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Exploring the design of physical artefacts to visualise household consumption for encouraging sustainable practices

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ABSTRACT

Although household consumption contributes to climate change, it can be challenging to comprehend the consequences and effects from a personal perspective. In this paper, we explore the design of physical data visualisations to promote sustainable practices within households. We conducted 15 household design workshops involving household members to explore physical designs and envision the potential use of physical artefacts in the home to promote sustainability behaviours using five low to medium-fidelity prototypes. The findings from these workshops highlight the need to balance aesthetics, abstraction, and the presentation of actionable information in the design of physical artefacts. Based on our findings, we identify key design considerations for future design: (1) including all household members in the design process to reflect the collective goals and values of the home, fostering a sense of ownership and engagement, (2) considering child-friendly design in physical artefacts to promote awareness, education, engagement, and sustainable values in children, (3) and considering nature-based visuals to reduce the mental burden of information overload.

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Physical data visualisation; Sustainability; Household consumption; Design workshops; Physical artefacts; Child-friendly design

1. Introduction

The global challenge of mitigating greenhouse gas emissions calls for concerted efforts across all sectors of society, with households emerging as a critical focal point as they are linked to nearly two-thirds of these emissions according to consumption-based accounting (UNEP, United Nations Environment Programme 2020). In response to this pressing need, a variety of interventions have been proposed, ranging from government initiatives (Lilley 2009; Lim, Stolterman, and Tenenberg 2008) to the use of information and communications technologies such as screen-based visualisations (Barreto et al. 2022; Fijnheer et al. 2021; Gupta, Barnfield, and Gregg 2018; Katzeff et al. 2020; Perera et al. 2023c; Quintal et al. 2013; Whitmarsh, Haggar, and Thomas 2018) and data physicalizations (Perera et al. 2024; Sauvé, Bakker, and Houben 2020; Stegers, Sauvé, and Houben 2022). These interventions aim to provide households with insights into their consumption, enabling people to make more informed decisions that can help reduce household environmental impacts.

In particular, Data physicalization, with its tangible and interactive nature, has shown unique potential and advantages in promoting and motivating individuals to engage in sustainable practices (Dumičić et al. 2022; Perera et al. 2023b). Data physicalizations are helping to bridge the gap between digital information and the physical world, offering a more creative and mindful way to look at data (Eslambolchilar et al. 2023) that resonates deeply with users (Jansen and Hornbæk 2016). However, a challenge persists in the landscape of data physicalization design: the limited capacity of existing designs to foster collaborative discussions and interpretation encompassing all family members that would seamlessly integrate into the home environment (Perera et al. 2023b).

In this paper, we present insights resulting from 15 design workshops that explored households' preferences and expectations concerning physical artefacts visualising home consumption, while envisioning their integration into the home context. Aligning with prior work (Lim, Stolterman, and Tenenberg 2008), we constructed five low to medium-fidelity prototypes to support workshop activities and gathered household feedback and ideas to further iterate the design of physical visualisations. Our work contributes to the growing

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body of Physical Data Visualisations in Human-Computer Interaction (HCI) research. First, we present our findings on the potential multifaceted role of physical artefacts at home, considering design, location, privacy and function, attachment towards household objects, and the use of intrinsic motivation and child-friendly design to increase household engagement. This complements research investigating the design of physical artefacts to curtail consumption in the home context (Bartram, Rodgers, and Woodbury 2011; Gustafsson and Gyllenswärd 2005; Katzeff et al. 2020; Sauvé, Bakker, and Houben 2020; Steg 2008; Stegers, Sauvé, and Houben 2022). Secondly, based on our findings, we provide design considerations to engage all household members in the physicalization design process (Perera et al. 2023c; Rode 2010; Scott and Scott 2015; Whitmarsh, Haggar, and Thomas 2018). In particular, to contextualise the suitable size of prototypes, their appropriate location in the home and the consideration of child-friendly design elements in physical artefacts (Bae et al. 2023; Fleck et al. 2017; Hutchison, Ellsworth, and Yovich 2000) Further, to consider the education and engagement of children in sustainable practices, and the utilisation of shape-changing objects and nature-based empathetic visuals in design, so as to minimise the mental stress of information overload (Dumičić et al. 2022; Eslambolchilar et al. 2023; Jansen et al. 2015; Sauvé, Bakker, and Houben 2020; Stegers, Sauvé, and Houben 2022).

2. Related work

To clarify how our work builds on prior ideas and concepts around physicalization, we briefly present the background of data physicalization and its characteristics, benefits and limitations. We then focus on the role of data physicalizations and the existing opportunities to study the design of physical artefacts for encouraging sustainable practices at home.

