating that they think about it in their everyday lives (P4, P6, P7-10, P12-15, P18-20, P24-27). Some participants were also engaged in the question through activism (P19) or being vegan (P7). Despite the breadth of knowledge and interest in sustainability among the participants, a set of (false) preconceptions about the climate impact of food production was also revealed. In particular,

Table 1: The demographics of participants including the group they were in and their age.

Group	Participants (Age/Gender)	Group	Participants (Age/Gender)
G1	P1 (23M), P2 (35F), P3 (22F)	G7	P13 (23F), P14 (22F), P15 (23M)
G2	P4 (22M), P5 (51F)	G8	P16 (25F), P17 (23F)
G3	P6 (20M)	G9	P18 (25F), P19 (24F), P20 (30F)
G4	P7 (22F), P8 (21F)	G10	P21 (28M), P22 (21M), P23 (22M)
G5	P9 (24F), P10 (24F)	G11	P24 (22F), P25 (23F), P26 (23F)
G6	P11 (24F), P12 (22F)	G12	P27 (22M)

participants repeatedly claimed that transportation had a large carbon footprint across all food products, with it being described as 'bad' (P11-12, P17). However, the fact that asparagus had a large carbon footprint from transport was in certain cases met with surprise (P12), indicating possible underlying preconceptions around the climate impact of vegetables in particular. In addition, several participants believed that water consumption from producing e.g. asparagus led to large amount of carbon emissions in agriculture (P10, P12, P16-17, P20, P24-26).

6.2 Materiality and tangible data interactions

A large theme from our data revolve around the qualities of our data physicalization, mainly the tangible interactions with data, how materialization of carbon emissions makes abstract notions more concrete, and how the data physicalization conveyed information to participants.

6.2.1 Sense-making through tangibility. One of the benefits of the physicalization was that the tangibility supported sense-making. P16 expressed that *"I feel that it becomes very... Having the asparagus in the one hand and then this [Carbon Bit] in the other. It gives a whole different understanding of food production"* (P16). As the participant touched upon, being able to physically pick up the food product and the Carbon Bits and weighing them up against each other provided a rich understanding of the food system due to the embodied and tangible qualities of the data physicalization. This was also stated by the participants in G9.

> Participant 18: *It has a very large impact to make it so visual.*
> Participant 19: *Yes it is so visual!*
> Participant 18: *And this thing with getting the blocks into your hands...*
> Participant 19: *It is both your visual senses and your motor skills that are in play. You get, in some sort of way, this climate consciousness into your bodily senses and under your skin in another way than I am used to.*

The participants made clear that the combination of multiple modalities in the sense-making process with the data physicalization helped them relate to the emissions of the food system at large and their own impact on the food system.

Another aspect of this richer understanding was the playfulness of the materials, especially the Carbon Bits: *"My desire for stacking blocks is activated by this. That is for sure."* (P21). Also, P17 mentioned that if it had been a more passive way of displaying the carbon emission data, e.g. using an infographic, then the participant would have acknowledged the information but not letting it crystallize, *"Yeah well then [if presented with information in a passive manner] I would probably just have been like... yes yes that is super but not actually taking it in. But in this way it was possible to really see the differences in a physical manner and that was very like... Okay... WOW!"* (P17). Physicalizing data also resulted in sizes and volumes becoming more visible and comprehensible for the participants, which to a large degree supported their sense-making processes as expressed by P16 *"I think... right now when we are standing here and weighing and measuring it becomes much more comprehensible."* (P16). This aspect of interacting with the data physicalization, how the tangible interactions with the materialization of CO2 made emissions more comprehensible and concrete, will be unfolded more in the following section.

