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Exploring Household Preferences for Visualising Consumption Information: Towards Data Physicalizations to Promote Sustainable Practices

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This paper explores household preferences for visualizing consumption data and investigates the potential of data physicalizations to enhance user engagement and promote sustainable practices within households. We conducted semi-structured interviews with thirteen households, utilizing a combination of images and low-fidelity prototypes to gain insights into participants' preferences, ideas and feedback on visualizing consumption information. We requested participants to discuss an object in their home that symbolizes sustainability. The results revealed different emotional responses, from empathy to repulsion, triggered by different visual representations. Our findings also identified certain physical objects and locations within the household that play a role in fostering family collaboration towards sustainable practices. Participants preferred having a physical representation of their consumption data within their homes over a screen-based display. In light of these findings, we open space to consider designing physicalizations that encourage collaboration, enhance user engagement and motivate households to reduce their consumption.

RESEARCH HIGHLIGHTS

- A study was conducted to explore household preferences for visualising consumption data.
- The study revealed participants' preferences towards physical data visualisations to display household consumption data.
- The study provides insights into considerations for designing physical data visualisations for household consumption.

Keywords: *data physicalization; climate change communication; sustainable HCI; household consumption*.

1. INTRODUCTION

Household consumption plays a significant role in climate change, linked to nearly two-thirds of global greenhouse gas emissions according to consumption-based accounting (UNEP, 2020). (Druckman & Jackson, 2010) identified various household activities contributing to climate change, such as wasting food, commuting and overuse of electricity and heat. These can have detrimental environmental effects, including resource depletion and increased pollution (Orecchia & Pietro, 2007). Efforts to address climate change require innovative strategies to reshape consumption practices (Inyim *et al.*, 2018). Visualizations, which leverage human interest and understanding, can play a vital role in motivating reduced consumption (Meena, 2020). However, people often lack awareness of how their daily activities impact the climate (Stegers *et al.*, 2022). Eco-feedback technology, including various visualizations, has been developed to encourage sustainable practices. These include smart meters and in-house displays (IHD) (Zhang *et al.*, 2019), web-based apps and mobile applications (Katzeff *et al.*, 2020), games (Jan *et al.*, 2021), thermal imaging (Gupta *et al.*, 2018), virtual environments (Chen *et al.*, 2012), tangible user interfaces (Doshi *et al.*, 2017) and data sculptures (Sauvé *et al.*, 2020, Stegers *et al.*, 2022). Data physicalizations, in particular, transform 2D data into interactive objects, integrating information into daily routines (Kuznetsov & Paulos, 2010, Stegers *et al.*, 2022).

Despite these efforts, there remains a gap in understanding the depth of resource consumption (Costanza *et al.*, 2012) in households. Eco-feedback technology, on its own, may not be compelling enough to encourage change in practices (Brewer *et al.*, 2015). While visualizations can increase awareness, they may not necessarily lead to resource conservation practices as they have low engagement as they only convey the problem (amount of resources utilized) rather than making a connection between the problem and a solution (Abrahamse *et al.*, 2018, Goodhew *et al.*, 2014). To bridge this gap, it is essential to consider the complex socio-technical setting of households (Snow *et al.*, 2013). Research in this area should not only focus on functionality but also incorporate aesthetics and the emotional aspects of technology within homes (Mccarthy & Wright, 2004, Perera *et al.*, 2024a, 2024b, Rasmussen *et al.*, 2017, Steg, 2008).

To explore technology design in homes to promote sustainable practices, we conducted interviews with 13 households to further understand household consumption practices as well as contextual factors and experiences influencing household

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consumption practices. We found comforting and revolting images, objects for bonding and home locations that could foster social connections and engagement within households to collaborate towards sustainable practices (Baillie & Benyon, 2008, Choi *et al.*, 2005, Vaisutis *et al.*, 2014). Based on our research, we propose design opportunities for family collaboration and personalization to motivate reducing consumption (Benders *et al.*, 2006, Casado *et al.*, 2017, Desjardins *et al.*, 2015, Salo *et al.*, 2016).

2. Related Work

To situate our work, we consider relevant research in Human Computer Interaction related to visualization of home consumption. We describe eco-feedback visualizations in the literature (screen-based visualizations, ambient visualizations, data physicalizations) and their limitations to highlight the opportunities for design to support household consumption curtailment.

2.1. Technological Efforts Addressing Household Consumption

In the realm of HCI, various visualizations have been developed and assessed for addressing household consumption. Research suggests that abstract representations effectively provide eco-feedback and educate occupants regarding consumption (Goubran *et al.*, 2021). These visualizations offer an opportunity for Sustainable HCI to bridge the gap between the abstract concept of climate change and a tangible, social experience. The focus of recent interventions has shifted from prescribing behaviour to users to designing technology to support the user in the process of moving towards sustainable practices (Laschke *et al.*, 2015, Sauvé *et al.*, 2020).

2.1.1. *Screen-based Visualizations*

Smart meters are implemented to make people aware of their consumption and potentially encourage households to reduce it, though their impact is limited (De Dominicis *et al.*, 2019, Zhang *et al.*, 2019). Challenges in engaging with meter readings include the lack of a clear connection between the problem of overusing resources and potential solutions to reduce it (Goodhew *et al.*, 2014). In addition, the small screens and inconvenient positioning of smart meters hinder their usefulness (Bartram *et al.*, 2010).

Most screen-based visualizations offer promising avenues for encouraging sustainable practices. For example, (Chen *et al.*, 2012) leveraged a virtual aquarium to influence energy savings at home, The Green Machine (Marcus, 2015) is a mobile application that visualizes individual energy usage providing the ability to compare usage with friends, and tips to reduce energy consumption, Ecopanel (Katzeff *et al.*, 2020) explored how visualizing food shopping patterns can impact people's purchasing choices and InterANTARCTICA is an interactive interface engaging users with the consequences of climate change through tangible surfaces (Bérigny & Wang, 2015). Certain screen-based visualizations use gamification techniques, including missions and competition, that can encourage users to take sustainability efforts (Deterding *et al.*, 2011, Xianfeng *et al.*, 2020). It is argued that empathetic visuals can enhance user engagement (Fernando *et al.*, 2009, Stegers *et al.*, 2022) while symbolic feedback (such as visualizing the replacement of trees with appliances (Holmes, 2007)) can raise awareness of climate change (Dillahunt *et al.*, 2017, Nielsen *et al.*, 2015, Pousman & Stasko, 2006). However, screen-based feedback may disrupt visual attention and detachment from the physical environment (Bakker *et al.*, 2015, Eslambolchilar *et al.*, 2023, Jáuregui & Couture, 2019)as fully visual systems, while beneficial, may not be optimal due to the need for intentional effort and focused attention (Bartram, 2015, Sadeghian *et al.*, 2017). To encourage sustainable practices, cohesive visualizations are required, offering continuous engagement, simplicity and guidance for users to act on their consumption data (Darby, 2010).