Information visualisation utilises the dynamic and interactive medium of graphical computers (screen-based methods) to devise new external aids that communicate data (Card, Mackinlay, and Shneiderman 1999). However, physicality is important to comprehend the world around us because people are naturally adept at engaging with it through their senses, sight, sound, and touch (Jansen 2014). Within this context, the widely used screen-based method is comparatively restricted; it cannot evoke other senses associated with physicality since it can only address the visual sense (Jansen 2014). A physical artefact seeks to communicate information through its aesthetic and functional aspects, serving as an externalisation of data; therefore, exploring the design of physical data visualisations is helpful for better communication of information to an audience (Jansen 2014). As visible in Figure 1, different methods of visualising information can be categorised based on their 'focus' and 'manifestation' (Jansen 2014; Zhao and Moere 2008): Focus could be either 'functional' or 'artistic', while Manifestation is either 'physical' or 'virtual'. They are all directly driven by, or indirectly inspired by, the visual representation of abstract data.

Though physical representations of data have been produced for centuries (Dragicevic and Jansen 2012; Dragicevic, Jansen, and Moere 2019), it has recently been recognised as an emergent research area (Jansen et al. 2015) across many domains including sustainability, physical activity, and personal informatics (Sauvé et al. 2023) as it promotes embodied learning (Lindrup, Menon, and Biørn-Hansen 2023), interactivity (Stegers, Sauvé, and Houben 2022), aesthetically pleasing visuals (Antifakos and Schiele 2003; Degraen et al. 2022; Hong et al. 2015; Yoon et al. 2013), engagement with different senses (Eslambolchilar et al. 2023; Jansen and Hornbæk 2016), use of non-visual perception (Jansen and Hornbæk 2016; Katzeff, Wessman, and Colombo 2017), and enables democratisation of data (Houben et al. 2016; Lindrup, Menon, and Biørn-Hansen 2023). Through

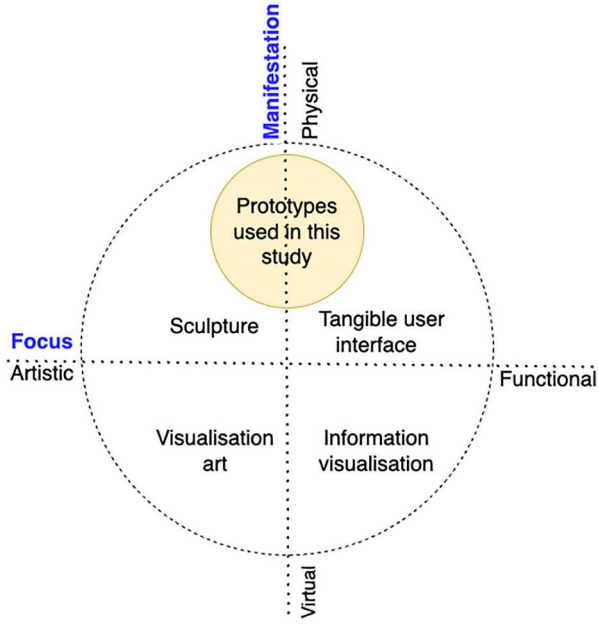

Figure 1. Framing the prototypes utilised in this research study aligning with Zhao and Moere (2008) model for classifying data visualisation methods: Focus indicates whether the works are more oriented towards a medium for artistic expressions or as tools for improving productivity in goal-based tasks, Manifestation describes whether the work takes a relatively more virtual approach or a more physical approach.

their work on 'tangible bits', Ishii and Ullmer (1997) introduced the concept of physical data representations. In Zhao and Moere (2008) introduced the term 'data sculpture' as 'a data-based physical artefact, possessing both artistic and functional qualities, that aims to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it'. Then 'data physicalization' was described later by Jansen et al. (2015) as 'a physical artefact whose geometry or material properties encode data'. Data physicalization incorporates elements from data visualisation, tangible computing, data art, data design, data artefacts, data perceptualisation, and shape-changing interfaces (Lindrup, Menon, and Biørn-Hansen 2023).

2.1. The role of physical data visualisations to promote sustainable practices

Physical data visualisations have been explored in areas related to sustainability including climate change (Perera et al. 2024; Studio Olafur Eliasson 2014; TEN x TEN, MINN LAB 2017), green lifestyle (Jennett et al. 2016), waste production (Stefaner 2019), air (Posavec and Quick 2014) and water pollution (Dragicevic and Jansen 2017), energy consumption (Backlund et al. 2006; Katzeff, Wessman, and Colombo 2017; Stegers, Sauvé, and Houben 2022), and food consumption (Lindrup, Menon, and Biørn-Hansen 2023; Sauvé, Bakker, and Houben 2020; Sauve, Dragicevic, and Jansen 2023). For instance, Ecorbis (Stegers, Sauvé, and Houben 2022) and Flower Lamp (Backlund et al. 2006) encourage people to think about their home consumption. Peacetime (Katzeff, Wessman, and Colombo 2017) and Clockcast (Rasmussen et al. 2017) encourage shifting residential electricity consumption times. Edo (Sauve, Dragicevic, and Jansen 2023), Econundrum (Sauvé, Bakker, and Houben 2020) and Babbage Cabbage (Fernando et al. 2009) are physical visualisations that represent carbon emissions and convey social or ecological information. Physicalizations have the potential to be integrated into everyday activities, enhancing awareness of consumption data (Sauvé, Bakker, and Houben 2020; Stegers, Sauvé, and Houben 2022). Physicalizations incorporate data into the physical environment and daily routines to help people become more aware of their data (Eslambolchilar et al. 2023) by blending into the background and not interfering with the user's activities, giving an abstract knowledge of data that can be in the periphery of attention (Bakker, Hausen, and Selker 2016; Perera et al. 2023b).