6.2.2 Materializing CO2: Making the abstract concrete. The participants mentioned that the data physicalization made abstract notions more concrete. For our participants, carbon emissions and food production are two very abstract concepts both when separated and even more when combined. Prior to interacting with the data physicalization, we asked the participants whether carbon emissions of food production is something that they are familiar with and that they have a frame of reference for, P25 said *"No. No idea what so ever. I think that it is this thing with kilo of CO2. I am not sure what it means."* (P25). Additionally, in a dialog between P18 and P19, P18 expressed that *"The connection between the weight and CO2 is very abstract because it is something that exists out in the atmosphere somewhere. It is abstract things we are talking about..."* (P18). P19 followed up with saying *"Yes. It is also because of the fact that it is something that you read and talk about and something that you consider in the supermarket..."* (P19) and P18 interjected *"... When you are in the supermarket and you just see a number for carbon emissions or a statement on a product that just says 'CO2 emissions for this product are low' then you do not really know what it means. Instead, when it is possible to compare between different things as we could with this, it all of a sudden becomes more concrete."* (P18). As the participants touch upon, the experience with estimating the emissions of a food product made an otherwise very abstract notion of CO2 into a concrete and relatable notion. In group 11, P25 also mentioned this aspect of fostering a relation to the emissions, *"I think it is a very good visual element [with the Carbon Bits] since the idea of kilos and grams of CO2... you have no relation to that. It becomes easier when you are able to move the blocks around so that you can see and, ESPECIALLY, feel how many there are [...] and, adding atop of that, it gives a strong impression that you have to place them around yourself."* (P25). In this quote, P25 not only states that the Carbon Bits, and the data physicalization that they are part of, have an inherent ability to foster a relation to the abstract notion of CO2 emissions, also the fact that the participant had to move them around themselves made a strong impact. This idea of moving CO2 around and staying in the interaction was one that was deliberately embedded into the Carbon Bits through the materialization process by making them a size that makes it difficult to move more than two at a time. The participant ends with saying, *"I really feel that I can remember it better when I now have been part of this. As opposed to if I just saw some kind of poster or pie chart or something."* (P25). P6 also touched upon the impact of the physicality of the interaction by saying *"Well they are much more. They have much more bigger.... like WOW. Triple impact for me than just a diagram because if you can feel weight you can touch something that is more... closer to our everyday."* (P6). As the participant said, the tangibility and intermodality [51] (i.e., simultaneously seeing and feeling CO2) had a large impact on his way of understanding CO2 emissions.

6.2.3 Need for relational information. Even though the interaction with the data physicalization helped the participants with making the abstract notions of CO2 in the atmosphere and as a waste product of energy consuming activities more concrete, some participants (P14, P20-22) explicitly stated that they found it hard to understand the impact of e.g. 1.6 kg worth of Carbon Bits on the agriculture platform without having something to compare it with. During their interactions with Carbon Scales, G10 discussed how much 800 grams of CO2 actually is:

> Participant 21: *So we have 200g on each platform. That is a total of 800g. For one package of cheese? That does not tell me anything. I have no idea.*
> Participant 22: *No it is a bit difficult...*
> Participant 21: *I do not know what 800g of CO2 even means.*
> Interviewer: *Whether it is a little or a lot?*
> Participant 21: *Yes. If it is corresponding to an annual account of CO2 or something like that?*

Additionally, P22 expressed, a bit later in the study, that, *"I would have liked some kind of comparison beyond the weight... for example it would be interesting to know how much [CO2] a tree absorbs in a year."* (P22). This last comment from P22 sheds light on possible use cases for the tangible bits that will be discussed in section 7.3. The need for relational information was also touched upon by P20 *"I need some kind of frame of reference to other products... That, for example, lamb is twice as much as chicken or something."* (P20). While the physical data representation provided an understanding of the material aspects of CO2 as an immaterial material [73], it did not communicate relational information between different food products which literature has shown is important for comprehension of environmental data [63].

6.3 Collective sense-making and negotiations around environmental data

The social aspect of the data physicalization was interesting because it fostered situations of negotiating knowledge of CO2 emissions and collective sense-making between the participants. In our study, we invited groups of 2-3 people but also individual participants to gain an understanding of the differences between how people negotiate and make sense of CO2 emissions when in groups and individually. While the one person groups (i.e., G3, G12) mostly had a problem-solving mindset (see section 6.3.2) — they sought to solve the data physicalization by placing the Carbon Bits on the correct platforms in the most efficient manner — the 2-3 person groups used different strategies, especially for the first estimation, that we will touch upon in the following.