2.1.2. *Ambient Visualizations*

Ambient displays, integrated into everyday items such as clocks (Broms *et al.*, 2010, Kjeldskov *et al.*, 2015, Rasmussen *et al.*, 2017) and power cords (Gustafsson & Gyllenswärd, 2005), have served as tactile reminders of energy usage. In addition, the Ambient Canvas, a dynamic kitchen backsplash, visually represents energy consumption through layered light waves (Bartram *et al.*, 2011). Metaphors, such as statistical charts illustrating water levels in a washroom, have been used to promote reduced water consumption (Kappel & Grechenig, 2009), though users sometimes revert to old habits after the visualizations are removed (Wemyss *et al.*, 2019). (Iribagiza *et al.*, 2020) developed an In-Home Display (IHD) using a metaphor of a baby's lungs to provide air quality feedback and encourage the adoption of liquefied petroleum gas cookstoves that resonated with households, reminding them of their children's health. However, practical challenges arise with ambient displays, such as the need for suitable placement of the screen display to ensure visibility and usability (Bartram *et al.*, 2010). Moreover, these approaches often remain isolated and lack integration into a holistic household ecosystem that considers the diverse practices and contexts of home life (Bartram *et al.*, 2010, Perera *et al.*, 2023c). Interaction with ambient visualizations might be confined to specific screens or locations and is typically limited to observing or perhaps interacting with a screen, where the level of engagement might be less compared to physically interacting with tangible visualizations (Bartram *et al.*, 2010, 2011, Perera *et al.*, 2023c, Wemyss *et al.*, 2019).

2.1.3. *Data Physicalizations*

A physical artefact whose geometry or material qualities encode data is referred to as a 'data physicalization' or 'physical visualization' (Dragicevic *et al.*, 2021). It offers varying levels of data abstraction by engaging different human senses (Eslambolchilar *et al.*, 2023) to enhance user experience. Data physicalizations, with their artistic and functional qualities, are gaining popularity across domains, promoting public engagement (Daniel *et al.*, 2019) and better user experience (Dumičić *et al.*, 2022, Eslambolchilar *et al.*, 2023, Hornecker *et al.*, 2023, Mccarthy & Wright, 2004, Rasmussen *et al.*, 2012). Unlike traditional visualization techniques on 2D digital displays, physical forms of data visualization improve the tangible aspect of visualizations seamlessly integrating into daily routines and raising awareness of consumption data (Eslambolchilar *et al.*, 2023, Hornecker *et al.*, 2023, Kuznetsov & Paulos, 2010). They provide an abstract understanding of data in the periphery of attention (Bakker *et al.*, 2016, Eslambolchilar *et al.*, 2023) by blending into the background and occupying physical spaces in homes without disrupting people's daily routines (Stegers *et al.*, 2022, Weiser, 1999, Wisneski *et al.*, 1998). This makes them valuable tools for busy lifestyles (Rasmussen *et al.*, 2017), establishing an intimate link between people and the presented information (Jáuregui & Couture, 2019). This facilitates user engagement, emotional connection and sustainable actions. For example, Econundrum (Sauvé *et al.*, 2020) and Babbage Cabbage (Fernando *et al.*, 2009) are physical visualizations that represent carbon emissions and convey social or ecological information, respectively. Ecorbis

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(Stegers et al., 2022) and Flower Lamp (Backlund et al., 2006) are data physicalizations that are intended to help individuals think about household consumption. Peacetime (Katzeff et al., 2017) and Clockcast (Rasmussen et al., 2017) investigated the potential of households' electricity load balancing by shifting consumption times. Further, art installations such as Orbacles and Ice Watch incorporate natural elements to convey sustainability and climate change messages (Eliasson, 2014, TENxTEN, 2017).

This present work aims to explore household preferences for visualizing consumption data by utilizing images from existing literature and low-fidelity prototypes. We used these to present various existing consumption visualizations to households, enabling us to gather insights into households' preferences. This work is inspired by a wide range of literature on consumption visualization discussed above, including screen-based visualizations (Chen et al., 2012, Katzeff et al., 2020, Marcus, 2015), ambient visualizations (Bartram et al., 2010, 2011, Kappel & Grechenig, 2009), data physicalizations (Backlund et al., 2006, Sauvé et al., 2020, Stegers et al., 2022), as well as the integration of features such as shape-change (Rasmussen et al., 2012) and gamification (Gupta et al., 2018). The rationale is that the combination of these elements can provide an understanding of how different visualizations can influence household engagement with consumption data.

3. Study Design

In this study, we conducted 13 semi-structured household interviews to gain insights into households' expectations and preferences for visualizing consumption data (Perera et al., 2023b). We have published a conference paper on this study (Perera et al., 2023a) and here we present an extended version of it expanding on the study design, findings and the discussion sections. An initial survey informed the design of these household interviews, which aimed to investigate various aspects of household consumption, including electricity, gas, water and more (Perera et al., 2023c). Aligning with prior work (Lim et al., 2008), we used low-fidelity paper prototypes and images for communication and idea sharing rather than formal design evaluations (Lim et al., 2008).

An interview approach is well suited for providing an in-depth understanding of real-life contexts, issues and how they unfold in practice (Lazar et al., 2017, Stegers et al., 2022). The semi-structured nature of the questions allowed for flexibility and guided discussions based on participants' responses. This method helped uncover the relationships between households' experiences and existing strategies for reducing consumption, considering the contextual factors (individual, collective, socio-cultural) influencing household consumption practices. The interviews, conducted between July 2022 and October 2022, had an average duration of one hour and a half. They were divided into four parts: understanding daily household activities, exploring existing consumption reduction strategies, assessing visualizations used in the literature and gathering thoughts on proposed technologies and new ideas. While six interviews were conducted in participants' homes, seven were conducted online via Microsoft Teams as the participants opted online meeting due to personal reasons. As the purpose of the interviews was to understand household practices and preferences, conducting some of the interviews online did not impact the quality of the study. All participating households provided informed consent, and participants received a £50 voucher as a financial incentive. Ethical approval for the study was granted by the ethics committee of the School of Computer Science and Informatics, Cardiff University (approval no: COMSC/Ethics/2022/056).

3.1. Participants

Interviews were conducted in Wales, UK, and 13 households were recruited through social media, university groups, and mailing lists. These households included members aged 18 to 54, and all were owner-occupied. In this exploratory study (Allmark, 2004) we aimed for diverse representation, including varying socio-economic contexts, consumers and prosumers (prosumers, accounting for three households, had solar panels, while the other houses did not have solar panels and were active consumers concerned about reducing consumption). Participants spanned different income categories defined by the UK Office of National Statistics (ONS, 2019) and varied in household types, including single-user, couple/partner houses and family homes. The data collection reached saturation after the 13th interview, where the development of new codes significantly decreased. Participants were contacted by email to confirm their willingness to participate and were asked, at this time, to think about household objects symbolizing sustainability or climate change, which provided them with the opportunity to think about their responses ahead of the interview.

3.2. Data Collection

The study included 13 semi-structured household interviews to gain insights into households' expectations and preferences for visualizing consumption data. The interview had four parts: 1) Firstly, participants described their daily actions related to household consumption, 2) Secondly, they explained existing consumption monitoring and curtailment methods in their home, 3) Thirdly, we gathered households' views on consumption visualizations from the literature and 4) Fourth, we displayed two low-fidelity paper prototypes ('moving flowers' and 'Betta fish' in Fig. 1)) and two visualization images ('lighting chandelier' and 'wall-climbing men' in Fig. 1)) to understand participant views and any new ideas. Finally, we asked participants to present the object or image they brought from their home symbolizing sustainability or climate change and describe why and how they think it relates to sustainability. We also requested participants to reflect on the prototypes and images and suggest design ideas. Our participants gave us feedback, comments and critiques on the prototypes and images. Participants also sketched their design ideas while some participants explained their ideas verbally. Participants did not get involved in the actual designing of the prototypes. Instead, we used their suggestions to design and refine the prototypes. The semi-structured household interview can be found in Appendix A (in this paper, we only report on results from activities 3 and 4 in the question guide. Results of activities 1 and 2 are reported separately in (Perera et al., 2023c)).