It is argued that when physical visualisations are applied to personal data, it might result in changes in behaviour by encouraging self-reflection (Sauvé, Bakker, and Houben 2020; Thudt et al. 2018). Previous research has stated that including participants in producing their own personal data physicalizations encourages reflection as it requires data consideration and decision-making in their design (Dumičić et al. 2022; Perera et al. 2023b; Stusak 2015). Participatory data physicalizations amplify this through engagement and fostering a sense of uniqueness and ownership (Khot et al. 2017; Moretti and Mattozzi 2020; Nissen and Bowers 2015; Panagiotidou, Görücü, and Vande Moere 2020; Sauve, Dragicevic, and Jansen 2023; Swaminathan et al. 2014; Thudt et al. 2018). Leveraging the abstract nature of data physicalizations can enhance confidentiality while protecting against overexposure to others, providing personal data privacy (Stusak et al. 2014). Additionally, it is argued that slow-motion feedback (Sauvé et al. 2020; Vermeulen et al. 2014) and comparison of personal data may assist reflection on data (Sauvé, Bakker, and Houben 2020; Stusak et al. 2014). Moreover, users find physicalizations fascinating and enjoy exploring them; however, our understanding of the benefits of creating useful physicalizations for data exploration and easy-to-understand representations is still limited (Stusak 2015).

2.2. Limitations of existing home-based physical visualisations for sustainability

Many existing physical visualisations designed to promote sustainable resource consumption in domestic contexts lack features that could support users' engagement and collaboration across an entire family (Wessman and Olsen 2015). Achieving collective sustainable consumption levels is a collective endeavour within a family (Vale and Vale 2008), but not all family members may understand or engage with the physicalization. For instance, children, young adults and parents may have varying levels of environmental awareness (Wessman and Olsen 2015). Typically physical visualisations provide a one-size-fits-all approach, offering little to no ability for users to choose the specific data items they wish to engage with (Stegers, Sauvé, and Houben 2022; Perera et al. 2023b). This could lead to information overload, as users may be presented with data that is not personally relevant or engaging to them (Fernando et al. 2009; Stegers, Sauvé, and Houben 2022). Further, most physical visualisations are utilitarian and often fail to establish a meaningful connection with their users through their design; in particular through demonstrating a lack of empathy for the environment (Perera et al. 2023b; Stegers, Sauvé, and Houben 2022), which could be a useful feature to

increase user engagement with sustainable behaviours (Sauvé, Bakker, and Houben 2020).

3. Methods

In October 2021, we started a project to explore the design of physical artefacts to promote sustainable practices in UK households. The first phase involved a survey (22 responses) and 13 household interviews to understand consumption practices, values, and factors influencing household consumption (Perera et al. 2023a, 2023b, 2023c). Specifically, this study revealed certain strategies taken by households to reduce their consumption, challenges in moving towards sustainable consumption practices, and design preferences towards visualising home consumption information in a physical artefact (for example, including visuals that invoke empathy and provide the ability to set goals). Building upon these findings and previous research, the second phase presented in this paper consisted of 15 household design workshops conducted in Wales, UK, to gain deeper insights into preferences and expectations related to informing the design of physical artefacts to promote sustainable consumption practices in homes. The workshops were conducted in each household for a duration of approximately one and a half hours. Five low to medium-fidelity prototypes (Jansen et al. 2015) were created for these workshops, serving as generative tools (Sanders 2000) to collect feedback, stimulate discussions, and gain insights into designing physical artefacts for household settings. The design workshops were held in the Summer of 2023, with ethical approval obtained from the ethics committee of the School of Computer Science and Informatics, Cardiff University (approval no: COMSC/Ethics/2023/077), and each household received a £25 voucher.

3.1. Participants

During the initial study, we used our university social media group and mailing lists for participant recruitment and invited previous participants to this second study. Here, 10 households (H1 to H10) with adults ranging in age from 18 to 54 years old participated in the design workshops (Table 1). We recruited five additional households through the university email network due to the attrition of previous participants. Overall, our household participants had one to six people per household, including two single-occupants, five shared homes between partners or tenants, and eight family homes with children. Although we did not directly involve children, we learned about children's design interests through their parents.

3.2. Design workshops: procedure

The household workshops started with participants being presented with a summary of findings from prior household interviews (phase 1) and identified user needs and attributes (Perera et al. 2023b, 2023c). Then, they were introduced to key design implications based on our initial study findings and prior research, including empathetic visuals, peripheral and interpretable, aesthetics and non-intrusiveness, intrinsic reward systems, collaboration, goal setting, actionable feedback, inform non-negotiable consumption, and positive reinforcement. Aligned with previous research (Alsos and Svanæs 2006; Bailey and Blackmore 2022; Gómez-Maureira and Kniestedt 2019), in the think-aloud session, the participants were asked to explain their answers while ranking the design implications according to their preferences and importance. Participants were also asked to explain and rank which sustainable practices would be most useful to visualise, which included electricity, gas and water consumption, food wastage, travel, and recycling practices.