6.3.1 Negotiating emissions. As the participants were not sure about both the distribution and the amount of CO2 emitted in production of one of the three food products we brought, they engaged in collective sense-making processes where they negotiated their understandings of emissions and food production with each other. One of the issues that the majority of groups (G1-4, G8-10, G12) discussed was the impact of transport for various food products, especially for the asparagus where the three participants in G1 (P1-3) discussed whether asparagus are transported with flight or ship *"And transport... There has to be some transport."* (P2) *"well that is not bad if they are transported with cargo ship to here..."* (P1) and P2 responding *"You think they are transported by ship? I am quite sure that they are flown here... or?"* (P2). This example shows the kind of collective sense-making that happens between the participants when trying to reach a common understanding of the emissions for a food product.

Another example of the sense-making that took place during the interactions was between P16 and P17 from G8. Regarding transportation and packaging of the hamburger, P17 mentioned that *"Well it is only paper that is used for wrapping the burger. If we compare it to the cheese, it does not have a lot of packaging."* (P17) and P16 answered *"But that depends on the scope of the emissions... because the patties for the hamburger probably also come in packaging."* (P16), *"Oh yes. But does that not go under transport?"* (P17). In this dialogue, we can see the complexities of communicating CO2 emissions unfolding themselves in the interactions between the participants but also how they are reasoning back and forth toward a common understanding. A sense-making process that was enabled by the data physicalization and the format in which the participants work together on a shared goal. This form of reasoning also played out when placing Carbon Bits where the participants engaged in negotiations about estimates. A discussion in G11 shows an example of how the participants negotiated their estimates among each other:

> Participant 26: *I had probably just put three more bits on it.*
> Participant 24: *Then let us put two of the heavy ones over here [pointing at agriculture platform]. And just a little more on packaging?*
> Participant 26: *I do not think that will do. But should we just try like you proposed? [P26 puts two blocks on agriculture] And then I would place one of the light ones here [P26 points at packaging].*
> Participant 24: *Okay. But do you think it is enough?*
> Participant 26: *I am not sure. Let's try and see!*

From the quote, we want to showcase the delicacy of the estimation process. When in groups of two and three, the participants spent a large amount of time on negotiating between each other about their estimates to make sure that everyone had a say. If the participants experienced disagreements, they also brought forth their individual understandings of the emissions connected to the food product in order to solve disagreements, as the following negotiations between the participants in G7 show:

> Participant 15: *Oh yes. Everything is probably packed in boxes and plastic wrappings during transport*
> Participant 13: *Yes.*
> Participant 15: *That is true. There is probably a lot of transport involved in producing them.*
> Participant 14: *Yes. There are a lot of parts, beef patties, the buns, some lettuce and such that all needs to be packed until it reaches the processing facilities.*
> Participant 13: *But still I think that it is those [points at processing and agriculture platforms]... I actually think those are the worst.*
> Participant 14: *My immediate thought is agriculture but it might actually be worse in processing.*
> Participant 13: *You think?*
> Participant 14: *Yes. Think of the buns... They are almost plastic-like! [places a Carbon Bit on each platform].*
> Participant 15: *I'm thinking... My immediate intuition is to make these two platforms [points at processing and transport] the heaviest. I do not think packaging is so bad because it is probably packaged in bulks.*

The above discussions highlight the negotiations that comes into play when participants were engaging in estimating CO2 emissions in a social environment. Although all the participants had some knowledge about CO2 emissions from food production, the data physicalization put this knowledge to the test as they found out that their individual understandings had to be compromised in various ways.

