# *Ecorbis*: A Data Sculpture of Environmental Behavior in the Home Context

**Brigitte Stegers**
Eindhoven University of Technology
The Netherlands
b.a.stegers@student.tue.nl

**Kim Sauvé**
Lancaster University
United Kingdom
kim.sauve@lancaster.ac.uk

**Steven Houben**
Eindhoven University of Technology
The Netherlands
s.houben@tue.nl

**ABSTRACT**

We are in the middle of a climate crisis. Never before has the impact of climate change been this visible, problematic, and timely. While most people have a basic awareness of the enormous potential impact of climate change, the reality is that only a few people have a detailed understanding of how their own (combined) personal activities − including food, transport, energy − impact the climate. In this pictorial, we explore the design process and principles of a data sculpture − *Ecorbis* − that is designed to help people reflect on how their day-to-day activities translate to climate impact. *Ecorbis* provides abstract and numerical weekly feedback on the overall environmental behavior of households and allows for in situ reflection and comparison. We conducted an initial 8-day field study with two families that highlighted that *Ecorbis* raised environmental awareness on climate impact and that the layered design of *Ecorbis* facilitated reflection.

**Authors Keywords**

Data Sculpture; Sustainable HCI; Climate Change Communication; Eco-feedback Technology

**CSS Concepts**

• **Human-centered computing ~ Human computer interaction (HCI);** User studies; Visualization;

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the Owner/Author.
*DIS '22*, June 13–17, 2022, Virtual Event, Australia
© 2022 Copyright is held by the owner/author(s).
ACM ISBN 978-1-4503-9358-4/22/06.
https://doi.org/10.1145/3532106.3533508

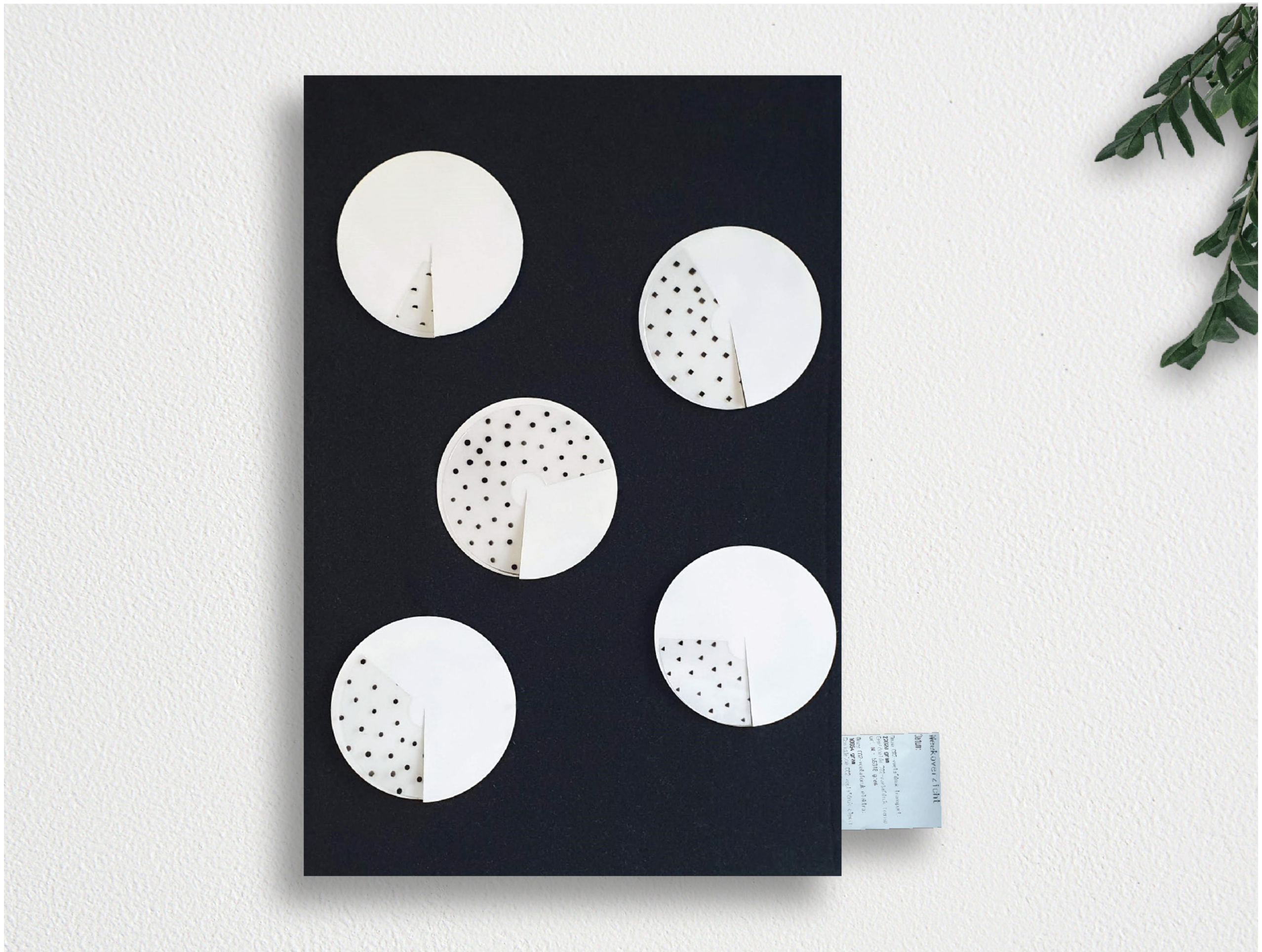


**Figure 1:** The final design of *Ecorbis*. All individuals within a household can report their daily behavior of five categories via a smartphone application. Households gain insight into their weekly environmental behavior through the abstract data sculpture and a numerical overview via the receipt. The receipt is printed weekly and presents the weekly overview of the household, the average climate impact per category of comparable househoulds, and a novel fact about climate behavior.

## INTRODUCTION

Climate change is one of the most imperative environmental challenges to be tackled today. The climate is changing due to increased levels of $CO_2$ and other greenhouse gasses, resulting in a rise in overall temperature on earth [46]. Research shows that 72% of carbon emissions are caused by household consumption [17]. For decades, scientists expressed their concerns about climate change, but despite the attention, action on climate change has not been there or had little effect, and $CO_2$ emissions continue to rise [18].

The majority of the global population acknowledges the existence of climate change and the problems associated with it. However, people remain unaware of the direct influence their everyday behaviors have on the climate [12, 13]. One of the challenges is that climate change is intangible, hence it does not naturally provide direct feedback on how everyday behaviors impact the climate [30]. Climate change communication aims to translate environmental information into knowledge for everyday life [10]. With the use of eco-feedback technology, awareness can be drawn to everyday behavior and the relative consequences of individual actions [12, 44]. While Ferreira et al. [10] show the breadth of work on climate change communication, there are still substantial open challenges around less developed themes (such as lifestyle) and the framing of the message.

Our work explores and presents how a data sculpture can create environmental awareness, in a home context, by communicating the associated carbon emissions of everyday choices. First, we elaborate on our design process and present a set of design principles. Second, we describe the final design of *Ecorbis* that operationalizes these principles, and report on an exploratory field study. Finally, we discuss the future implications of our work for sustainable HCI.

## RELATED WORK

### Intangibility of Climate Change

Previous research of Moser [30] described the challenges of the lack of visibility and immediacy of everyday behavior on the climate. The complexity and invisibility of the climate change problem has to compete against basic human necessities such as having food, which without consideration, can be at odds with climate-conscious living [17, 31]. Perceived inequity is another challenge that climate change brings to the table: *"What does it help if I would change my behavior if others don't change?"* [13]. Therefore, collective effort is necessary in tackling the climate change problem as humans commonly compare individual behavior to other people, and only the behavior change of many influences the climate [11, 25]. Prior research has shown that a shared system, *Econundrum* [36], that focused on climate change communication, stimulated reflection and social comparison. However, *Econundrum* [36] only focused on food consumption and not on the climate impact of everyday behavior in general. To translate the complex topic of climate change, the system drew from work on eco-feedback systems: *"Eco-feedback technology provides feedback on individual or group behavior with a goal of reducing environmental impact"* [12].

### Personal Data

The study of Ferreira et al. [10] analyzed 40 recent projects on climate change communication. The projects were categorized based on themes, contexts, audiences, used media, scopes, actionability, and framings. As visible in Figure 2, the way of communicating information (Message) and the location of the projects