Next, we introduced participants to five prototypes one after the other and encouraged them to envision their potential use in their own households, providing feedback, critique, and further ideas. To ensure consistency, the workshop protocol included questions regarding the prototypes, such as data representation clarity, support for home collaboration, suitability for daily routines and the home environment, and suggestions for improvements. The sessions concluded with inquiries about participants' favourite prototypes and their overall thoughts on physical artefacts.

Participants were given various materials for creating their physical artefact designs, including coloured papers, hard sheets, pens, pencils, glue, and scissors. Some participants conveyed their ideas through sketches on paper; others verbally explained their ideas, using materials (sheets for folding into shapes or indicating colours), expressing that they were not skilled in creating physical artefacts or drawing. Only one household attempted to create a physical artefact.

3.2.1. Design of the prototypes

We designed five low to medium-fidelity prototypes (Lim, Stolterman, and Tenenberg 2008) to explore the design space for visualising household consumption information through physical artefacts and gathering user feedback. The prototypes were not meant for actual usage or considered as a formal evaluation (Lim, Stolterman, and Tenenberg 2008) but served as generative tools (Sanders 2000) for envisioning and communication. They were designed to implement design

Table 1. Participant demographics information.

Household	Household Type[1]	Members in the house	# of participants	Age ranges	Gender. Male-M, Female-F
H1	SH	4	2	25–34	M, F
H2	SH	2	2	25–34	M, F
H3	NF	4	2	35–44	M, F
H4	NF	4	2	45–54	M, F
H5	SO	1	1	35–44	F
H6	NF	6	1	25–34	F
H7	NF	5	2	35–44	F, F
H8	SH	2	2	25–34	M, F
H9	SH	4	2	45–54	M, F
H10	NF	3	2	35–44	M, F
H11	SO	1	1	18–24	M
H12	NF	4	2	25–34	M, F
H13	SH	3	1	25–34	M
H14	NF	4	2	35–44	M, F
H15	NF	4	2	25–34	M, F

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

implications from the literature and participants' suggestions from phase 1 (Perera et al. 2023b, 2023c). Prototypes 1, 2, and 3 were medium-fidelity (implemented using Arduino Uno microcontrollers, stepper motors, piezo, LEDs, switches, resistors, and potentiometer). Prototypes 4 and 5 were low-fidelity paper prototypes. Consistent with findings from the initial study, the prototypes were sized to be suitable for placement on a table or a window sill.

Aligned with Buxton (2010) and Lim, Stolterman, and Tenenberg (2008), the goals of low-fidelity prototypes were to understand user preferences and experiences with different artefact designs and provide participants with opportunities to envision the prototype's function that is largely affected by what the prototype could *do* rather than what it might *look like* (since it is low fidelity) (Buxton 2010). The goal of the medium-fidelity prototypes was to gain an understanding of suitable technologies that could be used to implement a potential final prototype, help participants visualise how a potential final prototype could function, and also take us closer to the implementation of a potential high-fidelity prototype without having to spend time and cost into actually implementing one (Sanders and Stappers 2014). These prototypes were utilised as generative tools (Sanders 2000) to understand the design space for physical data visualisations that possess both artistic and functional qualities that aim to augment households' understanding of their consumption and encourage them to take-up sustainable practices. Aligned with Hutchinson et al. (2003), the prototypes also acted as technology probes, helping us to understand participants' desires and preferences, the technologies and engineering needed for a future high-fidelity prototype, and the goal of encouraging the participants to give suggestions and ideas for physical artefact designs.

Prototype 1 Inspired by participant suggestions during the initial phase of the study and leveraging prior work on Moving Flowers (Perera et al. 2023b), flower-shaped actuated physical ambient avatar (Hong et al. 2015), Laughter Blossom (Yoon et al. 2013), FamilyFlower (Degraen et al. 2022), LaughingLily (Antifakos and Schiele 2003), Flower Lamp (Backlund et al. 2006), Peacetime (Katzeff, Wessman, and Colombo 2017), Arduino Zoetrope project[1] (Arduino 2020), and blossoming flower displaying music data (Kim, Ananthanarayan, and Yeh 2015), we designed Prototype 1 to explore user engagement with a shape-changing data physicalization (Rasmussen et al. 2012) and the use of nature-based visuals (Dillahunt et al. 2017; Fernando et al. 2009; Perera et al. 2023b). This depicts a strip with eight images of a flower that gradually opens (from a flower bud to a full-bloom flower). The strip sits on an eight-sided cylinder, each side indexed as windows 0 to 8 and assigned a consumption value, with one flower overlayed on each window (full bloomed flower overlayed on 0th window (as marked in Figure 2)). The strip can rotate on a stepper motor connected to an Arduino Uno. The participant could set a weekly consumption goal: in this example, the pink-coloured window shows a consumption goal (e.g. 5 kWh electricity use this week). The strip starts at the