3.2.1 *Description of the images from the literature*

In the third activity of the study (Appendix A), we selected images from the literature to understand design considerations utilized by prior work to visualize household consumption (Bartram et al., 2011, Dillahunt et al., 2017, Fernando et al., 2009, Gustafsson & Gyllenswärd, 2005, Holmes, 2007, Iribagiza et al., 2020, Quintal et al., 2016, 2013b, Sauvé et al., 2020). We explored participants' opinions about six such considerations based on the literature: 1) use of different colours and lights (Bartram et al., 2011, Sauvé et al., 2020), 2) use of climate-related visuals (visuals attached to nature or climate) (Holmes, 2007, Quintal et al., 2013b), 3) use of empathetic visuals (Dillahunt et al., 2017, Fernando et al., 2009), 4) using images of household objects (visuals attached to a household item) (Bartram et al., 2011, Rasmussen et al., 2017), 5) using images of regular objects (visuals with no attachment to

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TABLE 1. Participant demographics information.

Household (H)	Household type[1]	No. of members in the house	No. of participants in the discussion	Age ranges of the participants	Genders of the participants	Mean average annual household income
H1	NF	4	1	18–24	Male	31k to 36k
H2	SH	4	2	25–34	Male, female	43k to 67k
H3	SH	2	2	25–34	Male, female	43k to 67k
H4	SH	2	2	25–34	Male, female	11k to 26k
H5	NF	3	2	25–34	Male, female	11k to 26k
H6	NF	4	2	35–44	Male, female	43k to 67k
H7	NF	2	1	45–54	female	43k to 67k
H8	NF	3	2	25–34	Male, female	43k to 67k
H9	NF	2	2	45–54	Male, female	> 67k
H10	SO	1	1	35–44	female	36k to 43k
H11	NF	6	1	25–34	Female	43k to 67k
H12	NF	5	2	35–44	Female, female	26k to 31k
H13	SH	2	2	25–34	Male, female	> 67k

[1]Household Type (NF—Nuclear family, SH—Shared house between partners, SO—Singe Occupant)

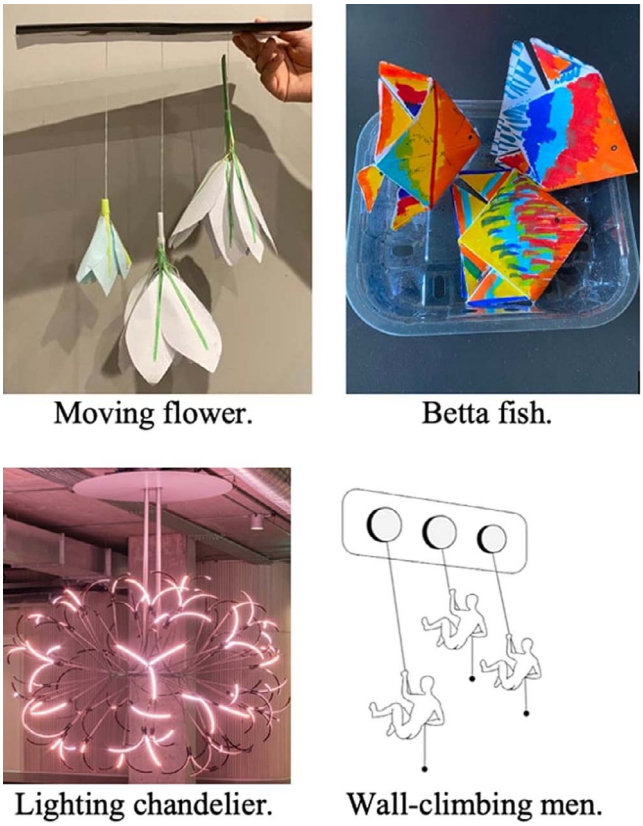

FIGURE 1. 'Moving flower' and 'Betta fish' are two low-fidelity paper prototypes. 'Lighting chandelier' (JasonBrugesStudio, 2022) (Reaction Diffusion (2022), Jason Bruges Studio. Image credit: Josh Partee), and 'wall-climbing men' are two images. We utilized these in the fourth activity of the household interviews (images reused from (Perera *et al.*, 2023a)).

nature or climate) (Gustafsson & Gyllenswärd, 2005, Quintal *et al.*, 2016, Sauvé *et al.*, 2020) and 6) use of visual that increase shock value (Iribagiza *et al.*, 2020).

3.2.2. *Design considerations for low-fidelity paper prototype and images*

For the fourth activity (Appendix A), we designed two low-fidelity paper prototypes (Lim *et al.*, 2008) ('moving flower' and 'Betta fish' in Fig. 1) and utilized two images as visualizations ('lighting chandelier' and 'wall-climbing men' in Fig. 1) to communicate the concept of data physicalization to participants and get their thoughts and ideas. From here on, we shall refer to each low-fidelity paper prototype or image as follows: 'moving flower' as MF, 'Betta fish' as BF, 'lighting chandelier' as LC and 'wall-climbing men' as WM. Each low-fidelity paper prototype or image addresses a design consideration identified through the literature: 1) shape-change of objects (Rasmussen *et al.*, 2012) (MF of Fig. 1), 2) static physicalizations (Sauvé *et al.*, 2020) ('lighting chandelier' of Fig. 1), 3) empathetic visualizations (Fernando *et al.*, 2009) (BF of Fig. 1) and 4) gamified visualizations (Bühling *et al.*, 2012, Jan *et al.*, 2021, Jan Fijnheer *et al.*, 2019, Willemsen *et al.*, 2011) (WM of Fig. 1). Moreover, in the process of preparing these low-fidelity paper prototypes and images, we were inspired by the considerations in the literature to design for: 1) household collaboration (Stegers *et al.*, 2022), 2) peripheral interaction (Nielsen *et al.*, 2015, Rasmussen *et al.*, 2017, Stegers *et al.*, 2022), 3) shared location in the house (Stegers *et al.*, 2022) and 4) visually appealing images (Mccarthy & Wright, 2004, Steg, 2008).

Leveraging prior work (e.g., flower-shaped actuated physical ambient avatar (Hong *et al.*, 2015), Laughter Blossom (Yoon *et al.*, 2013), FamilyFlower (Degraen *et al.*, 2022), LaughingLily (Antifakos & Schiele, 2003), Flower Lamp (Backlund *et al.*, 2006), Peacetime (Katzeff *et al.*, 2017) and blossoming flower displaying music data (Kim *et al.*, 2015)) and relating to Human–Plant Interaction (HPI) (Chang *et al.*, 2022), we designed the MF (Fig. 1) to explore the user engagement with shape-changing physicalizations (Rasmussen *et al.*, 2012) and use of nature-based visuals (Holmes, 2007). This is a set of three flowers that hang from a cardboard, which depicts flowers hanging from the ceiling of a home. Inspired by The Clouds (Rogers *et al.*, 2010), we designed the flowers to move vertically up or down by pulling a thread attached to each flower. They can also bloom by pulling a second thread that opens the petals (Fig. 2). The three flowers are used to depict different consumption categories, such as electricity, gas, food waste and transportation, with the facility to upscale or downscale the number of flowers. The vertical movement was used to depict the response to households' consumption: the higher the flower is, the higher the consumption, and the lower the flower is, the lower the consumption (Fig. 2). The lower the flower goes, it gradually blooms to depict a reward for having low consumption. Inspired by Econundrum (Sauvé *et al.*, 2020), LC (in Fig. 1) is an