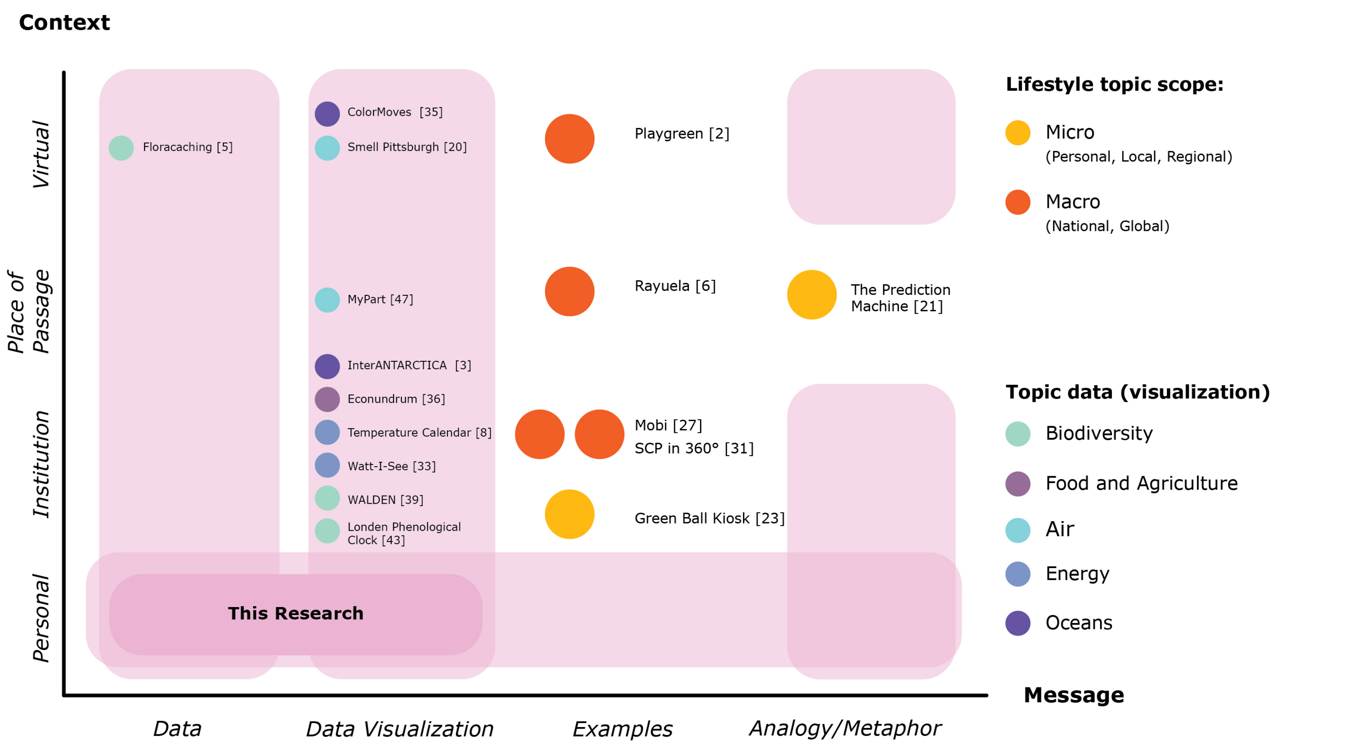
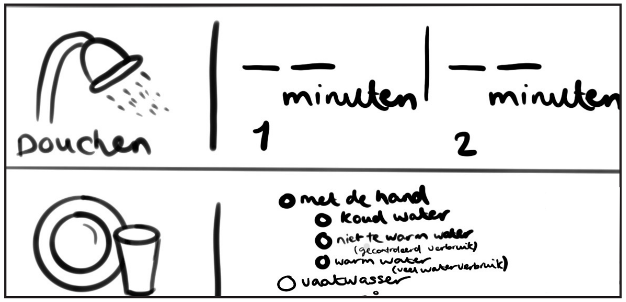



**Figure 2**: Framing our research by selecting 16 climate change communication projects from [10] that are mapped according to their Context and Message. Only 6 projects focussed on climate change communication of Lifestyle (yellow and orange), hence the pink areas indicate research opportunities within climate change communication and the topic of Lifestyle. In total, 9 projects communicated information through a Data Visualization and only 1 project communicated climate change information through Data. None of the projects were brought into a personal context.

The participants of the diary study were given an example in Dutch on how to collect the data per category (these are 2 out of 6 categories).




(Context) are underexplored in the Lifestyle theme. The majority of Lifestyle interventions [2, 6, 23, 27, 31] focused on communicating climate impact by using generic examples, rather than communicating data (visualizations) of personal behavior [10]. Within these studies, there has been no focus on how individual everyday behavior influences climate change, while prior research showed that interactive forms of communication led to more active engagement [30]. For example, the system of *Squeezy Green Balls* [23] was used to raise general discussions about green issues. In contrast, *Econundrum* [36] focused on communicating the climate impact of personal dietary choices which allowed participants to reflect on personal behavior. Moreover, the study on *Econundrum* showed that personal data increased environmental awareness, changed participants' attitudes towards climate change, and helped in creating a personal connection to the system. Therefore, it is interesting to investigate whether these design principles also apply to the lifestyle theme within a personal context. Research on the quantified self showed that self-monitoring helped in self-reflection and to effectuate behavioral change [24, 45]. As such, there are opportunities for eco-feedback technology to communicate and aid in self-monitoring of individual environmental behavior. Lastly, only one previous study [5] communicated information using data (Figure 2), and thus it shows an opportunity to explore a design that involves a numerical data representation.

### Data Sculpture

One approach to tackle the intangibility of the topic of climate change is the use of data sculptures: *"data-based physical artifacts, possessing both artistic and functional qualities, that aim to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it"* [50]. Figure 2 shows that the majority of interventions focusing on Lifestyle were deployed in public spaces, and not in a personal context. Introducing the concept of data sculptures in a home context could be an opportunity to show the influence of lifestyle choices on the climate more closely related to this context. By having a data sculpture in the periphery, users can be occupied with other activities but still easily access information when needed [1]. To trigger people and keep them interested over time, it would be useful to include curiosity principles within the design, such as a novelty element, partial exposure and/or an uncertainty element [48]. Research on *Watt-I-See* [30] showed that there is a preference towards immediate feedback and simple interfaces as it resulted in increased energy awareness. Prior research also indicates that physical data representations make data accessible and show more engagement than digital visualizations [22]. For example *LOOP* [37], a physical representation of activity tracking data in the home context, resulted in new moments of engagement due to its physical presence in the home. To conclude, a data sculpture is an effective way to translate a complex intangible topic into accessible information for households and society.

## DOMAIN STUDY

We explored the domain of climate impact by (i) a diary study and (ii) an auto-ethnographic study, and applied a mixed approach to gain an in-depth understanding of everyday behavior and the home context [41].

### Diary Study

An initial diary study was performed to gain insights into everyday behavior of different household types.

#### *Participants*

Through convenience sampling we recruited 3 participants (2 identified as female, 1 as male) with an average age of 33 years ($\sigma = 15.72$). P1 lived together with 6 other students while staying at their parents (household of 4) during the weekend. P2 lived together with their partner. P3 lived together with their partner and 2 children. The lead researcher (P4) was also included in the study to gain insights from a first-person perspective, and lived together with their partner.

#### *Procedure*

We introduced each of the participants to the one-week diary study after which they signed a consent form and we collected their demographics. They were allowed to collect quantitative data on everyday behavior in an online document or on paper and were also allowed to add their own insights in a qualitative way. We collected data of six different categories that operationalize insights from the book *How bad are bananas* [4] (which compares the climate impact for different activities): *showering*, *doing the dishes*, *washing & drying, driving by car*, *watching tv*, and *drinking alcohol*. These categories were chosen under the assumption that these are common daily activities and would trigger the most curiosity. After one week, the participants handed over the collected information to the researcher.

#### *Results*

In total, 92 data points were collected with an average of 23 data inputs per participant (Figure 3). For *doing the dishes* and for *washing & drying*, the people who did the dishes by hand and dried the laundry without a machine did so because they did not have a machine at their disposal. In addition, Figure 3 shows that not all activities were performed daily and that some activities were done for/with the collective household.

### Auto-Ethnographic Study

During the one-week diary study, the lead researcher also collected data on their own perspective, observations, and experiences by taking notes. After the study, the researcher was exposed to information from [4].

#### *Results*

After obtaining more knowledge on climate impact during the study, the lead researcher's perspective changed from rather confused, curious and frustrated, towards a more positive perspective such as useful, self-sustainable, aware, and conscious (Figure 4). The researcher mostly collected data in the evenings and accordingly reflected on the behavior of that day. This moment of engagement was most likely a result of the location of the data collection paper. They observed that certain activities cannot be changed in a short term, like driving with a polluting car (Figure 4). Furthermore, they observed that a student is often switching places during the week, wheras a family household generally has more structure. On the second day of the study, the researcher turned off the TV because it was only used as background sound and they became curious about the effect of this action (Figure 4). While collecting data, more awareness arose about individual behavior. The researcher experienced it as useful to compare environmental behavior of the same type of households as it is more directly related to personal environmental behavior. Additionally, they preferred to keep information private from visitors and noticed that when they shared information about the climate impact of different activities with outsiders, they reacted surprised. Finally, they realized that they were curious to know how other participants were behaving. The week after the study, the researcher experienced an increased awareness of environmental behavior. Before the study, they thought about climate change in general, but did not know how best to adjust their behavior. After the study, they noticed that they could make conscious choices in daily behavior and that, for example, showering behavior was adjusted.

### Conclusion Domain Study

Our domain study helped to show that a reflective medium triggered curiosity and helped in raising awareness on the sustainability of everyday behaviors. By including different activities, it allowed people to adapt behavior on the short-term (i.e. water usage) and over long-term (i.e. transport). The auto-ethnographic study confirmed previous insights from *Econundrum* [36] about the added value of a social frame of reference in raising environmental awareness. We learned from