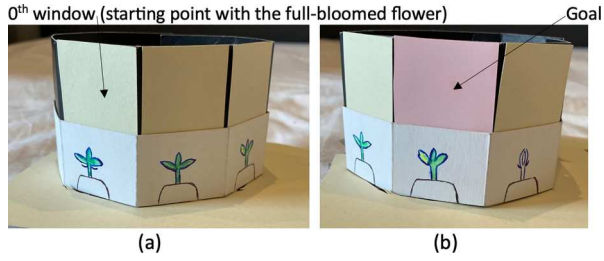

Figure 2. Prototype 1: (a) Each window in the cylinder is overlayed with a flower image. Rotation starts at the 0th window with the full-bloom flower on it. (b) Full-bloomed flower has rotated past the goal, therefore, the displayed flower image is partially-bloomed.

0th window at the full-bloomed flower and then keeps rotating to the right according to the home's consumption. At the end of the week, the household gets a full-bloomed flower if it stops rotating on or before the goal window; the flower image gradually shrinks if they have passed the goal window (Figure 2).

Prototype 2 Prototype 2 is a set of three bees moving down vertically to reach a flower. This was inspired by participants' suggestions and prior work on Pink Flowers and Switches (Daniel, Rivière, and Couture 2018), The Clouds (Rogers et al. 2010), Econundrum (Sauvé, Bakker, and Houben 2020), shape-change of objects (Rasmussen et al. 2012), and use of empathetic visuals (bees and flower) (Dillahunt et al. 2017; Fernando et al. 2009). The movement of the bee resembles household consumption, while the bee could only reach the flower if the consumption is below a preset goal (in this example, the yellow line shows a goal of 20 kWh of electricity or 6 kg of food waste per week). The flower rotates on a stepper motor (to give a sense of blooming as a reward if the goal is not exceeded). If the goal line is passed, the bee will not move further (it will be stuck between the goal line and the flower) and the flower will not rotate (Figure 3).

Prototype 3 Prototype 3 was inspired by gamification (Willemsen et al. 2011) where three spherical balls (resembling different consumption practices such as cooking and watching TV) move to reach a parallel target (which is the consumption goal set by the household). A set of LEDs connected to an Arduino Uno was used to depict the level representing the goal to visualise if the balls have passed the goal. A piezo was used to sound an alarm as the goal was reached (Figure 3).

Prototype 4 The position of the coloured petal-shaped hands on the 'clock' shows the weekly consumption per consumption practice. It depicts a clock interface on which flower petal-shaped hands (inspired by Ecorbis (Stegers, Sauvé, and Houben 2022)) move to display consumption. In this example, the orange-coloured hand depicts the weekly goal set by the participant. The remaining hands rotate clockwise according to the daily consumption; if any hands pass the orange-coloured hand, the household has consumed beyond the goal consumption (Figure 4).

Prototype 5 The position of the coloured circle on the 'clock' shows the weekly consumption per consumption practice. It depicts circular paths of varying diameters on a clock interface. In this example, the orange-coloured spherical ball depicts the weekly goal set by the participant. The remaining spherical balls rotate clockwise according to the weekly consumption; if any balls pass the orange spherical ball, the household has consumed beyond the goal consumption (Figure 4).

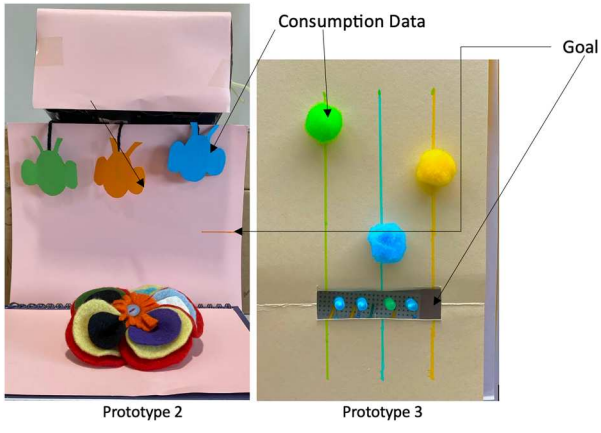

Figure 3. Prototype 2 (on the left): Three bees moving towards a flower; the bees depict different consumption practices. Prototype 3 (on the right): Three spherical balls depicting different consumption practices moving towards a goal.