6.3.2 Shifting modes of interaction. One aspect that became evident after multiple participants had interacted with the data physicalization was the shift in their mode of interacting with it. First, they were very cautious and spent a lot of time talking about their different understandings of the emissions connected to the product. This was captured in numerous field notes e.g. *"They started out being very quiet and careful."* (G10), *"They were, as the group before, also quite quiet and careful."* (G11), *"The participants seemed cautious in the beginning. They did not touch the CO2 bits until I prompted them to. After I did they started weighing them in their hands and playing around with them. They quickly realized that the bits have different weights and were, again, a bit cautious about using them to estimate with."* (G4), and *"They spend a long time discussing what they think the emissions for the hamburger are before even placing any of the bits on the platform."* (G2). When the participants pressed the button that showed how their estimates compared to benchmark values for the first time, we observed a significant shift in their mode of interacting with the data physicalization and among each other. From having a sense-making approach to the task where they were i.e. discussing the emissions, feeling the Carbon Bits, gaining a shared understanding through their negotiations, the participants showed a spontaneous spark of competence that was both visible in their discussions and in their body language (e.g., figure 3).

This shift in mode of interaction manifested itself in the participants leaning into the physicalization and vividly talking about

Figure 3: In the beginning, we observed that participants had a closed body language (left image); however, during interactions with each other and the data physicalization, this shifted to a very open, skillful, and curious body language (right image).

their understandings of the emissions (more details on this in section 6.4.2). We saw that multiple participants picked up and moved Carbon Bits in parallel and showed a large engagement in trying to make sense of the data physicalization. Participants started using words that can be interpreted as if they perceived Carbon Scales as a game — much different than before they pushed the button. While placing another bit on an already large tower of Carbon Bits, P6 and P21 mentioned that *"Now I am playing Jenga come on"* (P6) and *"Now we are just playing with toy bricks. Put on three more! [P21 places three bits on the agriculture platform]."* (P21). The first estimation that each group made took approximately 10 minutes but thereafter, each additional estimation took only 5-30 seconds. It clearly reveals a change in their perception and relations to the CO2 emissions; from careful sense-making to a competent form of problem solving. The change in their mode of interaction also shined through for the groups that picked multiple products. Here, the participants negotiated from an informed position and placed Carbon Bits in a confident manner. Although the products had different characteristics i.e. processed beef and wheat (hamburger), dairy (sliced cheese), and vegetables (asparagus), the participants were also able to transfer their knowledge about one product or product group to another. This form of literacy building was evident in all groups and from the looks of it, it might have been triggered through their sense-making with each other, supported by the tangibility of data physicalization.

6.4 Impact of interactions

This last theme builds upon the earlier ones by unfolding the impacts of collective sense-making through interacting with our data physicalization both in terms of how the data physicalization challenged preconceptions and supported CO2 literacy for food. During the participants' interactions, we logged the estimates that they made for each product. Especially, the first estimation that each group made was interesting as it showed their immediate understanding of CO2 emissions for the specific product. Figure 4 indicates how participants tend to reason when asked to estimate the carbon emissions of various stages of the life-cycle of their chosen food product.

From an interaction perspective, participants tended to start by placing one or two heavier Carbon Bits (corresponding to ~100-200g of CO2 emissions) on the platforms. In general, they overestimated (by a lot) the emissions associated with processing for all three food products. Participants also underestimated the emissions associated with agriculture for cheese and hamburgers and overestimated that of asparagus. They also underestimated emissions associated with long distance transport of food products such as asparagus (from Peru to Northern Europe). In the following, we will unfold the participants' reactions to the revealed differences between estimates and benchmark values.