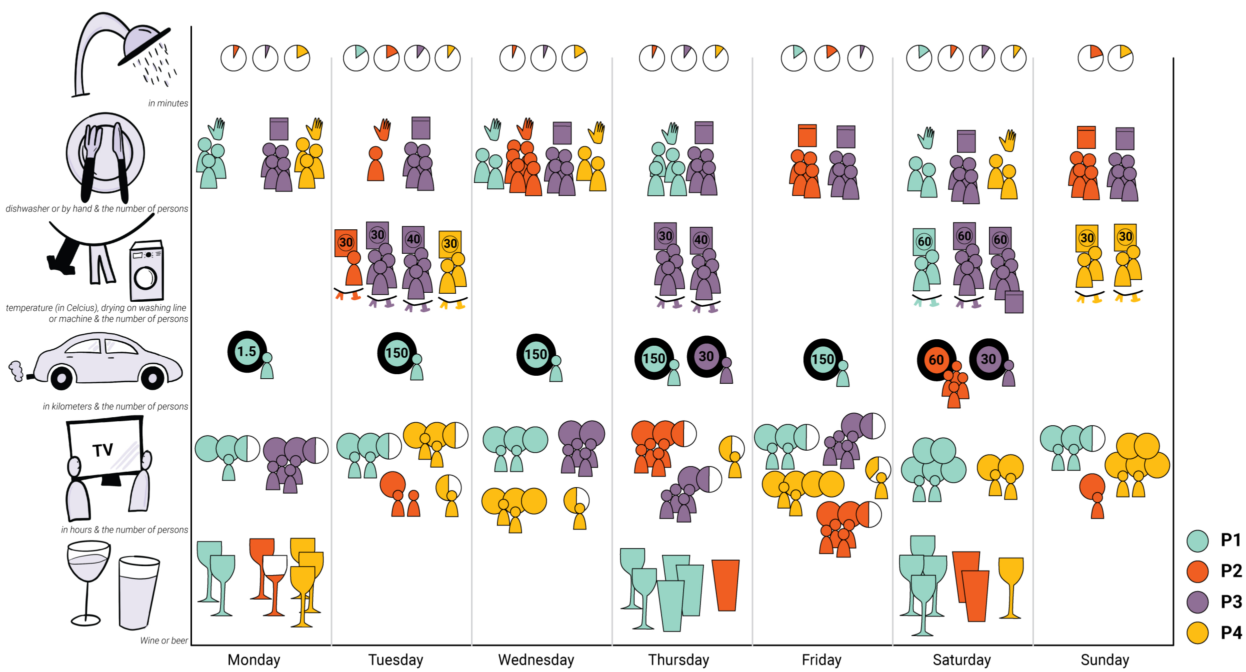



**Figure 3**: A week overview of the quantitative data from the diary study, for each day is diplayed which activities have been performed. Each participant is indicated by a different color, and for each activity the corresponding unit(s) is/are provided. For example, for 'doing the dishes', it is indicated per day how the dishes are done (by hand/machine) and for how many people.

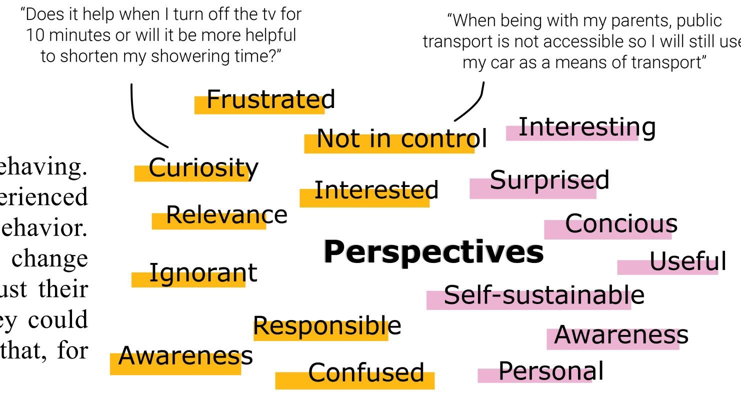



**Figure 4**: A representation of the lead researchers's (P4) perspective before (orange), and after knowing the climate impact of everyday behavior (pink).

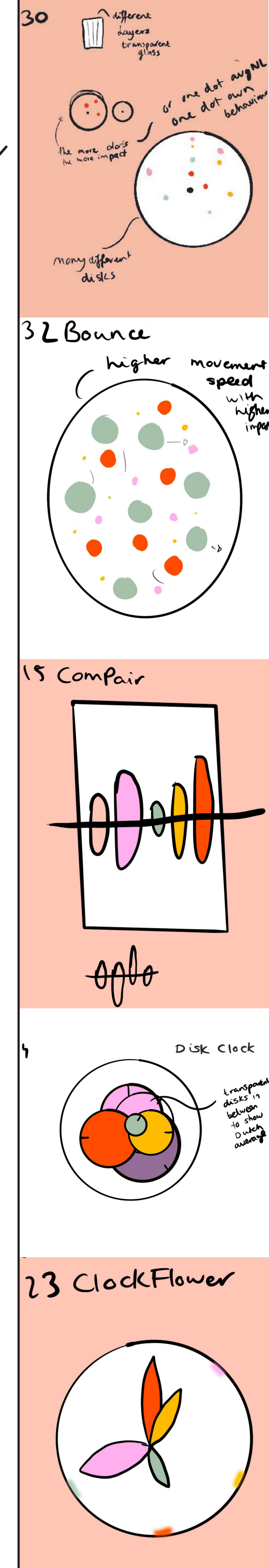
the diary study that the six categories are good units of data collection for our purpose. Besides, the diary study and auto-ethnographic study showed that a shared data sculpture can be especially relevant for family households, as certain activities are performed for/by a whole household. The researcher concluded that it would be best to communicate the underlying data in an abstract way, as they experienced that information was preferably kept private in the auto-ethnographic study. As such, this abstract representation can trigger curiosity of individual environmental behavior and promote a personal connection towards a complex and vast topic such as climate change. Finally, the auto-ethnographic study showed that the data sculpture should be positioned in a shared space.

## DESIGN PRINCIPLES

Previous research has shown that eco-feedback technologies including social comparison, personal reflection, physicality, and immediate feedback facilitated environmental awareness [12, 33, 36]. The combination of a literature review and domain study resulted in an improved understanding of designing a data sculpture for a home context. From these activities, we extracted the following design principles:

**D1. Family Household** – Similar to *Physikit* [19], the system focusses on family households as unit of analysis. The diary study confirmed that the system can be best designed for a family household as these generally have the most structure in their weekly routine. Moreover, the majority of everyday behaviors were performed as/for a whole household, like watching

5 of the 50 sketches with the most potential after the matrix analysis.




tv and doing the laundry. It is therefore most valuable to give a data overview of the complete household rather than individuals. Furthermore, by focusing on larger family households with more than two members, the intervention could have more collective impact.

**D2. Shared Space** – Within the family household, the physical artifact should be positioned in a shared space to allow for all members to reflect on their environmental behavior. Moreover, positioning the artifact in a central location will facilitate a meeting place for discussion [36]. Finally, prior work on *LOOP* [37] and *Physikit* [19] showed that a data-driven object in the home environment led to shared engagement and to new moments of individual engagement.

**D3. Weekly Abstract Overview** – The diary study showed that not all activities were performed daily. Hence, it is more effective to provide a weekly overview of the climate impact of everyday behavior, as it allows for post hoc reflection of behavior. To keep the information private but accessible, it is best to communicate data in an abstract way, and generalize categories into overarching themes, such as water consumption and electricity usage, to allow users to gain a general understanding of their environmental behavior. This resonates with the suggestion from Schneiderman [40] to always have a general overview of information and provide detailed information on demand.

**D4. Personal Data** – Self-monitoring [24] should be included within the ecology of the physical artifact as it will help users to reflect on behavior, which was also found in the study of *Econundrum* [36]. Furthermore, by showing personal information, people feel more connected and feel more personal relevance to the communicated information as was also stated in *Econundrum* [36]. Feedback should be communicated in the shared physical artifact immediately after users entered their data to avoid feelings of confusion, which is also supported by related work [33].

**D5. Social and Historical Frame of Reference** – As was mentioned in previous research [11, 19, 36] and confirmed in the domain study, the implementation of a frame of reference helps in stimulating personal reflection, social comparison, and the understanding of a complex and abstract topic. The diary study confirmed that curiosity arose towards environmental behaviors of others. To create the frame of reference, the average climate impact of the same type of households should be communicated in the designed system. Moreover, to compare environmental behavior, a historical frame of reference should be implemented in the designed system. In this way, it allows households to reflect on behavior of prior weeks which could stimulate a change in behavior and an increased environmental awareness.

**D6. Peripheral** – By allowing for peripheral interaction [1] with the physical artifact, the data visualization will merge with the environment similar to other everyday objects. In addition, glanceable peripheral interfaces [26] allow for multitasking and spontaneous interactions with the data sculpture, as observed in prior work [36].

**D7. Novel Fact** – During the auto-ethnographic study, the researcher experienced increased environmental awareness by knowing about the climate impact of certain products or activities, which resulted in information sharing with others outside the household. By implementing a weekly novel numerical fact on climate impact, the system not only influences one's own household, but also their immediate environment. The novel fact also helps to trigger curiosity and keep households interested over time [48].

## DESIGN EXPLORATIONS

To explore the design, we developed design matrices to evaluate 50 initial ideas. Subsequently, we used experience prototyping to inform the visual vocabulary of the data sculpture. The analyzes of the initial ideas and prototypes were performed by the lead researcher.

### Matrices

Based on the insights from literature and the domain study, two matrices were developed (Figure 5). We created two matrices to filter the most promising ideas out of 50 initial sketched ideas. In matrix 1, the *clarity* of the idea is positioned on the x-axis as the information on environmental behavior should be communicated in a clear, simple, and understandable way. The y-axis reflects on the *peripheral* nature of the ideas as it is important

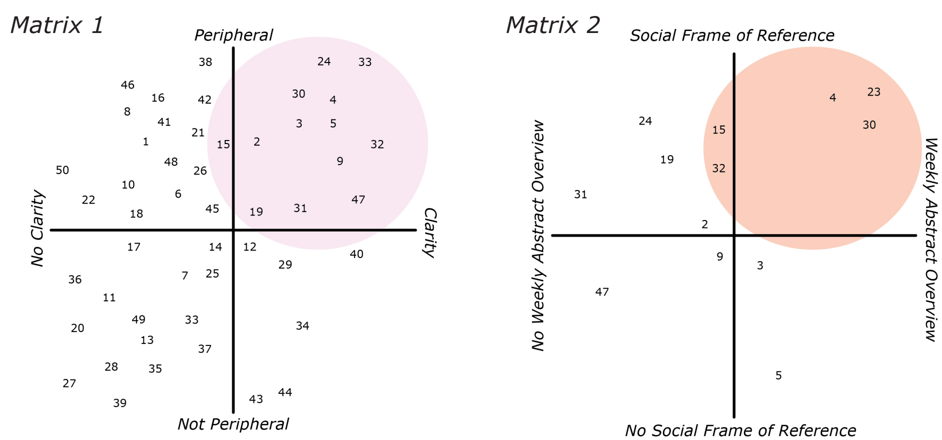



**Figure 5**: The 50 sketches were analyzed by the first matrix where the ideas were evaluated on their Clarity and the ability of the data sculpture to be Peripheral. The 13 concepts in the pink area of matrix 1 showed most potential and were analyzed again on their ability to allow for Shared Reflection and to provide a Weekly Overview in an abstract way. Finally, the concepts in the orange area had the most potential overall and were used as starting point for the prototyping.