3.3. Qualitative analysis

All workshops were recorded and transcribed to conduct reflexive thematic analysis (Braun and Clarke 2006, 2021) with the aid of NVivo (Version 1.7.1). We initiated the process by familiarising ourselves with the qualitative data, gaining context and understanding. Initial codes were generated to capture relevant participants' design ideas and feedback on prototypes, critically examining the impact of personal perspectives on code selection (Braun and Clarke 2006). We iteratively reviewed the transcripts and sorted the generated codes multiple times (over five times) to support the identification of themes. Initial examples of codes included 'convenience, visibility and impactfulness of physical artefacts', 'physical visualisation keeping a check on everyone', 'less understandability in bills and smart meters', and 'places at home and practices'. 'Experiences and preferences of interacting with physical artefacts at home' was identified as the main concept

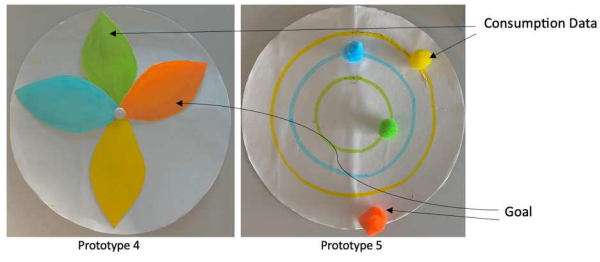

Figure 4. Prototype 4 (on the right): A clock interface with petal-shaped hands rotating clockwise according to home consumption. Prototype 5 (on the left): A clock interface with circular paths and spherical balls rotating clockwise according to home consumption.

for further exploration, as it was prevalent in the narratives of the participants, we continued discussing, revisiting and grouping the data into themes until no new themes emerged. We rearranged the overarching themes and placed sub-themes under the major themes, through discussion with the research team, until an agreement was reached.

4. Findings

In the following subsections, we report the varied perspectives of households related to the design of physical artefacts while considering the contextual differences of household dynamics and various needs that influence their engagement with physical artefacts. Regarding consumption practices, electricity was ranked with the highest importance for inclusion; while gas use and food waste followed in second and third place respectively. Regarding the design implications, participants selected interpretability as the most useful, and a historical frame of reference was the second most voted, while goal setting, aesthetics, and positive reinforcement followed the third, fourth and fifth place, respectively.

4.1. Beyond providing information: the potential multifaceted role of physical artefacts in the home

4.1.1. The importance of the emotional value and attachment to objects

A single-occupant household (H11) highlighted how he has organised his home, including having *'dedicated shelves for books, essential items like remotes, and religious sculptures that I have emotional value towards'*, and emphasised how emotional value influences the decisions about where to place things:

> Stuff with emotional value is something that I keep within my vision in my accommodation. So if your object is affecting my monthly consumption, that would create an emotional value for it to stay inside my accommodation. And then I shall look at it when I want'.

While household (H11) highlighted how an attachment to the physical artefact helps visibility and integration into the home, participants also expressed differing opinions regarding the location and size.

4.1.2. Location and size matters: balancing physical visualisation design in the home

Participants suggested different locations and sizes for the prototypes based on their outlook and expected use. For instance, three households (H1, H12 and H13) stated that Prototype 1 is suitable for the kitchen or *'in the lounge on the window sill, with the other indoor plant pots'*, and Prototype 2 could be *'next to the TV in the living room because it's nice and decorative'*. Three households (H9, H11, and H14) also commented on the need to have the physical artefact in a collaborative location in the house and how Prototypes 1 and 2 could be kept in a communal location such as *'in the middle of a dining table'*, and two households (H6 and H8) suggested hanging Prototype 4 on the kitchen wall.

Aligned with location, there were varying opinions regarding the size of the physical artefact, reflecting the importance of having the right balance. For instance, household (H1) summarised that a physical artefact's size should *'command its own presence'* and should not be *'put in the corner of a room and forget about it'*. While household (H2) mentioned that *'it will lose its impact if it's too small'*; however, four households (H2, H14, H13, H14) said that *'if it is too big then it will cover the window. So it should be not too big, not too small.* While participants desired the physical artefact to be positioned in a communal area and be suitably sized, these raised aspects regarding the privacy of their consumption data and its intended audience.

4.1.3. Balancing the visibility of data: enhancing privacy and support household collaboration

Participants from household (H11) expressed a desire to have the option to hide or turn off the consumption display of the physical artefact when guests are present:

> I'll try to hide the object as much as I can because when you have guests around, we don't really want them to monitor our bills. So we should have the autonomy to hide or turn off the real-time consumption.

In contrast, participants from another household (H9) mentioned that physical artefacts at home would provide more democratic access to consumption data:

> for other people in the household, it's not just me nagging them to save energy. Everyone will see the ways we use energy. It's kind of a reality check, but it also keeps a check on everyone else without sounding like me being a dictator. I think it's more democratic.

The man in household (H2) had access to a mobile app integrated with home energy supply through which he could track their consumption even though he *'never looked at that [mobile App]'*. However, the woman did not have access to this app, she does *'not see the devices or not even have the opportunity to see the times I'm most using stuff'*. She said that having a physical artefact would be *'useful to get to know the*

consumption that [thet] can see on the app and try to reduce it together'. The woman in another home (H15) said that although she uses mobile apps, she limits her children from using mobile devices, making it difficult to show them household consumption. She mentioned that through using a physical artefact, the children will *'remind each other and they will work together to reach the goal, which is our goal at the end'*. Participants explained that attachment to the physical artefact could lead them to position it within the household, fostering collaborative engagement while maintaining the privacy of consumption data. These visibility aspects made them consider the aesthetics and seamless integration into their home's decoration.