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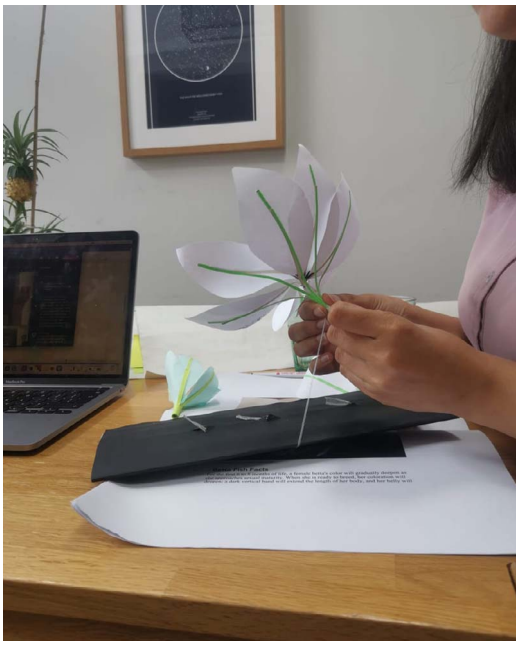

FIGURE 2. During household interviews, displaying the blooming function of the flower in the 'moving flowers low-fidelity paper prototype' that we designed for the study.

image that we used to communicate the idea of an installation with LED strips to visualise lighting up in different colours to inform occupants of their consumption (JasonBrugesStudio, 2022) (Reaction Diffusion (2022), Jason Bruges Studio. Image credit: Josh Partee). This visualization differs from MF in terms of its static (non-movement) state and use of non-empathetic visuals. BF was inspired by Tamagotchi (Bloch & Lemish, 1999), Pet-literal interface (Dillahunt *et al.*, 2017), empathetic biological media (Fernando *et al.*, 2009), natural colour change of Betta fish (Bettas, 2018). This was designed to depict the consumption level of the home through colour changes of a Betta Fish where it has vibrant colours when the consumption is low and pale colours at high consumption. We designed it to comprehend the users' opinions on colour changes with empathetic visuals of a fish. Finally, WM was inspired by gamification (Bühling *et al.*, 2012, Doshi *et al.*, 2017, Jan *et al.*, 2021, Jan Fijnheer *et al.*, 2019, Willemsen *et al.*, 2011) where three objects representing different consumption sectors (such as energy, water and food waste etc.) move autonomously to reach parallel targets based on household consumption. The idea is to depict the objects moving up towards the target when the consumption of the home is less and the object will move down away from the target at high consumption.

3.3. Data Analysis

Workshop recordings were transcribed to conduct reflexive thematic analysis (Braun & Clarke, 2006

2021) with the aid of NVivo (Version 1.7.1). We started by getting familiar with the qualitative data to obtain an improved understanding of the context and participants. We created codes to highlight important data, considering how our perspectives may influence the choice and understanding of codes. We reviewed the codes, looking for patterns, relationships and interconnections. We grouped similar codes to discover potential themes. We kept revisiting and refining themes and iteratively reviewing the transcripts to facilitate theme identification until no new themes developed. In each round, the research team discussed the results. We identified that user needs and preferences in visualizations that encourage sustainable household practices were a common theme among participants. Therefore, we rearranged the data to explore the challenges and opportunities related to this topic.

4. Findings

In the following subsections, we describe the multiple experiences of households attempting to lower their consumption while reconciling discrepancies in household dynamics and diverse requirements. We report our findings related to household objects that symbolize sustainability, aesthetic considerations and supporting household collaboration in designing data physicalizations, and concerns and challenges in designing physicalizations for households.

4.1. Exploring Household Objects Symbolizing Sustainability and Evolving Attitudes Toward Data Physicalizations

During the discussion of the object(s) participants brought that symbolized climate change or sustainability, six households presented refillable bottles, a reused wooden ornament, refillable face makeup, glass bottle and water bottle that has been used for the past many years. Two households mentioned that they did not understand the questions properly while the rest of the households could not locate such an item in the house. The six households that brought an object along spoke about the durability of the material, reusability and prevention of extra consumption and expenditure while displaying their object.

Four out of 13 households initially did not consider data physicalizations as their preferred method for visualizing consumption data. However, during discussions of Activities 3 and 4 (Appendix A), these households became increasingly inclined towards data physicalizations. They attributed this shift to the novelty and visual appeal of these physical representations: '*it was because the data physicalizations were extremely novel, not something we'd seen before, but in many cases beautiful, and I had not fully understood perhaps what these were initially. After discussing the ideas with you and seeing them, it became clear that these would actually be really visually striking things to have in the home – they would be much more impactful and empowering than a statistical chart*' (H4).

4.2. Aesthetic and Empathetic Considerations in Data Physicalization Design

4.2.1 *Balancing Aesthetics and Practicality: Integrating Data Physicalizations with Household Setting*

While displaying the images and prototypes we created (Activity 4), four households expressed the need for the 'moving flowers prototype' or 'lighting chandelier' (Fig. 1) to function as a normal light in the house when necessary: '*you could have different modes for lighting (…) such as energy mode etc.*' (H8). Participants conveyed that the visualization should not take too much space and needs to be independent of the space utilized for day-to-day activities: '*I really like things on the ceilings because ceilings are not really used at all (…) and they don't take up space. If it was on the kitchen work surface or on your desk, it would just be in the way*' (H2). A household (H1) was particularly intrigued by the autonomous functioning of the 'moving flower prototype' (Fig. 1): '*I quite like that. It will be nice in the house because there isn't anything else in the house that sort of moves in a very autonomous sort of way. (…) It is a "moving reminder"*'. The majority of the participants (11 out of 13 households) preferred to have a data physicalization in the house as a constant visual reminder coupled with a mobile or web application that provides

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a detailed view as '*it gives you the best of two worlds*' (H2 and H6). A household (H6) continued to explain their view of this: '*The physical object is for you as a reminder to achieve the goal and the app which actually tells you the rest of the information with the numbers and then so on*'.

4.2.2. *Aesthetic Appeal in Household Visualizations: Emotive Metaphors Shaping Consumption Awareness*

Our participants also emphasized the importance of visualizing household consumption in an appealing and attention-grabbing manner, serving as a visual reminder in their homes. All 13 participants expressed the desire for aesthetically pleasing visualizations. One participant (H2) favoured the 'moving flowers prototype' (Fig. 1), describing it as '*flowers are more of a visual that captures the eye*'. While displaying the images from the literature (Activity 3), 11 participants preferred visualizations based on emotive metaphors, particularly those involving living organisms. They believed these metaphors could have more '*life impact*' (H4) as they could relate to living beings emotionally. For instance, a household (H4) that owned a smart meter with numerical consumption data found it lacking emotional value. When shown images of nature-based visualizations, they expressed happiness and hoped their smart meters were replaced with '*a tree that travels up when you're using lots of power and then it looks normal when you're using the right amount of electricity relative to everybody else*'. Among the three categories of visualizations in Activity 3 (living metaphors, regular objects and household items), the living metaphors category was the most preferred, with 11 participants favouring it. A household (H2) even suggested a design of '*fish swimming across your ceiling rather than a terrestrial example of the butterfly and the birds and the flowers, you have the coral reefs or mangroves or seagrass with fish*'. H4 proposed designs of planting flowers for '*bees and butterflies for more active positive impact on the environment*'. These aesthetic and visual aspects made participants consider including their children in the consumption reduction activities and engage with the physicalization.