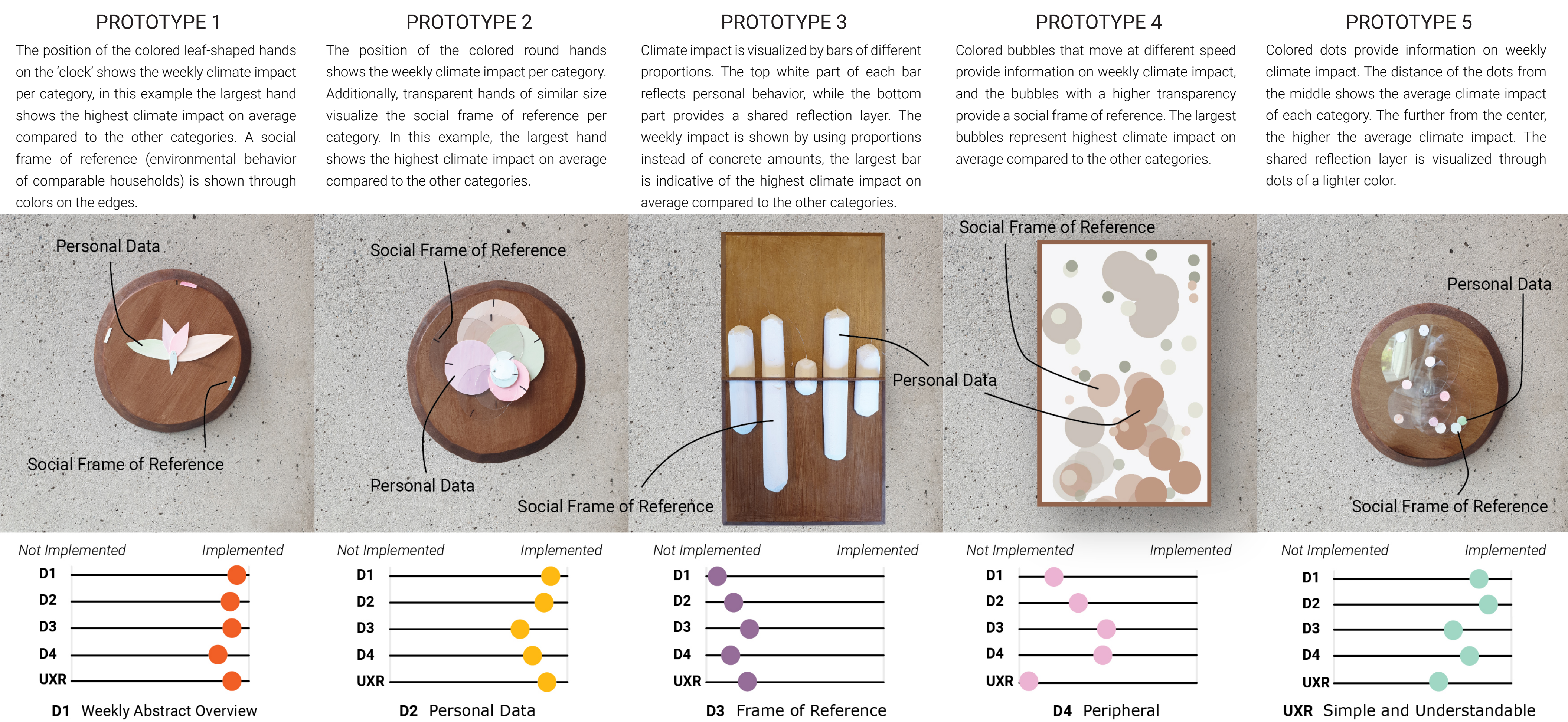



**Figure 6:** 5 different ways to represent personal environmental behavior.

that the design merges within the home context. Matrix 2 presents the *weekly abstract overview* on the x-axis and the *social frame of reference* element on the y-axis. Figure 5 illustrates that 5 ideas for climate change communication showed most potential.

### Experience Prototyping

The 5 most promising ideas were physically developed to further investigate their pros and cons as a climate communication means (Figure 6). The 5 prototypes were analyzed by determining the implementation of four applicable design principles: *weekly abstract overview (D3), personal data (D4), social frame of reference (D5)*, and *peripheral (D6)*; and their user experience *simple and understandable (UXR)*. This process gave the following insights:

Overall, Prototype 3 showed the least potential as it was perceived too abstract for people to be able to extract clear information for personal reflection and social comparison. Likewise, for Prototype 4 our analysis showed that a digital 2D representation of the data was not desirable, as occlusion of the bubbles could occur. Moreover, the change in speed to show data changes might not be very intuitive. During the prototyping process, we decided that the clock concepts should also give information on the average climate impact per category so households can get an understanding of the general climate impact per person. Prototype 5 was the clock with the least potential as the dots and their meaning were the most complex to understand.

Prototype 1 and Prototype 2 showed the most potential as because the user experience of both prototypes is experienced the best and ensures an understanding of the personal data and the social frame of reference. However, we experienced that Prototype 2 was a bit ambiguous when trying to obtain information about the average values of other households because of the transparent disks. In contrast, Prototype 1 shows a social frame of reference via the edge. The 'flower' shape also relates to the environment. Therefore, Prototype 1 showed the most potential and was used as starting point for an in-depth exploration. All insights from the initial prototypes were used to develop two new variations of Prototype 1; Prototype 6a and 6b (Figure 7).


**Figure 7: Prototype 6a** is a physical representation of environmental behavior in the form of a clock. The hands are leaf-shaped similar to a flower, and each size represents relative impact of a particular category. After entering data via the smartphone application, the hands will move and provide information on the weekly environmental behavior of a household. Through lights in the inner edge, a social frame of reference is created. **Prototype 6b** is similar, with the difference that the leaf-shaped hands are of equal size and covered with fabrics of different textures, to convey level of adaptability of each category. After entering data via the smartphone application, the hands will move and provide information on the weekly environmental behavior. In the inner edge, the same fabrics are used to provide information on the average climate impact of comparable households in the Netherlands. This allows users to touch the artifact to gain information.

We explored various materials during the prototyping process, and found that using a natural material such as wood would make the artifact look aesthetically pleasing in the home context. During the making process questions arose such as *"What is the added value of making a data sculpture if you are not able to physically interact with the clock?"*. Therefore, another version of Prototype 6a (Prototype 6b; Figure 7), with a similar shape, was developed to explore information collection through touch.

### Final Concept Development

Through the stages of prototyping, we obtained the following insights. First of all, we concluded that the different activities should be generalized into higher level categories (i.e. water, transport, drinks etc.), and the design of the hands should relate more to the actual information it conveys, while also maintaining privacy. Prototype 6b already showed more connection to the different categories by making a difference in adaptability (i.e. how easy it is to adjust behavior) through different materials. However, to make each higher level category stand out more we decided to represent each of them in a seperate 'clock' and use different patterns to indicate level of adaptability (Figure 8). Moreover, we realized that the data sculpture should include a historical overview to create a frame of reference for the household itself. In that way, weekly environmental behavior could be compared and households could see if their behavior improved. Hence, we envisioned a textual output that would capture weekly snapshots over time, and allow for static historical references while the visualization remains real-time. Besides, a practical challenge that comes with the design of a traditional 'clock' is that shape change is bounded to 360°, and the hands do not give indication of rotations beyond. Therefore, we imagined the hands not to be individual pointers, but to be transparent layers so we could visualize rotations beyond 360° through overlap of the material. These insights formed the foundation for the development of the final concept (Figure 8).

## ECORBIS

The goal of *Ecorbis* is to create environmental awareness and make people aware of how their everyday behavior influences the climate. The system of *Ecorbis* (Figure 9) consists of three design elements: (i) a smartphone application, (ii) the data sculpture with visualization of the data, and (iii) the printed receipt. Based on prior work [34], we present these elements according to three layers of information that together facilitate environmental awareness: (i) personal reflection, (ii) visual vocabulary, and (iii) frame of reference.

### Layer 1 Personal Reflection - Smartphone Application

*Ecorbis* visualizes the climate impact of everyday life of five different categories: (i) transport, (ii) electricity, (iii) water, (iv) paper, and (v) drink consumption.