4.2. Fostering sustainable practices through engaging and aesthetic artefacts

4.2.1. Fit household decoration besides providing consumption information

We came across a single-occupant house (H11) that mentioned prototypes 1 and 2 could be used as a *'showpiece in the home'* and would also inform the occupant about consumption. We also found that participants compared the aesthetics and potential utility of prototypes:

> I see this [pointing at Prototype 1] looking good, but it doesn't convey lots of information. These prototypes [pointing at Prototypes 4 and 5] don't look good, but they give lots of information for separate areas. So I want to incorporate both prototypes into one thing (H12).

Household H12 noted that simply providing information about consumption may not be sufficient to capture users' attention:

> it's only telling me what I'm doing. If I want this information, I'll know how to look it up on an app or a meter. But if this object is telling me in a more friendly and nice way, I'll look at it. That's why I'll put it in my home.

While two households (H1 and H11) suggested having a screen attached to the physical artefact which shows detailed information would be beneficial, while another household (H2) disagreed with this because it might resemble a smart meter and *'then isn't it just a smart meter with a pretty thing on top of it? And the point is that smart meters are not attractive anyway'*. As these households explained the need for aesthetics and engagement, participants further contrasted between smart meters and the prototypes, expressing concerns about causing anxiety when seeing consumption data.

4.2.2. The need for more engaging artefacts: from disengaging smart meters to calming and comforting physical artefacts

Household (H9), where a husband and wife lived, contrasted between their smart meter and Prototypes 1 and 2 explaining how the flower blooming made them feel calm:

> nature gives you its own rewards, animals and plants and just being around them makes you feel calmer. Whereas the smart meter that we have was literally like a medical box. It created anxiety even just to look at it.

In household (H2), partners lived who used a smart meter when we conducted our initial study from July to October 2022. However, during the design workshop in June 2023, they mentioned that they stopped using it a while ago as *'it wasn't very attractive. I think we turned it around initially, but then we switched it off, and we just don't need to see it every day'*. While in another household (H1) occupied by partners, the man explained that

> smart meters don't really have much longevity. They're quite exciting to begin with. And then you quickly lose interest, your old habits come back and you don't keep doing the good habits because you can't really relate well to it. So something that's a bit more relatable than a typical energy meter would give you that consistent want to interact or improve.

Another household (H11) highlighted how traditional consumption data presented through numbers can induce *'panic and stress, particularly during the initial moments of seeing data'*. The same participant mentioned that *'we could make changes with a visualisation through empathy like your objects (…) Then I think we won't be too stressed looking at it'*. In agreement with this, another household (H12) mentioned that the physical artefact should *'feel comforting to look at and feel like home'*.

4.2.3. Beyond awareness: enhancing curiosity and excitement, providing intrinsic motivation, and child-Friendly design

Household (H15) said that numerical data is difficult to understand for children; *'but kids will understand the [physicalization] concept better'*. Another household (H12) mentioned that any physical artefact *'needs to be kids friendly and that will encourage them to collaborate, and needs to be easy to use, even for the kids, not only for adults'*. Two households (H1 and H14) mentioned that a physical artefact which reveals its reward (through shape-change) overnight would *'work well with kids as it is unexpected. It's something the kids would be waiting for. It will be a challenge for the kids'*. Two households (H13 and H14) also expressed that seeing the flower bloom (in Prototype 2) brings excitement: *'there is*

curiosity there. I'm waiting for something to come out'. Another household (H13) described the connection between consumption and a flower blooming and said that it gives a sense of *'a prerequisite - like there's a connection between the two, I have to do the first step if I want to see the second step. It's more like a challenge. A bit like a game. I do like that'*. Aligned with this, all households preferred receiving rewards in a tactile form that could foster motivation: *'Seeing the flowers bloom is exciting. So if you create a big prize as a flower display, that's much better tactile than on a screen. It would help us keep motivated'* (H2).

4.3. Insights on prototype designs

We investigated the five prototypes by determining the implementation of six applicable design implications (D) identified in the initial study (Perera et al. 2023b, 2023c): D1 - Goal Setting, D2 - Positive Reinforcement, D3 - Peripheral, D4 - Consumption Data for each Practice, D5 - Understandability, and D6 - Aesthetics. As shown in Figure 5, we summarised the number of participants who indicated that they preferred the method of incorporating each design implication into a specific prototype.