6.4.1 Challenging preconceptions. The participants' immediate reaction after finishing the estimations was one of both surprise and disgust. After seeing the amount and the distribution of the Carbon Bits for a bundle of asparagus flown in from another continent, P18 and P20 reacted by saying *"You are kidding me right?!"* (P18) and *"Do not buy it! Sorry, but that has to be the conclusion."* (P20). In addition, the participants in G7 were surprised by the amount of CO2 emissions that come from agriculture when producing a hamburger *"I am really baffled that so much goes into agriculture. There is only such a small beef patty in there!"* (P14). Here, the weight of the Carbon Bits supported the participants in making sense of the food product and the emissions as exemplified by the participants from G8:

> Participant 16: *Wow that is a lot!*
> Interviewer: *You can try and take the bits up and feel how much it is.*
> Participant 17: *It is so heavy! Wow.. Has this small thing [bundle of asparagus] really emitted so much?*

From the quote, it can be seen that not only the visual impression from seeing the large stack of Carbon Bits made an impact on the participants. Also, the embodied relation that the participants got from the weight of the bits made an impact on their sense-making processes toward gaining an understanding of CO2 and food.

It became very visible, through participants' interactions with the data physicalization, that their preconceptions of food and CO2 emissions were challenged, *"Well at first I thought that I knew more about this than the average but then... now when I see the amount I*

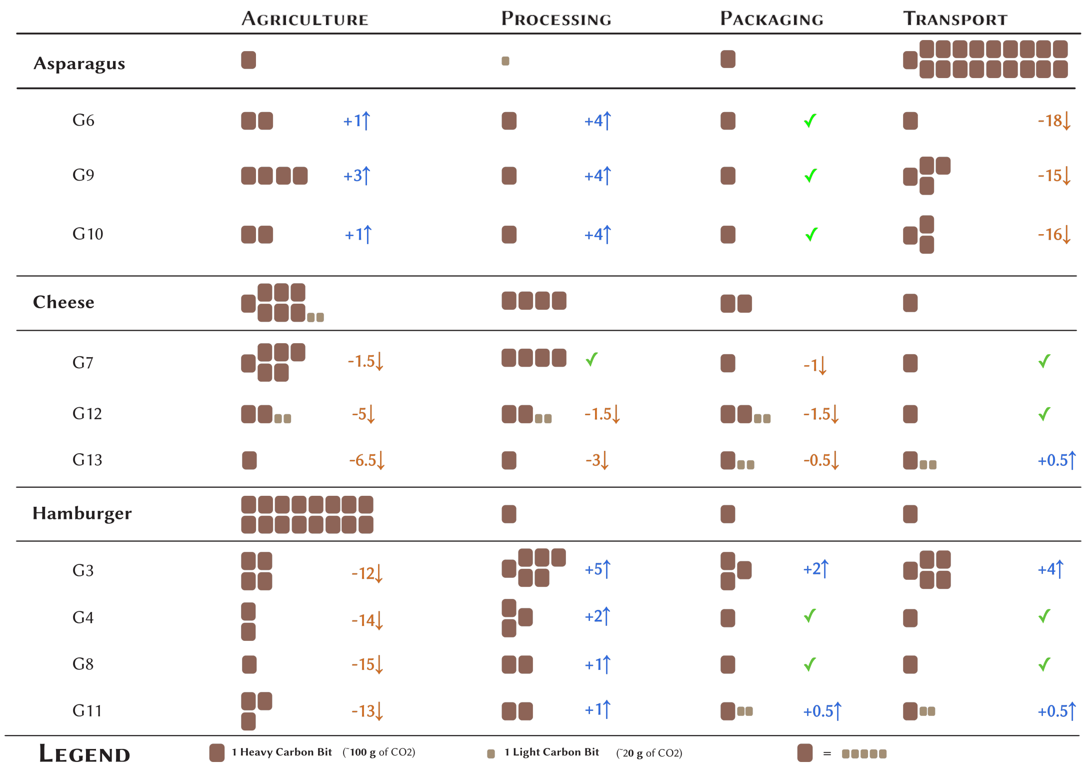

Figure 4: The first estimates of participants and the differences from benchmark CO2 emissions values for chosen food products (asparagus, cheese, and hamburger) in agriculture, processing, packaging, and transport. The numbers on the side of each entry indicate by how much the group overestimated (blue) / underestimated (orange) the value. Estimates from G1-2 were not captured due to technical difficulties.

am just feeling a little bit, not stupid, but surprised." (P6). Similarly, P4 expressed that *"I knew that it is a lot of emissions that come from food production. But THIS much? I had no clue."* (P4). While the participants had some prior knowledge about the impact of food production on the climate, it became apparent after the interactions that the data physicalization challenged this prior knowledge in a way that fostered a surprise effect in the participants.