4.3. Supporting Household Collaboration: Bridging Aesthetics and Child Safety

4.3.1. *Satellite System: Involving Children in the Conversation of Reducing Consumption*

A household (H9) suggested that it could be helpful to have different visualizations as a '*satellite system*' to approach different people in the household (children and parents): '*if you could somehow have satellite systems, like a hub and spoke. So we have the LED light thing ["lighting chandelier" of Fig. 1] in the hallway that we could see. And you stack those ["wall-climbing men" of Fig. 1) in the kids' room. But they are drawing on the same information and I think that would be a really good idea*'. H8 discussed handing over the object to her son for a week and asking him to take responsibility for reducing overall consumption: '*[referring to her son] Keep this in your room this week. You keep an eye on it. You tell us when are we doing a good job? When we are not doing a good job*'. These suggestions on collaboration and engagement with physicalization lead participants to consider the safety it brings in the presence of children.

4.3.2. *Balancing Aesthetic Preferences with Child Safety*

We noticed apparent concerns that were interspersed around children's safety, understandability of the data visualized and desire for collaboration within the household. Adults preferred to involve children in the house to collaboratively work towards reducing consumption engaging with the data physicalization. We noticed that the adults sometimes preferred certain features to be present in the intervention; however, they opted not to have them in the presence of their children. For example, two households (H6 and H12) preferred the 'moving flowers prototype' and 'wall-climbing men' (Fig. 1), however, they changed their views when they mentioned children as they thought those would impact the child's safety or the object's security. As participants explained the need to balance aesthetics with child-safety within the household, they also explained challenges they face related to visualizing consumption data.

4.4. Concerns and Challenges in Physicalization Design for Homes

4.4.1. *Interpretation challenges: Mapping Ambiguity between Physicality and Consumption Data*

Households desired to be clearly informed of their consumption and/or expenditure via visualization. A household (H12) explained that they wish to be educated to take an informed decision regarding how '*switching off the heating in an empty room would affect the overall consumption*'. Referring to the 'moving flowers prototype' (Fig. 1), household H11 attempted to understand what could be denoted through the blooming of the flower: '*[at the end of the day] it has bloomed. So I have done well, but then you would think, "how well?"*'. While displaying the images from the literature (Activity 3), another household (H7) attempted to understand how to map their consumption to the amount of melting ice referring to (Dillahunt *et al.*, 2017): '*If I start today with the polar bear, as the day goes by, the ice shrinks. But how would I know how much I would have used?*'. Therefore, households need to be offered a frame of reference for comparison: '*if it is giving [data] as the kilowatt use per day, then what is a good kilowatt?*' as H7 summarized.

4.4.2. *Actionable Weekly Feedback over Harsh Daily Feedback*

The husband of a household (H13) opted for daily feedback justifying it as '*weekly is too easy to ignore*', while the wife contradicted it by saying that daily feedback would be '*harsh*' and hence, preferred weekly feedback as it would allow her to plan the weekly consumption-related activities better and aid in planning for the next week. While seven households preferred instant feedback, six preferred daily and five preferred weekly feedback while five households opted for any one of these frequencies. Occupants of the same house disagreed with each other's preferences. Participants also explained their views on setting goals for their consumption and competing against each other at home to save resources.

4.4.3. *Using Goal Setting or Healthy Competition*

A household (H2) highlighted the value of comparing their consumption data to the UK average household, allowing them to set budgets and goals to control their consumption: '*we could look at the UK average and you can set a budget against it and then we are rewarded if, at the end of the day, we are within budget*'. They also expressed a preference for being able to view their previous consumption and track their spending progress. Another strategy discussed was the potential benefit of healthy competition. Household H3 shared an example of participating in a weekly step challenge with a partner using Fitbits: '*we both [the partners living in the house] have Fitbits and we participate in a weekly step challenge, (...) I might beat him in the step challenge*'. Another household (H2) extended this idea, related competition to a much wider scale elaborating on load-balancing: '*if the National Grid is telling you this is how much the UK is currently using and you could see it increasing when everyone wakes up, then you can almost try and*

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compete with that to use less [resources]'. However, two households (H9 and H11) expressed concerns that competition might not be effective for adults, as it could lead to '*naming and shaming*' rather than motivation. These perspectives on working as a household to reduce consumption lead participants to discuss how they will be motivated to engage with physicalization actively.

4.4.4. *Motivating Households towards Sustainable Practices: Using Shape Change of a Flower (Blooming) as a Positive Reward or Shock Value*

While displaying the images and prototypes we created (Activity 4), participants expressed a preference for positive reinforcement in visualizations. For instance, when discussing the 'moving flowers prototype' (Fig. 1), two households (H2 and H11) interpreted the flower's blooming as a reward for good consumption practices. Household H2 suggested that watching trees grow as they conserve resources could be a form of positive reinforcement: '*if you do really well during the day, then the living metaphor could be that you've planted lots of trees. So by the end of the day, you've got a really lush forest, whereas if you didn't do so well, maybe you only plant one or two trees. That to me feels like a more positive reinforcement*'. This idea was seen as more motivating than '*guilt and shame*' of seeing trees wilting (Quintal *et al.*, 2013b) or the polar bear drowning (Dillahunt *et al.*, 2017) while displaying the images from the literature (Activity 3).

Another household (H3) where the wife was originally from California favoured positive reinforcement, drawing an example from roadside signs that say '*thank you with a smiley face when drivers follow speed limits*'. While displaying the images from the literature (Activity 3), participants generally preferred visualizations that put their minds at ease over those that made them '*feel uncomfortable*' (H2), as the latter could be '*quite worrying*' and '*quite stark*' (H11), especially if they did not know how to reduce the consumption. While displaying images from the literature related to the display of a child's lungs in (Iribagiza *et al.*, 2020), a household (H10) cautioned against using shock value as a means of motivation, suggesting it would '*make people numb*'.

5. Discussion

In this research, we investigated how households prefer to visualize their consumption information by understanding their comments and feedback for existing work in the literature, and four low-fidelity prototypes we proposed. Our participants found objects in their homes that last a long period and refillable/reusable objects to be more sustainable. Our households favoured visuals with positive framing and empathetic images such as animals or trees. We also found that participants require all household members, including children, to engage in the act of reducing consumption. However, participants also had certain concerns, such as child safety around physical objects and how to interpret the information presented on a physicalization. In the following section, we discuss our findings relating them to the literature to highlight aesthetic and collaboration considerations of physicalization design, the need for features such as personalization and goal-setting and navigating certain challenges in physicalization designs.

5.1. Attaching Meaning to Images, Objects and Places: Opportunities for Design

A place is defined not only by its physical attributes but also by the emotions and meanings attributed to it within a home environment (Baillie & Benyon, 2008). Homes are rich in memories and emotional connections (Baillie & Benyon, 2008, Kirk & Sellen, 2010). Although attaching meanings to objects has been studied in the literature, smart tools designed for home consumption prioritize technology and put less emphasis on its aesthetics and connotations (Cheon & Su, 2018, Kirk & Sellen, 2010). People may attach personal meanings to objects based on their experiences, memories and emotions. Recognizing the meanings attributed to specific items may allow designers to personalize technologies, creating experiences that resonate with users on a more personal level. The idea of 'technology as experience' encourages a shift from a solely utilitarian approach to one that values the emotional experiences of individuals (Baillie & Benyon, 2008). Physical visualization research has recognized the need to understand how people interact with the material world, objects and spaces (Vaisutis *et al.*, 2014).