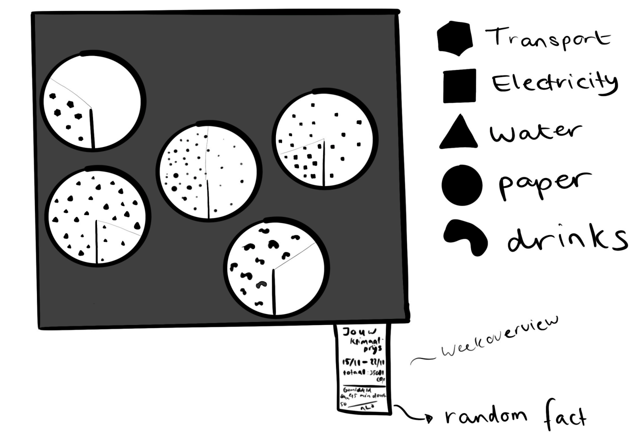



**Figure 8**: Initial sketch of *Ecorbis*.

The different categories and the related activities are chosen based on insights from the design process. The 'carbon footprint' is a commonly known way to translate environmental information, and represents the total amount of carbon dioxide that is directly and indirectly emitted by an activity or product [49]. The carbon footprints of the activities were estimated based on information from the book *How Bad Are Bananas?* of Berners-Lee [4]. To make it accessible for people to report behavior, the different activities contain closed options. For car use, for example, participants have the

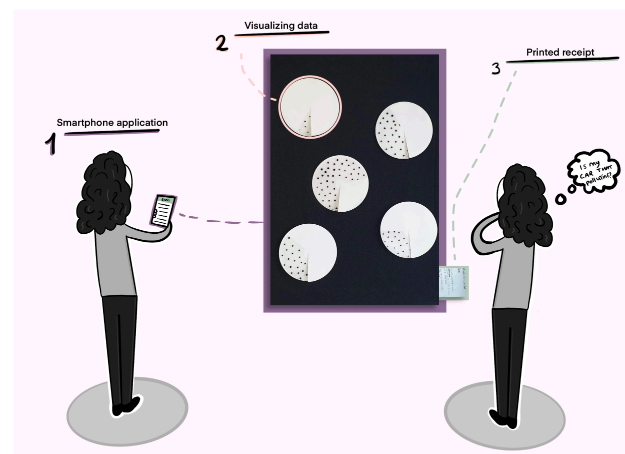



**Figure 9**: The 3 design elements of *Ecorbis:* a smartphone application, physical data sculpture, and printed receipt.

option to choose for a short trip, middle long trip, long trip, or extra-long trip. Transport includes the activities: train, bus, and car. Electricity involves the tumble dryer and watching TV. Water includes using the washing machine, showering, taking a bath, and doing the dishes. All elements from the category ‘water’ also use electricity, which is indicated by putting the electricity icon behind the activity but it is only visualized in the category ‘water’. Paper includes toilet paper and newspaper, and drink consumption involves coffee, tea, beer, wine, and water.

### Layer 2 Visual Vocabulary − Disk Design

The collected data of everyday behavior is communicated through a data sculpture (Figure 9). In contrast to Prototype 6a, the starting point of the ‘clocks’ are at the bottom similar to common ‘energy meters’. The icons as used in the smartphone application (Figure 10), are related to the icons used in the data representation (Figure 8). The more angular the shape (i.e. more vertices and less organic), the less easy it is to change the behavior. By using these abstract icons, the communicated information remains private. After data is entered in the smartphone application, the transparent disks start rotating to the total climate impact of that week (Figure 9). Each disk with abstract icons exists of several layers of transparent disks (4 or 5) and are connected using transparent tape to create a spiral of transparent layers. This spiral allows for shape-change by increasing the spatiality of the data representation [34]. The spiral allows rotating the disks 3 or 4 times. In this way, information on less polluting categories, such as ‘drinks’, can be obtained without being minimalized by ‘transport’. One rotation of a disk is equal to 60.000 gram of $CO_2$ and this amount was based on the insights from the diary study. The shared physical artifact shows data of environmental behavior for a week to allow for personal and household reflection.

### Layer 3 Frame of Reference − Printed Receipt

The last system component is the receipt (Figure 10), which is printed weekly. Prior research showed the potential for printed receipts with related information

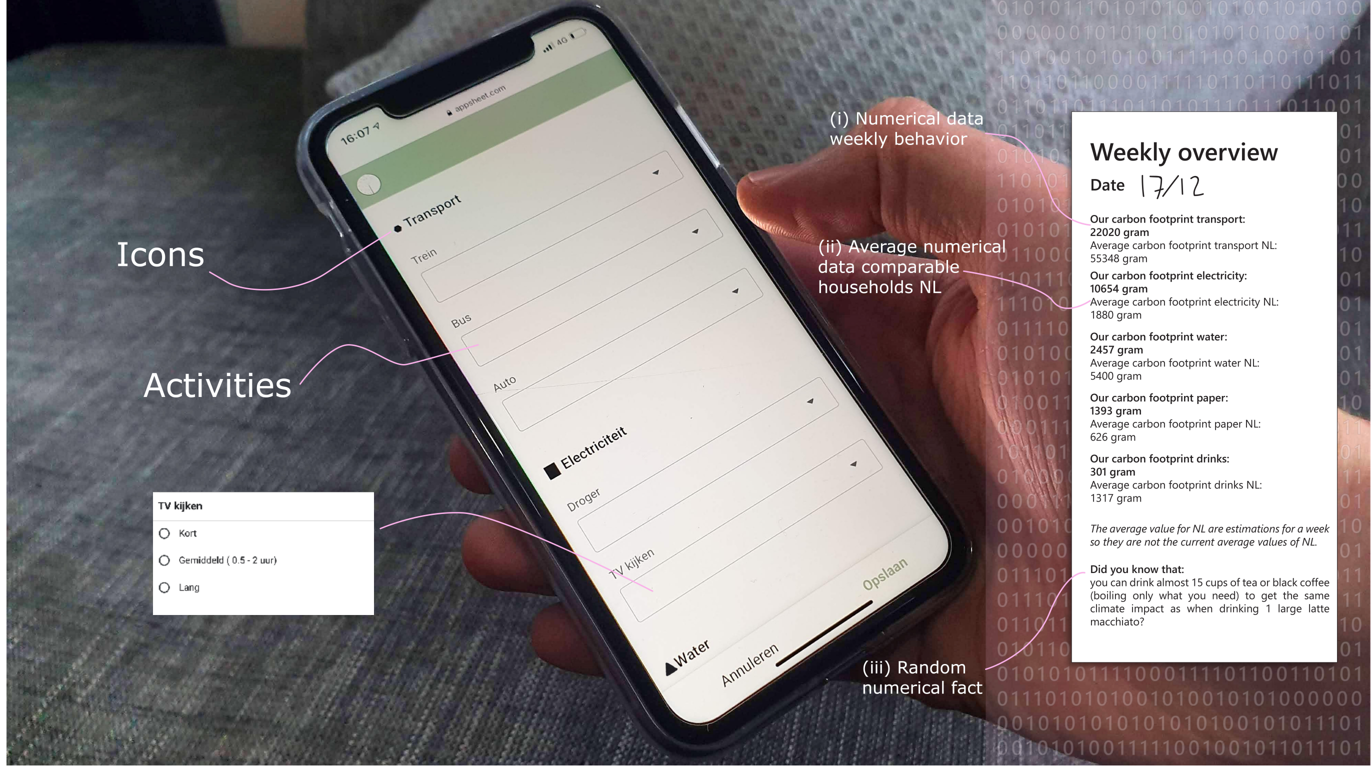



**Figure 10**: Impression of the smartphone application and the printed receipt.

to act as a conversation starter [26]. The receipt consists of three elements: (i) numerical data on weekly environmental behavior, (ii) average numerical data of comparable households in the Netherlands, and (iii) a random numerical fact comparing two activities and/or products. The numerical data of the environmental behavior shows the total carbon footprint of each category. The printed receipt allows for comparison of different weeks. Besides, for each category, the average total carbon footprint of comparable households in the Netherlands is shown to create a social frame of reference. Lastly, the receipt shows a random fact that relates climate impact to everyday activities to create another new frame of reference. Figure 10 shows an example of a novel fact.

### Implementation

We developed a smartphone application using a Google Form [14] and AppSheet (Figure 10) to allow for participants to collect data of their own everyday behavior. For a week, data was stored in a Google Spreadsheet [15] which communicated data to a Wi-Fi-enabled micro-controller in the data sculpture. The transparent disks are made of 2 mm thick acrylic and have a diameter of 19 cm. The black patterns were stencilled on the disks. Similarly, the white disks were also made of 2 mm thick acrylic, but with the back spray-painted white. The spirals are connected to stepper motors to allow for the rotation of the disks. A piece of dark felt-like fabric was used to make the disks stand out and to make them fit within a home context. A reset button is part of the system to bring the disks to the start position every time *Ecorbis* is turned off. The Wi-Fi-enabled microcontroller sends data to a larger microcontroller that controls the stepper motors and the mini thermal printer. The microcontrollers are powered by a power bank, and the printer and stepper motors by a 5V adapter.

## FIELD STUDY

The goal of the final study was to investigate how our layered data sculpture, *Ecorbis*, was perceived by households and how it could create environmental awareness in a home context.

### Participants

Two households were recruited by convenience sampling via face-to-face contact. Household 1 consists of four family members, of which three participate in this study. Household 2 consists of four participants. The average age of the participants is 41 years ($\sigma = 17.69$). All participants indicated being aware of climate change as a problem, but mentioned not being aware of how different activities compare to each other. The families were already behaving climate-consciously in some areas, for example by separating waste or turning off the lights when not needed. Since the studies took placing during Winter holidays, the weeks were structured slightly differently than usual. Additional information on the participants can be found in Table 1.

### Procedure

Before the study started, participants were asked to sign an informed consent after which *Ecorbis* was installed in the households and connected to the Wi-Fi. Afterwards, the smartphone application was added to the mobile devices of the participants. The study started with an interview to collect demographics and gain insights on participants' current attitude and behavior towards climate change. The participants were handed the Climate Change Attitude Survey [7] to gain insights into their attitude towards climate change. After the interview, which took approximately around half an hour, the participants were introduced to *Ecorbis* and were asked where they would position *Ecorbis*, which was in the dining room (household 1) and the living room (household 2). We asked about their first impression of the design, after which we further explained the system and handed over the diary. For a week, the participants reported their everyday behavior via the smartphone application. Additionally, participants used the physical diary to answer short daily questions about their experience with the *Ecorbis* system (i.e. questions about feelings and awareness) and the position of the disks. After a week, participants returned the diaries and we held a group discussion in which insights from the study were discussed. At the start of the final group discussion, the Climate Change Attitude Survey [7] was used again to compare their attitudes before and after the study.

| # | Household Number | Age | Gender | Occupation | At home (weekdays) |
|---|---|---|---|---|---|
| 1 | 1 | 52 | Male | Full-time job | Evenings |
| 2 | 1 | 51 | Female | Part-time job | Daytime and evenings |
| 3 | 1 | 21 | Male | Full-time job | Evenings |
| 4 | 2 | 61 | Male | Full-time job | Evenings |
| 5 | 2 | 54 | Female | Volunteer work | Daytime and evenings |
| 6 | 2 | 24 | Male | Student | Daytime and evenings |
| 7 | 2 | 21 | Female | Student | Daytime and evenings |

**Table 1**: Demographics of the participants of the field study.

### Data Collection & Analysis

We gathered quantitative data via the smartphone application and the Climate Change Attitude Survey [7]. The smartphone application collected timestamps of entries, the categories entered, and the total climate impact of households per category. Additionally, we gathered qualitative data from the interview, the group discussions, and the diary study and used it for a thematic analysis [16]. All interviews were audio-recorded with the consent of the participants and were transcribed by the researcher. We analyzed the quotes and categorized them into 11 themes. The interviews were conducted in Dutch, after which quotes presented in the result section were translated to English.