6.4.2 Building carbon food literacy. We observed how carbon literacy manifested itself in both the interactions with the data physicalization and the participants' discussions around the data. The field notes from G2 outline an example of the transformation that happened during their interactions *"[...] their stance changed completely from standing up right to leaning into the prototype and interacting a lot with both the bits and the platforms. They started pointing at the platforms to make their arguments and placing bits simultaneously on the weights. There seemed to be some kind of skill-acquisition happening after they realized how their initial estimation looked compared to the benchmarks and this engaged them to make sense of what these emissions are about - it was an interesting transformation to watch. It also made them use the bits in a skillful way - using them not only as weights but as things to talk with."* (G2). This transformation was also visible in G4 where P7 and P8 discussed the impact of having tried estimating one product and then another one after that (although the products were in different product groups). P7 mentioned that *"[...] it really helped to have tried the hamburger before on the understanding of the differences between products"* (P7) and P8 answered *"Yes. It makes you develop a whole different mindset."* (P8). The tangible interactions with the Carbon Bits and the development of a shared frame of reference through collective sense-making was mentioned by the participants as having a particular impact on the transformation of their understanding of the food system at large and the CO2 emissions that are emitted through the different processes of a product's life cycle.

7 DISCUSSION

Throughout this paper, we have investigated how physicalizing data can support collective sense-making of the carbon emissions from food production; attempting to combine both sustainability in and through design in our process. In this section, we reflect upon our work and outline possible future directions.

7.1 Sustainability through design

Our work presents an empirical account of how to design for collective sense-making through the use of physical data representations and materialization of carbon emission data. In our design process, we have drawn extensively on data physicalization literature, both in general and specifically in relation to sustainability. While data physicalization has opportunities for leveraging our perceptual exploration skills such as active perception and non-visual senses [51], we also show that it is beneficial for leveraging our embodied perceptions. This is particularly relevant in our case where the goal has been to support stronger relations and engagement with an immaterial material, CO2.

Our data physicalization aimed to embed the three layers of information that is outlined by Sauvé et al. [83]: personal reflection, visualization vocabulary, and social frame of reference. Personal reflection was made possible by the nature of the data physicalization which triggered the participants to reflect upon their own knowledge about emissions in the food system. The visualization vocabulary was established through the simplification of food production processes where we condensed all the processes into four main steps i.e. agriculture, processing, packaging, and transport. The social frame of reference can be seen in both the inclusion of multiple participants at once and using Carbon Bits and Carbon Scales to frame the participants' actions and vocabulary. Although we complied with design literature on layers of information in a data physicalization, we experienced that one aspect was missing in the interactions; namely, how the information can be seen in relation to other kinds of activities or processes such as how much CO2 a tree can absorb in a year (see section 6.2.3). This finding points to a possible extension of the three layers of information for data physicalizations Sauvé et al. [83] by emphasizing the need for relational information on sustainability matters.

We designed Carbon Bits to serve the purpose of making abstract notions of emissions in our atmosphere very concrete through the addition of weight to convey tangible and embodied understandings of emissions. The Carbon Bits were also intended to manifest connotations of crude oil and fossil fuels and at the same time be stackable to make manipulations possible (i.e., [6]). The addition of weight and narratives around what the Carbon Bits represent enabled us to foster embodied experiences of carbon emissions in food production. Combining design principles from data physicalization and materialization supported our endeavor of inviting people to tangibly and concretely make sense of otherwise immaterial material of our everyday; thus, expanding on previous work on attunement through materialization by stressing the impact of data physicalization in this endeavor [73]. We here highlight an opportunity, especially in SHCI research on environmental data, to draw on the strengths of data physicalization and materialization to foster relations with immaterial materials such as CO2; shifting from environmental data as matters of fact to matters of concern through critical engagement [23]. Environmental data on e.g. global temperatures, CO2 emissions, sea-level rises are often representing immaterial materials or events. Expanding on the constructive visualization paradigm [48], we want to highlight the benefits of bringing two concepts together, data physicalization and materialization, for designers of environmental data interactions that needs be tangible and comprehensible for non-experts.