Furthermore, understanding people's relationships with objects within the home has also been highlighted in the context of home archiving (Kirk & Sellen, 2010). As homes become more technologically advanced, there is a growing need for a deeper understanding of how technology impacts people's sense of place and their connection to objects. Our findings highlighted three features of objects and places around a household: Comforting vs. revolting images, Objects for bonding with household members and Places in the home for collaboration and engagement.

5.1.1. *Comforting vs Revolting Images*

Our participants suggested their opinions on using shock value as an enabler; the display of a child's lungs in (Iribagiza *et al.*, 2020) was perceived to be unsuitable for their household, which might desensitize people and make them ignore the importance of reducing consumption. This contradicts the findings of (Iribagiza *et al.*, 2020), who reported a preference for displaying a child's lungs. On the one hand, this indicates a preference for nature-based visuals, which evoke empathy and prompt action towards climate change (Pierce *et al.*, 2008). This preference may stem from humans' innate empathy for living organisms (McLuhan, 1967, Pierce *et al.*, 2008). Empirical studies on environment and behaviour support the idea that empathy enhances environmental attitudes and behaviours (Dillahunt *et al.*, 2017). Pleasant emotions aid learning and decision-making, and individuals are more likely to engage in environmental conservation initiatives when they have a deep emotional connection to the issue (Fang & Sun, 2016). On the other hand, this discrepancy may be attributed to the concept of frictional feedback (Laschke *et al.*, 2015), which introduces friction and choice to instigate change, inspiring reflection and alternative actions. In the context of our study, participants may prefer visuals that inspire positive emotions and connection, aligning with the idea that pleasant emotions aid learning and decision-making, making individuals more likely to engage in environmental conservation initiatives. Further investigation into integrating empathetic positive feedback with frictional feedback may be interesting to study how people adjust their practices accordingly. A balanced approach that combines both types of feedback may be effective; starting with frictional feedback to raise awareness and create a sense of urgency, while providing positive feedback to encourage and sustainable practices.

Further, our participants did not prefer negative feedback produced by seeing trees wilting (Quintal *et al.*, 2013b) or the polar bear drowning (Dillahunt *et al.*, 2017). These findings can also be related to the design language in data visualizations that support sense-making and communication of information (Hornecker *et al.*, 2023). These findings suggest that data visualizations,

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regardless of whether it is a plan visualization or a physicalization, would need to be positively framed with comforting images and messages that suit a household context. If the data representation goes beyond the visual into more physical presentation (Hornecker *et al.*, 2023), as the focus of the design is for a household context, we encourage the researchers to be mindful of the usage of different physical features, sound and smell to create a more pleasing communication platform in the home.

5.1.2. *Objects for Bonding with Household Members*

During the study, the 'moving flowers prototype' and 'wall-climbing men' (Fig. 1) led to collaborative discussions among household members, prompting adults to consider how their children might interact with them. This suggests a willingness among parents to involve their children in fostering pro-environmental behaviour. This implies that certain features may be appealing to children, leading parents to envision their children's preferences for data physicalizations. Considering our study's finding that households alter their preferences for visualizations in the presence of children, it becomes apparent that the meanings people attach to objects (Baillie & Benyon, 2008, Kirk & Sellen, 2010) can differ when children are around. This merits further research to understand why certain objects prompt associations with family members and how family bonds can be leveraged in technology to promote consumption reduction.

5.1.3. *Places in the Home for Collaboration and Engagement*

Our findings highlight the importance of looking at households as a collaboration among people (Rode, 2010, Scott & Scott, 2015, Whitmarsh *et al.*, 2018) to obtain insights regarding the practices and how this understanding could inform the design of visualizations for curtailment of consumption. Reflecting on these findings and previous HCI research in household consumption, our study explained the importance of understanding household dynamics and attaching meanings to objects and places in the home (Baillie & Benyon, 2008, Vaisutis *et al.*, 2014) in order to design technology for household consumption (Bühling *et al.*, 2012, Chen *et al.*, 2012, Jan Fijnheer *et al.*, 2019, Hansen *et al.*, 2020, Iribagiza *et al.*, 2021, Kuznetsov & Paulos, 2010, Willemsen *et al.*, 2011). Understanding how individuals within a household interact, collaborate and attribute meaning to their surroundings and objects allows designers to design technology that seamlessly integrates with existing practices and preferences and resonates with the users on a personal level. Technologies that harmonize with existing household practices maybe more likely to be adopted and incorporated into daily routines.

Our participants discussed how the prototypes would fit into the dining room as everyone gathered there. This gives the sense of a focal object within the house (Nisbett & Masuda, 2003) where people gather around and it gives a valuable opportunity for collaboration. Within the family household, a data physicalization can be positioned in a shared central space (e.g., the living room (Nielsen *et al.*, 2015)) to allow all members to reflect on their environmental behaviour and it will facilitate a meeting place for discussion (Stegers *et al.*, 2022). Notably, a household (H9) presented the idea of having a 'satellite system' suggesting that the methods of motivating children and adults may be different and designers need to cater to these needs to achieve the result of producing an object that motivates each person to reduce their consumption. This informs us that certain places in the house facilitate collaboration and foster engagement. Additionally, parents prefer to engage their children in collaborative household activities. Future research could investigate using the influence of such shared places to inform the design of visualizations that promote resource curtailment.

5.2. Design Implications

The place called home will continue to evolve. More technologies will become part of the home. Technology use at home involves the aesthetic, functional and overall experiences of people (Baillie & Benyon, 2008). Different people encounter these in different ways, at different times. For designers, the key message is to design so that people can fit technologies into their lives and recognize the differing experiences that the home accommodates. It is essential to understand that no single strategy will work for everyone because individuals have different motives, choices and circumstances (Starke *et al.*, 2020). Using a combination of strategies discussed below tailored to households may be a successful approach to encourage people to engage in sustainable activities.

5.2.1. *Empathetic Peripheral Data Physicalization with a Positive Message and Actionable Suggestions*

Our findings suggest that a visualization aiming at household consumption reduction should positively reinforce users towards adopting sustainable practices. For instance, (Dillahunt *et al.*, 2017) reported that the polar bear interface was effective in their study, however, we found that our participants did not prefer to look at the polar bear drowning but rather wished to see it surviving. Data physicalizations have the potential to evoke emotional responses and create a deeper connection between individuals and their consumption data. By incorporating design elements that elicit empathy, concern or satisfaction, data physicalizations could foster a sense of responsibility and motivate individuals to make positive changes in their consumption practices.

We found that participants also preferred to understand their consumption practices and get to know ways of reducing it. (Ferreira *et al.*, 2021) claimed that there is an opportunity to design technology for household consumption to give actionable suggestions. Actionable suggestions may provide practical guidance and empower individuals to make sustainable choices. By breaking down larger goals into actionable steps, individuals could build momentum and sustain their efforts over time. By emphasizing the positive impact on the environment, cost savings, health or community well-being, individuals could be motivated and encouraged to continue making sustainable choices.

5.2.2. *Personalization of Feedback to the Household Context*

The usefulness of the feedback of the visualization is known to have problems, such as after a certain period of usage of the feedback devices, users may relapse to consumption practices prior to the intervention (Quintal *et al.*, 2013b). (Pierce *et al.*, 2008) stated that when curtailment did not happen in their study, the feedback was displayed too infrequently (e.g. monthly). Nevertheless, our findings contradict the concern regarding the time duration as participants perceived daily feedback to be harsh and instead preferred weekly feedback. This suggests that personalization or tailoring the feedback to the specific needs and preferences of each household by considering their unique circumstances, consumption patterns and goals could be an opportunity to create useful data physicalization. Personalized feedback increases relevance and resonates more effectively with individuals (Houben *et al.*, 2016). Personalization may take into consideration aspects

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such as household size, location and lifestyle, resulting in providing relevant and suitable suggestions.