## FINDINGS

Herein, we first discuss our quantitative results and then present the themes extracted from the qualitative data.

### Quantitative Data

The quantitative data showed 348 data inputs through the smartphone application. In total, household 1 had 160 data inputs via the smartphone application with an average amount of 53 data inputs per person for 8 days. Household 2, had 188 data inputs via the smartphone application with an average amount of 47 data inputs per person. Figure 11 visualizes the data inputs for the different categories per day for both households. The results of Figure 11 show that not all categories did have an input every day which confirmed the insights from the diary study. It also shows at what moment of the day data was submitted to the app. In total, 57 data entries were submitted in the morning (3pm – 12am), 89 data entries in the afternoon (12am – 6 pm), and 91 data entries in the evening (6pm – 3am). This illustrates that most of the time data is submitted in the afternoon and evenings, when most participants are at home. The aggregated questionnaire data on climate attitudes (5-Likert scale, $\bar{x}$: 4.33, $\sigma = 0.73$) shows that participants believe the climate is changing and show an intention to change their behavior as a result. Table 2 shows the total carbon footprints for both households. For household 2, transport goes beyond the boundary of the data sculpture of 240.000 gram $CO_2$.

### Qualitative Data

We present our qualitative findings through 11 themes: general insights, awareness, understanding, personal data and overview, social comparison, historical comparison, physicality and location, shape and aesthetics, weekly overview, periphery, and novel fact.

***General Insights*** − Overall, *Ecorbis* was well received by both households and they found it interesting to participate in the study. Household 1 indicated that such a system does not exist yet. Participants indicated they were concerned about the climate but also explained that sometimes a certain trigger is needed: *"Actually, I think about it only when I see it on TV"* (P2). We observed that especially financial aspects triggered participants to make a change in behavior: *"If you show a positive climate attitude, that will also be felt in your wallet"* (P4). It was also indicated as challenging to change current behaviors and P7 felt that a systemic approach is needed to tackle a problem such as climate change, including action of the government.

| Categories | Household 1 | Household 2 |
|---|---|---|
| Transport | 163653 | 462508 |
| Electricity | 7455 | 4582 |
| Water | 17976 | 26913 |
| Paper | 7070 | 3460 |
| Drinks | 9868 | 12152 |

**Table 2**: The carbon footprint (in grams) per category per household.

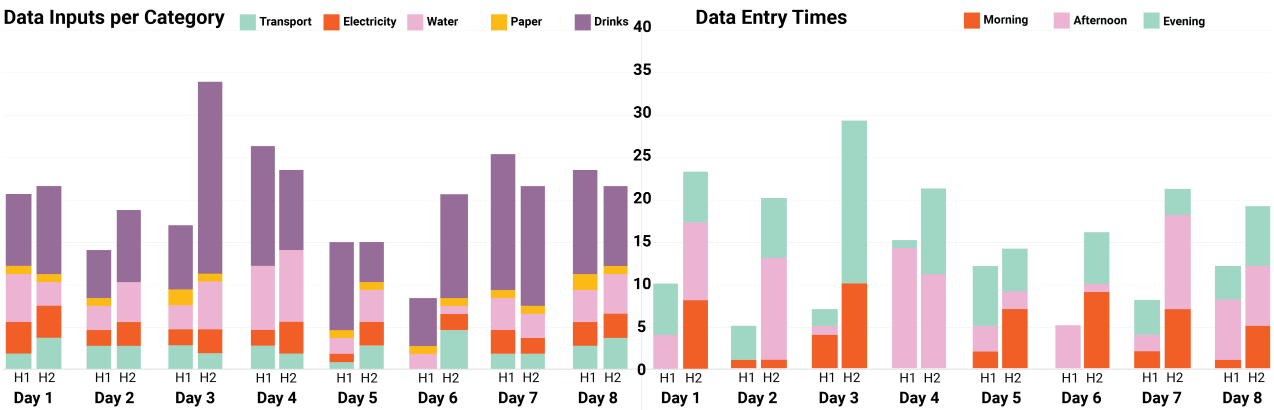



**Figure 11**: The left diagram shows the number of data inputs per category per day for both households. The right diagram shows on which moment of the day data was submitted by both households.

***Awareness*** – Before the participants started using the system, they were not aware of what activities could be changed to reduce their climate impact, but P1 did have a suspicion: *"I immediately think of power guzzlers or gas"*. P1 also indicated the following: *"Maybe a bottle of wine is even worse for the environment than 5 times using the tumble dryer, but I don't really know that."* When participants were asked about a specific goal for the week, P5 mentioned: *"Then I would first have to know what I have to save on [..] I'm very curious about that"* and P7 said: *"It is mainly my goal to gain insights on my climate impact and then I can see what I am going to do with the information"*. We observed that *Ecorbis* in combination with the smartphone application let participants think about their behavior. Members of household 1 indicated the following in their diary: *"My impact is especially big because of my car usage"* (P1). P2 and P3 also asked themselves: *"Is the climate impact of electrical driving also that big?"* All participants experienced an increased awareness, for example P2 and P3 indicated in the diary that *Ecorbis*'s system helped them to think consciously about everyday behavior and P5 mentioned: *"Ecorbis is a great way to make you aware of your environmental behavior."* In group discussions, participants mentioned that a longer period of use would provide better insights to eventually change behavior. Figure 11 shows that the number of data inputs did not decrease throughout the week. In combination with the results from the group discussion, it can be said that the participants showed sustained engagement with the system. On the last day of the study, P1 noted in the diary that it even felt like a routine. Lastly, the group discussions showed that for five participants the system resulted in discussions outside the home which is also indicative of and increased awareness of the participants.

***Understanding*** – At the beginning of the study, participants needed an explanation to get started. During the group discussion, we observed that the households did not know which category belonged to which disk. This shows that either more time is needed to gain knowledge, that the icons need to be adjusted, that more information should be provided through the smartphone application, or that information should be revealed on the data sculpture when participants want it. P1 and P3 stated in the diary that it would be valuable to put letters of the categories on the physical artifact to distinguish categories. These participants wrote in their diary which categories belonged to which disks. Four participants also indicated that they especially entered data when having sight on *Ecorbis* to see how the disks rotated. This shows that participants tried to understand how their everyday behavior influenced the climate. This is also linked to the quantitative data from Figure 11, that showed that participants mostly reported data in the evening or the afternoon, which were the moments the they were mostly at home. However, P6 mentioned the following: *"I did not see the disks move very much so I stopped watching the disks after filling in the data."* This indicates that the value of 60.000 $CO_2$ for one rotation may be too low to get specific insights about all categories, except for transport. P2 mentioned a number of times during the discussion that transport should be omitted from the physical artifact and also P1 indicated that the category of transport was not motivating: *"Driving is very harmful to the environment. My insights are not as specific for the other categories."* This shows that transport is a complex category and that the impact of transport overshadowed the other categories in the data sculpture. However, P1 also indicated: *"Transport does have the most impact, so you can do the most about it yourself."* Lastly, P7 suggested to add numerical data of the climate impact of the particular activities to get more insights into the impact of specific activities.

***Personal Data and Overview*** – We observed that participants experienced the system as innovative and P1 indicated: *"You normally have an idea about climate change or you read something about it in numbers, but that is not visual"* where P3 added the following: *"In this way you experience it yourself!"* Both households indicated that the privacy aspect of visualizing data was not a problem and that they would not mind if visitors understood their data. This may also be due to the fact that climate behavior is shown for the entire household instead of individuals. Within both households, discussion arose on communicating personal data to participants to make it personal for individuals. Household 1 agreed that a household overview would be the best because some members also performed tasks for other members, such as washing. P5 also indicated: *"We occasionally said to each other: have you already filled in your data?"* which shows collective engagement.

***Social Comparison*** – Both households indicated during the discussion that they did not know how an individual change in behavior would help the climate: *"What is my* *personal contribution if I see all those factories?"* (P2) and *"Will it help if I turn off my lights for just half an hour?"* (P2). P5 and P7 also showed curiosity for the environmental behavior of household 1. This indicated an interest towards social comparison. However, four participants indicated that it must concern information from the same type of households: *"If there are big differences and they are somewhat the same type of households, I would like to know how they behave differently"* (P5). P3 also mentioned that through a social comparison, points of improvement are more visible. P7 also would like to compare environmental behavior between members of their own household.