Jansen et al. [51] state that interactivity, in the form of physical manipulation, is key for fostering learning which they base on the embodied cognition thesis [11]. The interactivity of our data physicalization, manifested mainly in the Carbon Bits and the interplay with the Carbon Bits and Carbon Scales, was perceived by participants as to make their interactions with our data physicalization meaningful (see section 6.2). Previous data physicalizations have been mostly passive in their nature (e.g. [83, 98]), inviting people to glance at them, touch them etc. but not necessarily make changes to them. Throughout our design process, we have had a strong focus on interactivity for our data physicalization as a way of having people *stay in the interactions* with carbon emissions as this is a central part of sense-making; to stay with the data and grapple with it.

In his book on sense making, Weick answers the question '... how does action become coordinated in the world of multiple realities?', by stating that people share a 'referent', a common experience, about which they may infer different meanings but which continues to tie those understandings together [94]. Through our empirical work, we demonstrate that the Carbon Bits and Carbon Scales, along with the narratives surrounding them, can form a scaffolding around which such referent experiences can be organized, to achieve collective sense-making about environmental data [94]. Although such sense-making does not 'solve the problem of unsustainable food production' which previous, more technocentric, approaches to SHCI design might have sought [13], it makes meaningful engagement with sustainability issues possible and emphasizes a move toward an ethics of sustainability that engages with issues beyond our moral responsibilities as individuals to act — echoing the arguments from SHCI litterature [73, 80]. Although we were not able to quantitatively measure the effect from interacting with the prototype, our findings provide a rich account of experiential outcomes and reflections at the moment of interaction. A future step for this line of research could be to more thoroughly investigate how collective sense-making contributes to CO2 literacy both on the short and long term.

7.2 Sustainability in design

The tendency of the so-called invention and disposal paradigm [8] and irresponsible material acquisition for design artifacts is troublesome. Drawing on Mankoff et al. [68]'s concept of sustainability in design, we did an attempt to not introduce unnecessary consumption into our design process through reusing, upcycling, and salvaging a number of materials as a way of exploring how this can change the approach of designing physical data artifacts. Before proceeding, we need to stress a central limitation of our work with sustainability in design. We are privileged researchers situated in a well-funded university in a metropolitan city in northern Europe. This has had a large impact on the kinds of materials that we were able to salvage since we had access to well-equipped maker-spaces, design-studios etc. Our approach with not introducing unnecessary consumption in the design process would probably look completely different in a context where the invention and disposal mindset is not as dominant and high quality materials such as micro computers, wires, metal bolts and screws are not scrapped or not possible to source at all. Besides this limitation, we did an attempt at working with sustainability in design and want to encourage this way of doing interaction design work. While this way of designing was uncomfortable and impacted the visual appeal of the data physicalization, we can also point out several strengths with this approach to design work; especially, in the combination with material-centred design [97]. A central design principle of material-centred interaction design is 'interaction-first' which aims to have the designer reflect upon what kind of interactions should be for a given design [97]. In our project, the materials that we could salvage shaped the possible interactions. A traditional design project might involve making a blueprint for an artifact and then acquire the needed materials after — this process was largely turned around in our project. We started with a conceptual idea of our data physicalization. However, through the search for materials to reuse, upcycle, or salvage for the design, we found that the materials to a large degree led our design process. The materials (wooden pieces, screws to add weight etc.) were the deciding factors for the specifics of our design. The design process itself became a collective sense-making process that involved the authors locating, gathering, and repairing/upcycling scrap materials at the university maker-space and at maker-spaces in and around the city. So while we had an interaction-first mindset when looking for materials to represent carbon emissions, we had a *materials-second* mindset since these shaped our process in several ways. This *interaction-first and materials-second* mindset can very well support designers in creating more meaningful relations to the materials they use when designing and at the same time steer away from the dominant invention and disposal paradigm [8].