5.2.3. *Goal Setting as a Strategy*

Aligning with (Barreto *et al.*, 2022) and (Abrahamse *et al.*, 2005), participants in our study mentioned being able to set goals (Locke & Latham, 1991) and controls over their consumption. Although the literature states that comparative feedback, where one's own energy use in relation to others, has shown success in reducing energy consumption, our participants highlighted that people rather prefer goal-setting over competition (Abrahamse *et al.*, 2018): some participants did not prefer competing among the household occupants that they perceived to be derogatory to one's performance, therefore, goal-setting could be a more effective strategy to motivate people towards environment-friendly activities instead of competition and comparison. While competition may lead to naming and shaming, goal setting encourages households to work towards specific, achievable objectives. Moreover, goal setting may allow for a more individualized and flexible approach, recognizing that different people may have diverse circumstances, preferences and starting points, empowering individuals to take control of their actions, leading to a more sustainable and positive impact. It is difficult not to notice its resemblance to existing behavioural models such as goal-setting (Locke & Latham, 1991) to what would enable such goals to define individualized strategies to achieve them.

5.2.4. *Reward in the Form of Shape Change to Motivate Reduction of Home Consumption*

(Quintal *et al.*, 2013a) stated that visual technology should neither reward nor punish the users, but it should keep them interested (Consolvo *et al.*, 2009). Our findings partially justify and partially contradict this statement as we discovered that households preferred to be rewarded for good practices, however, they do not want to be punished for high-consumption practices. This calls for further studies to discover the fine balance between providing consumption information and positive reinforcement, as the wrong approach could discourage people. (Stegers *et al.*, 2022) and (Quintal *et al.*, 2016) argued that future work could further investigate how a system could promote sustainable practices through the influence of an extrinsic motivator on behaviour for long-term engagement. However, it is argued that extrinsic motivations, such as monetary rewards, discounts, rebates and incentives, are effective but only last as long as the incentive or penalty exists or is substantial; but intrinsic motivations are resilient and long-lasting once triggered (Bartram, 2015). Aligning with this, we found that participants interpreted the blooming of the flower in the 'moving flower prototype' (Fig. 1) as an intrinsic motivator; it does not provide any incentive, however, it is intrinsically motivating. This means the shape change of a blooming flower can create intrinsic motivation in people, acting as an intrinsic reward for reducing home consumption. Therefore, investigating the design of a shape-changing object that intrinsically motivates the user through its change of shape, could be useful to encourage households to take pro-environmental actions.

5.2.5. *Navigating Interpretation Challenges*

During our interviews, participants encountered difficulties in interpreting visual representations of consumption, which creates trade-offs between accuracy and clarity (Egan *et al.*, 1996). They needed to have the capability to interpret their consumption against an allocated starting point and compare it against a benchmark. Our study also explained that when information is presented numerically, participants were not familiar with the units of representation (Rasmussen *et al.*, 2017), therefore, they need to be offered a frame of reference for comparison. In this case, aligned with (Barreto *et al.*, 2022), we discovered that the usage of colour codes would aid better comprehension. However, during our study, a household raised a concern about colour-blind users not being able to interact with a colour-coded lighting system conveniently. We discovered that some participants preferred movement (shape-change) (Rasmussen *et al.*, 2012) more than colour-coded lighting. Future research could further investigate the usage of shape-changing objects to design *moving reminders* to provide clear and specific data to households in an attractive form.

5.3. Reflections on Study Design—Future Directions

While our study did not employ a large representative sample of UK households, it is not unusual that qualitative research uses sample sizes similar to ours (Caine, 2016, Gardner & Abraham, 2007, Graham-Rowe *et al.*, 2014, Mann & Abraham, 2006). Nevertheless, future research might consider replicating this study with a larger sample of UK households to explore and get an in-depth understanding of context-specific insights into our findings. It is important to emphasize that the primary aim of this research is not generalizability but gaining insights into contextual household practices and experiences. Despite the recruitment through the university network, our participants came from diverse backgrounds, family sizes, locations and socioeconomic statuses. Additionally, we used snowball sampling to recruit three families unaffiliated with the university, further enhancing the diversity of the participant pool. A varied selection of participants from various backgrounds, socioeconomic statuses, cultures and viewpoints could benefit future work.

6 Conclusion

This paper emphasizes the significance of considering household dynamics, contextual factors and collaboration when designing household data visualizations for reducing household consumption rather than solely focusing on the technical aspects. The findings suggest that using shape-changing objects, creating empathetic and aesthetically pleasing visuals, designing for peripheral interaction and maintaining simplicity in information display can lead to useful visual designs for households. Goal-setting appears to be a more motivating strategy than competition and comparison, and incorporating rewards through shape changes in objects may encourage pro-environmental activities. This paper contributes to the ongoing discussion about designing technology for household consumption reduction and collaborative design approaches.

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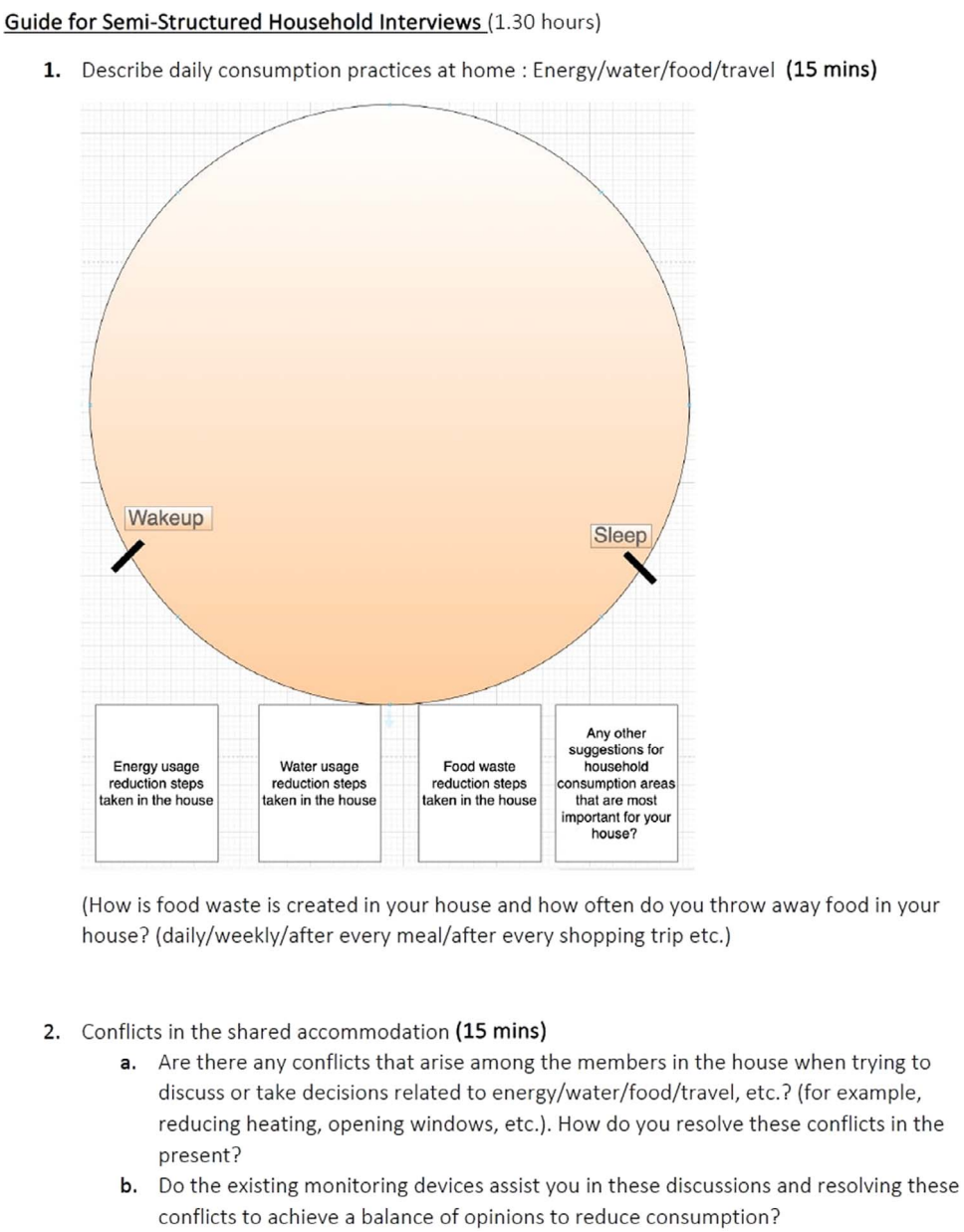
A Semi-structured Household Interview Guide