***Historical Comparison*** − *"I would be especially interested in comparing my own behavior"* (P3). This quote shows a preference of a historical frame of reference. P1 mentioned that it would be interesting to compare 'days', in the situation of the study. P5 suggested to print the overview of own environmental behavior on a weekly basis: *"It's about comparing a pattern"* (P5). Besides, P2 explained that historical comparison would also trigger personal reflection: *"I have to know how it is possible that I have less impact for a week and then I have to think about it carefully."*

***Physicality and Location*** − Both households positioned the artifact in a place where discussion could be triggered. Household 1 agreed that the physical artifact could be best positioned in the dining room (Figure 12): *"In that way, you can discuss about the artifact together"* (P3). Household 2 indicated to have little space in the dining room and positioned *Ecorbis* in the living room. P7 mentioned the usefulness of having the information physical: *"I think that when it's physical that you pay more attention to it because you actually see it. With a phone you really have to look up information, which you probably will not do."* Within both households, discussion arose whether the physicality is essential for communicating information on environmental behavior. During the group discussion, a consensus arose within both households that a physical object would be the best way to communicate information about climate change. P2 said: *"You have to see the object because an iPad ends up in a drawer"* and the participants agreed that an overview on the smartphone would be forgotten over time. P2, P4, and P6 also indicated that it would be best to make the physical artifact smaller so that *Ecorbis* could hang on the wall. P4 said: *"The smaller, the easier!"* and P2 commented more than once on the size of the artifact. It was communicated to the households by the researcher that in the ideal scenario the prototype would be a small artifact for on the wall. The physical receipt was perceived as contradictory: *"It would be nice if the receipt could be arranged in a different way, such as via the app so that it is more environmentally friendly"* (P2). However, in general, the receipt was perceived positively and P5 used the receipt as a point of discussion with visitors.

***Shape and Aesthetics*** − Regarding the shape and aesthetics of *Ecorbis*, insights emerged about the possibility of personalizing and/or resizing the design. We observed that the overall experience of the physical artifact was positive: *"I believe it is a very nice object"* (P5). P4 said: *"You can make climate change insightful in this way!"* Participants suggested that a personalized data sculpture would be nice: *"It would be nice if you could choose your own style. So if you have an industrial interior you can also choose an industrial designed artifact"* (P1). P5 also mentioned: *"I think it looks nice. It is very neutral. Of course you can make all kinds of beautiful things out of it later."* P1 added that contrasting colors are needed to make it visually clear.

***Weekly Overview*** − The group discussion showed that a weekly overview would fit best in communicating information on environmental behavior. P7 supported this consensus: *"I think a week would be best. Not a day, that is too short to show a pattern"* and also P6 substantiated the choice for a week overview: *"When doing it for a month, you might start forgetting things you entered."* Household 1 had an extensive discussion on this topic but finally all agreed that a weekly overview would be best. P3 suggested to show a complementary daily overview via the smartphone application.

**Figure 12**: *Ecorbis* positioned in the dining room of household 1.

***Periphery*** − P1 preferred the idea of the artifact on the wall and P2 also indicated: *"In that case the artifact is less noticeable."* P5 mentioned that *Ecorbis* was never disturbing to the household members eventhough the artifact was visible at all times, indicating that the object was in the periphery. Nonetheless, *Ecorbis* immediately attracted the attention of the visitors according to P5.

***Novel Fact*** − The innovative fact that was displayed at the bottom of the receipt was received positively. P5 mentioned that especially the facts helped to start thinking about own behaviors. During the start interview, the researcher also communicated a fact about the climate impact of two activities to household 1, after which P2 said: *"I think it's interesting that you come up with good examples. [...] I think an example is good for many people to create awareness."* We also observed that especially the concrete examples stuck in people's minds and P1 mentioned: *"The facts make it fun. In that case, it is not abstract anymore."* P2 described curiosity towards the facts and said that it would be best if a new fact is communicated every week. Besides, P4 and P5 mentioned that the novel facts were shared with others.

## DISCUSSION

This study showed that a personal data sculpture such as *Ecorbis* can create awareness on environmental behavior. Through reflection, households gained insights into how different categories of their personal lifestyle influenced the climate. The numerical data provided an extra understanding of abstract data and the novel fact helped in making the complex information accessible. In addition, our research showed that for creating awareness within a home environment, it is most effective to present a joint representation as many activities are performed for/by several people. Our study also showed that there is a preference towards a physical way of communicating data on environmental behavior as it makes it less easy to ignore and forget. However, an insight that emerged during the research is the possible contradiction with the topic of climate change and the use of a printed receipt in *Ecorbis*. On the one hand, the physicality of the printed receipt was positively received and also served as an object for discussion. Nevertheless, future work could explore more sustainable ways to communicate a historical frame of reference and a novel fact, such as through a smartphone application.

Ferreira et al. [10] discussed previously how climate change communication should focus more on less developed themes (such as Lifestyle), actionability, and further steps for users. Whereas *Ecorbis* was successful in creating environmental awareness on everyday behavior, it did not provide concrete information on the impact of individual activities/products or further steps for more sustainable behavior, which was also observed for *Econundrum* [36]. The study on *Physikit* [19] showed that when households spent most time at home, they were able to make sense of the data as they were regularly exposed to the PhysiCubes. Hence, this implicates that an environmental coupling [38] – in which the physicalization is co-located with its audience – could support regular engagement and sense-making of the data. Moreover, an environmental coupling [38] between the data sculpture and its users allows for people to be flexible when submitting data. Future research could further investigate the influence of different spatial couplings on environmental awareness.

Our study showed promising results in using a combination of numerical data and an abstract data visualization, and it would be interesting to see how the design principles such as the abstract overview (D3) and social and historical frame of reference (D5) can be applied for other topics or within different contexts. To give an example, the complementary smartphone application could be expanded to provide more concrete information and further support the understanding of environmental behavior. Future work could further investigate how a system could elicit environmental awareness, but also promote sustainable behaviors and support users in their journey. In addition, the influence of an extrinsic motivator on behavior and long-term engagement can be examined, as our study showed that a financial element triggers behavioral change. The study on *Watt-I-see* [33] also discussed the lack of an extrinsic motivator to change behavior. Nonetheless, prior research [28] also states that an economic incentive should be handled with care because it can be counterproductive in the long term. An extrinsic motivator that could be examined is goal-setting. Setting simple and immediate goals could be an extrinsic motivator to stimulate long-term engagement and behavioral change [32], for example by adding a threshold value as was done with *Physikit* [19]. It can also be studied how a triggering element in a home environment influences the environmental behavior of households [19]. Such an alert could facilitate focused attention in case a user set threshold is reached. The study with *Ecorbis* shows that a curiosity principle [48], in this case novelty, resulted in curiosity, awareness and shared discussion. Further research could investigate how other curiosity principles [48], such as partial exposure, could trigger long-term engagement.

Our research illustrated how a complex category such as transport can introduce challenges in communicating everyday behavior as it was exponentially more impactful and more difficult to change than the others. Future work could investigate how personalization of the design could accommodate for categories that create exponentially different climate impacts. Similarly to *Physikit* [19], an user interface could allow for the configuration of the visualization to accommodate for any changing users needs over time. For example, users could alter their preferred categories, social and historical frame of reference, making it more likely to sustain long-term engagement.

Prior work [42] discussed how eco-feedback can even go beyond its traditional use and potentially foster engagement and togetherness between separately located families, while also providing a social frame of reference. Whereas some prior work [23] recommends that short-term deployments of climate change communication is beneficial to let them stand out, more long-term use could be investigated. There is an opportunity for larger-scale simultaneous testing to see how (semi-)public social comparison affects environmental awareness. Moreover, the visualization could potentially implement different social frames of reference, for example by placing individual energy usage in relation to larger industrial energy costs. This relates to the notion of Dourish [9] that sustainable HCI should maybe reconsider not to focus on actions of the individual, but how they can be placed in a larger political and cultural context.

## CONCLUSION

To conclude, our study showed promising findings on designing a data sculpture on environmental behavior for the home context. Since climate change is an invisible and intangible problem, it is important to translate this abstract and complex topic into personal, tangible, and actionable information for households. Our initial findings showed that the layered design of *Ecorbis* facilitated the development of environmental awareness which may also alter long-term individual and household behavior. Although no conclusions can be drawn on long-term effects, our study provides interesting routes for future research.

## REFERENCES

[1] Saskia Bakker and Karin Niemantsverdriet. 2016. The Interaction-Attention Continuum: Considering Various Levels of Human Attention in Interaction Design. *International Journal of Design*, 10(2), 1-14.

[2] Mary Barreto, Michelle Scott, Ian Oakley, Evangelos Karapanos, Nuno J. Nunes, Sofia Gomes, and Joana Gomes. 2013. Playing for the planet: designing toys that foster sustainable values. In *Proceedings of the 31st European Conference on Cognitive Ergonomics* (*ECCE '13*). ACM, New York, NY, USA, Article 16, 1–6. https://doi.org/10.1145/2501907.2501947

[3] Caitilin De Bérigny Wall and Xiangyu Wang. 2009. InterANTARCTICA: Tangible User Interface for Museum Based Interaction. *International Journal of Virtual Reality.* 8, 3, 19–24. https://doi.org/10.20870/IJVR.2009.8.3.2737

[4] Mike Berners-Lee. 2020. *How bad are bananas?: the carbon footprint of everything*. Profile Books.

[5] Anne Bowser, Derek Hansen, Jenny Preece, Yurong He, Carol Boston, and Jen Hammock. 2014. Gamifying citizen science: A study of two user groups. In *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW Companion'14)*. ACM, New York, NY, USA, 137–140. https://doi.org/10.1145/2556420.2556502

[6] Abhiruchi Chhikara and Luke Hespanhol. 2020. Rayuela: Delivering Serious Information Through Playful Interactive Installations. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20)*. ACM, New York, NY, USA, 661–667. https://doi.org/10.1145/3374920.3375288

[7] Rhonda Christensen and Gerald Knezek. 2015. The Climate Change Attitude Survey: Measuring Middle School Student Beliefs and Intentions to Enact Positive Environmental Change. *International Journal of Environmental & Science Education*, 2015, 10(5), 773-788

[8] Enrico Costanza, Ben Bedwell, Michael O. Jewell, James Colley, and Tom Rodden. 2016. 'A bit like British Weather, I suppose': Design and Evaluation of the Temperature Calendar. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 4061–4072. https://doi.org/10.1145/2858036.2858367

[9] Paul Dourish. 2010. HCI and Environmental Sustainability: The Politics of Design and the Design of Politics. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10)*. ACM, New York, NY, USA, 1–10. https://doi.org/10.1145/1858171.1858173

[10] Marta Ferreira, Miguel Coelho, Valentina Nisi, and Nuno Jardim Nunes. 2021. Climate Change Communication in HCI: a Visual Analysis of the Past Decade. In *Creativity and Cognition (C&C'21)*. ACM, New York, NY, USA, Article 5, 1. https://doi.org/10.1145/3450741.3466774

[11] Leon Festinger. 1954. A Theory of Social Comparison Processes. *Human relations*, 7(2), pp. 117-140.