An aspect of our approach to sustainability in design that is open to criticism is our use of epoxy resin in the Carbon Bits. Our considerations in relation to the use of epoxy resin was that it allowed us to make the bits uniform and sturdy for future use; however, the material can also be seen as highly unsustainable due to the fact that it is made of plastic and is very difficult to separate again. This compromise shows the kinds of tensions that can happen when trying to balance convenience, sustainable consumption, and functionality in the design process. We had the possibility to use, for example, plant resin; however, this was deemed inconvenient to salvage and also to interact with. In addition, advances in 3D printing with food waste [38], in particular coffee grounds, could also inform future work sustainability in design for data physicalizations. On the topic of food waste, we do acknowledge that there is a certain irony in purchasing high emission food products (for the field study) to spark new discussions on the topic. We attempted to keep these purchases to a minimum and prepared meals using the food products after the study was completed. Our work with sustainability in design, hence, is not flawless. That said, we want to highlight this issue and spark conversations in the design community about how we can move toward sustainability in design of interactive systems as this has been largely overlooked by the SHCI community in the past [39].

7.3 The multi-purpose of Carbon Bits

As our findings suggest, Carbon Scales is only one possible use case for the Carbon Bits. While this prototype has been beneficial for making sense of how emissions are distributed as a way of 'unblack-boxing' parts of our food system, it does not relate the information to other activities that produce or consume carbon dioxide. This was deemed to be out of the scope of this iteration; however, we can see how the Carbon Bits can be vehicles for communicating such information in a playful and tangible manner. This materialization of carbon emissions, our Carbon Bits, are not bound to Carbon Scales. They can be used in a variety of different ways to communicate carbon emissions in tangible, interactive, and comprehensive ways to non-experts. An example that was suggested during our design process was to make use of crank-powered interactions [67] to connect the effort it takes to produce a food product in the various processes of agriculture, transport etc. to our bodily effort through a prototype that invites people to try and make Carbon Bits by hand cranking. The embodied experience of carbon emission data could foster the kind of attunement to climate issues which SHCI has called for [4, 73] and, further, mark a move away from solely creating data interactions that accommodate to our cognitive knowledge.

Through the use of data narratives [29] such as introducing the Carbon Bits as 'captured carbon-dioxide from the atmosphere that is condensed into small blocks', we both intended to bring forth this aspect of embodiment and at the same time make the material, carbon emissions, more concrete as we also mentioned above. The ability to change the narratives surrounding both the Carbon Bits and the Carbon Scales enhances their versatility and multi-purposed nature. For example, positing a Carbon Bit as the amount of carbon dioxide a mature tree can absorb in X days (see section 6.2.3), can open up for new opportunities of engagement.

8 CONCLUSION

Comprehending the food system and the impact it has can be difficult given its abstract nature. In this paper, we have presented a Research through Design process in which we have investigated how physicalizing data can support collective sense-making of carbon emissions generated by the global food system; attempting to combine both sustainability in and through design in our process. The focus on sustainability through and in design of a data physicalization that aims at fostering collective sense-making led us to explore the materiality of CO2 emissions and ways to design through less resource use. Our findings show that collective sense-making can be enabled through interactive data physicalizations and that this can support carbon literacy. However, more research is needed to be able to measure the specific effects on carbon literacy both on short and long term. Based on the Research through Design process, we expand on a) sustainability through design by arguing for the value of physical data representations and artifacts that let people *stay in the interactions* as this can support collective sense-making, and b) sustainability in design by showcasing the value of designing with an *interaction-first and materials-second* mindset.

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