Guide for Semi-Structured Household Interviews (1.30 hours)

1. Describe daily consumption practices at home : Energy/water/food/travel **(15 mins)**

(How is food waste is created in your house and how often do you throw away food in your house? (daily/weekly/after every meal/after every shopping trip etc.)

2. Conflicts in the shared accommodation **(15 mins)**
   a. Are there any conflicts that arise among the members in the house when trying to discuss or take decisions related to energy/water/food/travel, etc.? (for example, reducing heating, opening windows, etc.). How do you resolve these conflicts in the present?
   b. Do the existing monitoring devices assist you in these discussions and resolving these conflicts to achieve a balance of opinions to reduce consumption?

FIGURE A3. Semi-structured Household Interview Guide—Page 1.

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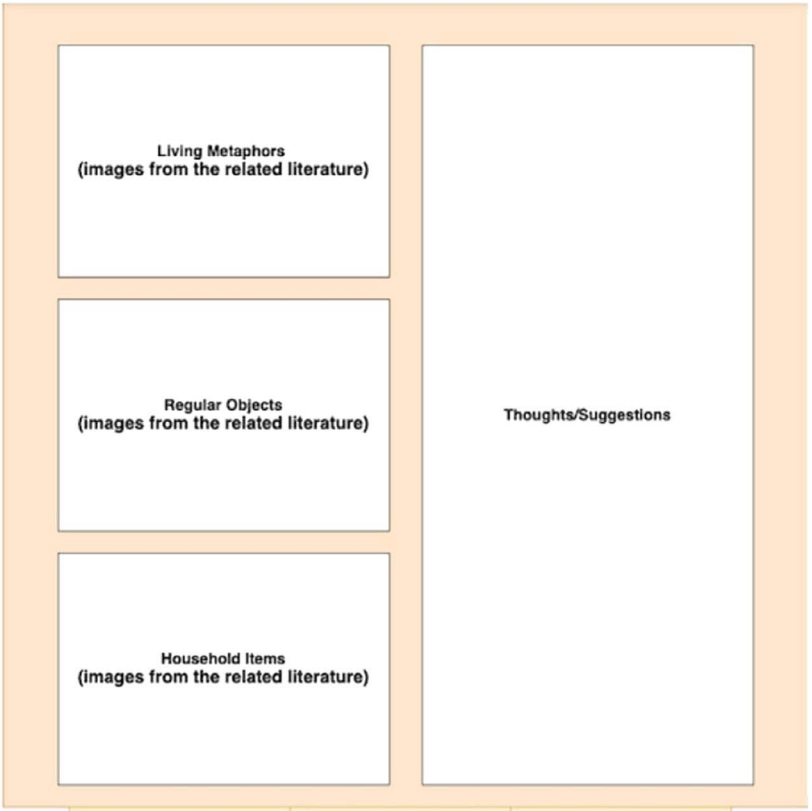
3. Visualisation related questions **(20 mins)**

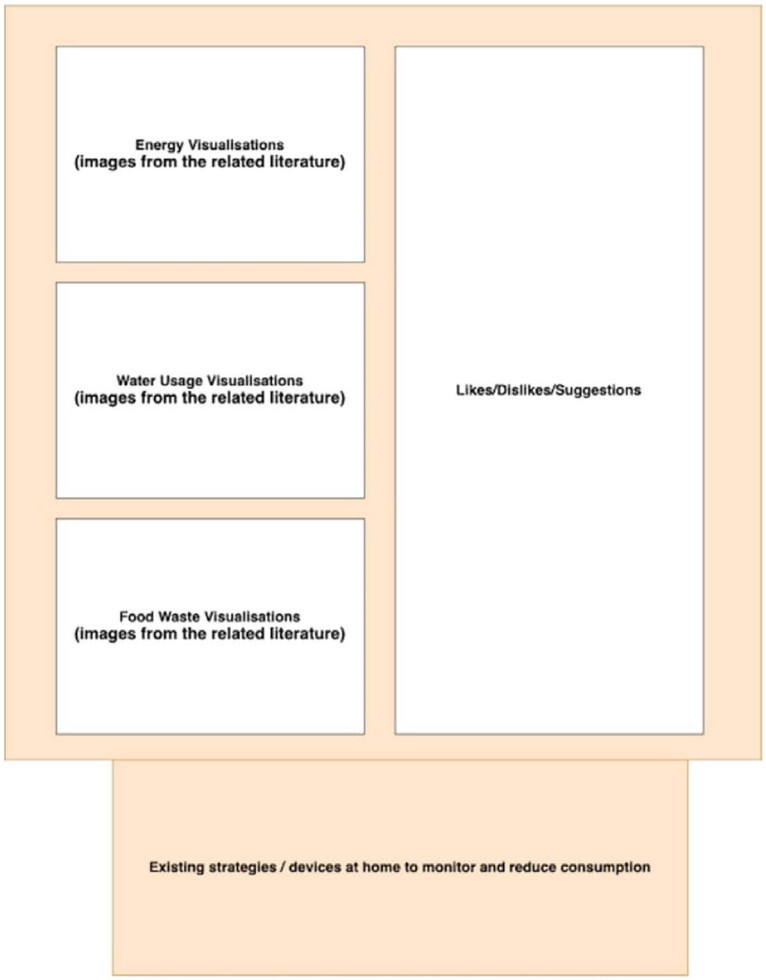


Most Preferred	Good to have features in the visualisation	Good to have data in the visualisation

a. How often do you use mobile phones? How many apps have you installed approximately?
b. Do you like to use mobile apps? Would you like to enter your daily energy/water consumption through a mobile app?
c. Explain why you prefer (the households' answer for the question in the initial survey on most preferred visualization method) type of visualisations for sharing?

FIGURE A4. Semi-structured Household Interview Guide—Page 2.

4. Visualisation activity **(40 minutes)**



a. What additional features do you think would be beneficial to be present in these existing strategies/devices mechanisms?
b. Discuss the object they have brought that represents sustainability to them.
c. Provide paper prototypes and ask them to change them or reflect on them, comment, critique.

FIGURE A5. Semi-structured Household Interview Guide—Page 3.

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