[12] Jon Froehlich, Leah Findlater, and James Landay. 2010. The Design of Eco-Feedback Technology. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 1999-2008. https://doi.org/10.1145/1753326.1753629

[13] Robert Gifford. 2011. The Dragons of Inaction: Psychological Barriers That Limit Climate Change Mitigation and Adaptation. *American Psychologist 66*(4), 290–302. https://doi.org/10.1037/a0023566

[14] Google Forms - create and analyze surveys, for free. Retrieved from https://www.google.com/forms/about/

[15] Google Sheets - create and edit spreadsheets online, for free. Retrieved from https://www.google.com/sheets/about

[16] Greg Guest, Kathleen M. MacQueen, and Emily E. Namey. 2012. Applied Thematic Analysis. SAGE Publications, Inc., https://doi.org/10.4135/9781483384436

[17] Edgar G. Hertwich and Glen P. Peters. 2009. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environmental Science and Technology* 43, 16: 6414–6420. https://doi.org/10.1021/es803496a

[18] Matthew J. Hornsey and Kelly S. Fielding. 2020. Understanding (and Reducing) Inaction on Climate Change. *Social Issues and Policy Review* 14, 1: 3–35. https://doi.org/10.1111/SIPR.12058

[19] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. 2016. Physikit: Data Engagement Through Physical Ambient Visualizations in the Home. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1608–1619. https://doi.org/10.1145/2858036.2858059

[20] Yen-Chia Hsu, Jennifer Cross, Paul Dille, Michael Tasota, Beatrice Dias, Randy Sargent, Ting-Hao (Kenneth) Huang, and Illah Nourbakhsh. 2019. Smell Pittsburgh: community-empowered mobile smell reporting system. In *Proceedings of the 24th International Conference on Intelligent User Interfaces (IUI '19)*. ACM, New York, NY, USA, 65–79. https://doi.org/10.1145/3301275.3302293

[21] Rachel Jacobs, Steve Benford, Ewa Luger, and

Candice Howarth. 2016. The Prediction Machine: Performing Scientific and Artistic Process. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. ACM, New York, NY, USA, 497–508. https://doi.org/10.1145/2901790.2901825

[22] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3227-3236. https://doi.org/10.1145/2702123.2702180

[23] Charlene Jennett, Ioanna Iacovides, Anna L. Cox, Anastasia Vikhanova, Emily Weigold, Layla Mostaghimi, Geraint Jones, James Jenkins, Sarah Gallacher, and Yvonne Rogers. 2016. Squeezy Green Balls: Promoting Environmental Awareness through Playful Interactions. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. ACM, New York, NY, USA, 389-400. https://doi.org/10.1145/2967934.2968102

[24] Alan E. Kazdin. 1974. Reactive self-monitoring: The effects of response desirability, goal setting, and feedback. *Journal of Consulting and Clinical Psychology, 42*(5), 704–716. https://doi.org/10.1037/h0037050

[25] Bran Knowles, Oliver Bates, and Maria Håkansson. 2018. This Changes Sustainable HCI. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Paper 471, 1–12. https://doi.org/10.1145/3173574.3174045

[26] Lisa Koeman. 2017. Urban visualisation: the role of situated technology interventions in facilitating engagement with local topics. Doctoral thesis, UCL (University College London). .

[27] Jayadev Madyal, Laura Platte, Julia Arndt, Marlon Spangenberg, and Konstantin Zähl. 2020. MoBi -An Interactive Classroom Robot Helping Children to Separate Waste. In *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (HRI '20)*. ACM, New York, NY, USA, 629–630. https://doi.org/10.1145/3371382.3379459

[28] Ezra Markowitz and Azim Shariff. 2012. Climate Change and Moral Judgement. Nature Climate Change 2, 243–247. https://doi.org/10.1038/nclimate1378

[29] Tara Matthews. 2006. Designing and evaluating glanceable peripheral displays. In P*roceedings of the 6th conference on Designing Interactive systems (DIS '06)*. ACM, New York, NY, USA, 343–345. https://doi.org/10.1145/1142405.1142457

[30] Susanne C. Moser. 2010. Communicating climate change: history, challenges, process and future directions. *Wiley Interdisciplinary Reviews: Climate Change, 1*(1), 31–53. https://doi.org/10.1002/WCC.11

[31] Reese Muntean, Alissa N Antle, and Kate Hennessy. 2020. Communicating Sustainable Consumption and Production in 360° Video. Proceedings of the 2020 ACM Designing Interactive Systems Confer-ence. https://doi.org/10.1145/3357236.3395460

[32] Ian Oakley, Monchu Chen, and Valentina Nisi. 2008. Motivating Sustainable Behavior. *Ubiquitous Comput*, 174–178.

[33] Filipe Quintal, Clinton Jorge, Valentina Nisi, and Nuno Nunes. 2016. Watt-I-See: A Tangible Visualization of Energy. In *Proceedings of the International Working Conference on Advanced Visual Interfaces (AVI '16)*. ACM, New York, NY, USA, 120–127. https://doi.org/10.1145/2909132.2909270

[34] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Hu-man Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 735-744. https://doi.org/10.1145/2207676.2207781

[35] Francesca Samsel, Sebastian Klaassen, Mark Petersen, Terece L. Turton, Gregory Abram, David H. Rogers, and James Ahrens. 2016. Interactive Colormapping: Enabling Multiple Data Range and Detailed Views of Ocean Salinity. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 700–709. https://doi.org/10.1145/2851581.2851587

[36] Kim Sauvé, Saskia Bakker, and Steven Houben. 2020. Econundrum: Visualizing the Climate Impact of Dietary Choice through a Shared Data Sculpture. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS'20)*. ACM, NY, USA, 1287–1300. https://doi.org/10.1145/3357236.3395509

[37] Kim Sauvé, Saskia Bakker, Nicolai Marquardt, and Steven Houben. 2020. LOOP: Exploring Physicalization of Activity Tracking Data. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society (NordiCHI'20)*. ACM, New York, NY, USA, Article 52, 1–12. hhttps://doi.org/10.1145/3064857.3079175

[38] Kim Sauvé, Miriam Sturdee, and Steven Houben. 2022. Physecology: A Conceptual Framework to Describe Data Physicalizations in their Real-World Context. *ACM Trans. Comput.-Hum. Interact.* 29, 3, Article 27 (June 2022), 33 pages. https://doi.org/10.1145/3505590

[39] Bertrand Schneider, Matthew Tobiasz, Charles Willis, and Chia Shen. 2012. WALDEN: multi-surface multi-touch simulation of climate change and species loss in thoreau's woods. In Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces (ITS '12). ACM, New York, NY, USA, 387–390. https://doi.org/10.1145/2396636.2396707

[40] Ben Shneiderman. 2003. The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. *The craft of information visualization.* Morgan Kaufmann, 2003. 364-371. https://doi.org/10.1016/B978-155860915-0/50046-9

[41] Wina Smeenk, Janienke Sturm, Jaques Terken, and Berry Eggen. 2019. A systematic validation of the Empathic Handover approach guided by five factors that foster empathy in design. *CoDesign, 15*(4), 308–328. https://doi.org/10.1080/15710882.2018.1484490

[42] Stephen Snow, Dhaval Vyas, and Margot Brereton. 2015. When an eco-feedback system joins the family. *Pers Ubiquit Comput 19*, 929–940 https://doi.org/10.1007/s00779-015-0839-y

[43] Nancy Smith, Shaowen Bardzell, and Jeffrey Bardzell. 2017. Designing for Cohabitation: Naturecultures, Hybrids, and Decentering the Human in Design. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17).* ACM, New York, NY, USA, 1714–1725. https://doi.org/10.1145/3025453.3025948

[44] Yolande A.A. Strengers. 2011. Designing eco-feedback systems for everyday life. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2135–2144. https://doi.org/10.1145/1978942.1979252

[45] Melanie Swan. 2013. The Quantified Self: Fundamental Disruption in Big Data Science and Biological Discovery. *Big Data 1*(2), 85–99. https://doi.org/10.1089/big.2012.0002

[46] The Royal Society and National Academy of Sciences. 2020. Climate Change: Evidence & Causes. The Royal Society. Retrieved from https://royalsociety.org/~/media/royal_society_content/policy/projects/climate-evidence-causes/climate-change-evidence-causes.pdf

[47] Rundong Tian, Christine Dierk, Christopher Myers, and Eric Paulos. 2016. MyPart: Personal, Portable, Accurate, Airborne Particle Counting. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16).* ACM, New York, NY, USA, 1338–1348. https://doi.org/10.1145/2858036.2858571

[48] Rob Tieben, Tilde Bekker, and Ben Schouten. 2011. Curiosity and Interaction: making people curious through interactive systems. Proceedings of HCI 2011 The 25th BCS Conference on Human Computer Interaction. 361–370. https://doi.org/10.14236/EWIC/HCI2011.66

[49] Thomas Wiedmann and Jan Minx. 2008. A Definition of 'Carbon Footprint'. *Ecological economics research trends, 1*, 1-11.

[50] Jack Zhao and Andrew Vande Moere. 2008. Embodiment in Data Sculpture: A Model of the Physical Visualization of Information. *Proceedings of the 3rd international conference on Digital Interactive Media in Entertainment and Arts - DIMEA '08*. https://doi.org/10.1145/1413634.1413696