Prototype 1 was preferred by two households (H1 and H10) for its simplicity and ease of understanding. Many households expressed concerns about its limited representation capabilities: *'it has only one flower which does not give enough information. The consumption for different areas or history should be displayed through different flowers'* (H1, H7, H11, H12, and H14). Prototype 2 was the preferred choice of eight households (H2, H5, H7, H11, H12, H13, H14, and H15). One household (H12) raised concerns about the

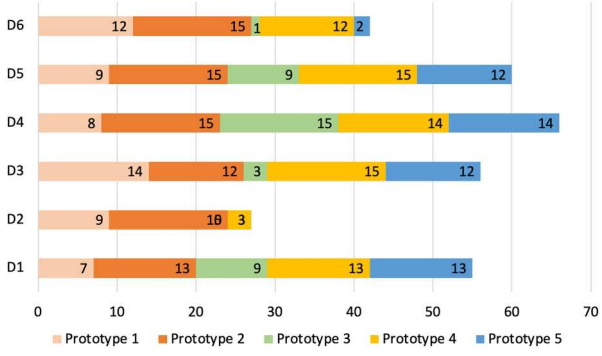

Figure 5. The number of participants who indicated their preference for how each design implication was integrated into a given prototype. Six applicable design implications (D): D1 - Goal Setting, D2 - Positive Reinforcement, D3 - Peripheral, D4 - Consumption Data for each Practice, D5 - Understandability, and D6 - Aesthetics.

perception of seeing a bee *'stuck is scary'* as it shows *'something bad happening to the bee'* and suggested continued movement even after passing the consumption goals. Prototype 3 was not preferred by any participants, primarily due to the inclusion of lights and sounds, which were generally disliked and felt *'lacked uniqueness'* (H13). Prototype 4 was preferred among six households (H2, H3, H4, H6, H8, and H9) for its subtlety. However, some thought it was *'boring'*, and a significant limitation was potential misinterpretations, especially by children: *'the kids will use more [resources] to open the flower more. But then I'm exceeding the goal'*. Although Prototype 5 was perceived to be understandable, peripheral and informative, aesthetics played a major role, and none of the households considered it their top choice:

> even though it is informative, we will ignore it after a few days because I'm done learning. It's just like looking at information on an app daily; why would I put this on the wall if it's not looking nice (H12).

5. Discussion

We investigated household preferences for physical artefact designs to support people's engagement in sustainable consumption practices. A physical representation of data shares the 'functional qualities' of information visualisation; however, in contrast to information visualisation, physical artefacts convey data through physical affordances (Zhao and Moere 2008). Therefore, the five prototypes utilised in this study differ from 'virtual' information visualisation as they are 'physical' forms of representing data. The findings of this study provide valuable insights into designing physical data visualisations for the home context. Having a collection of low to medium-fidelity prototypes helped us to gain feedback from the participants in two ways: (1) certain participants were more comfortable with low-fidelity prototypes, therefore, they tended to suggest changes more comfortably and then ease into the medium-fidelity prototypes, and (2) the medium-fidelity prototypes helped in participants understanding of how technology could be applied to achieve the design goals in a future high-fidelity prototype.

Designing physical artefacts for the home is complex due to the need to address diverse user preferences in the home context (Perera et al. 2023b, 2023c). There is no one-size-fits-all approach to encouraging households to reduce consumption; it requires a multifaceted approach combining design, technology, user preferences and experiences to create engaging and user-friendly solutions (Dumičić et al. 2022). Based on the

findings from our study, we offer the following design opportunities for the future design of physical artefacts / data physicalizations to encourage sustainable household practices.

5.1. Physical artefacts for different home contexts: engaging all household members in the design

During our workshops, we found that participants thought of the other household members when envisioning physical artefacts at home and proposed communal locations in the house for aesthetic integration and collaboration, suggesting that all members of a home should be involved in designing a data physicalization. It is argued that integrating participants into producing their personal data physicalizations offers an engaging and reflective approach (Dumičić et al. 2022; Sauve, Dragicevic, and Jansen 2023). Aligned with this, participatory data physicalizations could set the created artefact apart from other physicalizations and strengthen the user's emotional connection to it (Dragicevic, Jansen, and Moere 2019; Khot et al. 2017; Moretti and Mattozzi 2020; Nissen and Bowers 2015; Panagiotidou, Görücü, and Vande Moere 2020; Sauve, Dragicevic, and Jansen 2023; Swaminathan et al. 2014; Thudt et al. 2018). It is also stated that while producing personal data physicalizations initially sparks user engagement, this interest may diminish over time (Khot et al. 2017; Thudt et al. 2018). However, our study findings suggest that introducing tactile rewards, such as a blooming flower through shape-change (Rasmussen et al. 2012), could provide emotionally resonant data physicalizations with excitement and motivation among household members. This merits future research to explore enhancing intrinsic motivation through shape-change (Rasmussen et al. 2012) instead of including an extrinsic reward system (Perera et al. 2023b).

5.2. Choice of physicalization's size for home environments

During our workshops, we also found that the size of a data physicalization should be substantial enough to command attention and serve as a reminder but not so large as to become obtrusive. The size of a physicalization is a necessary consideration that must align with its intended purpose and expected user interactions (Dumičić et al. 2022). While large physicalizations have demonstrated their value in fostering communal experiences and discussions (Aragón, Jasim, and Mahyar 2021; Claes and Moere 2015; Daniel, Rivière, and Couture 2019; Keefe et al. 2018; López García and Hornecker 2021; Moretti and Mattozzi 2020; Perovich et al. 2021; Regan et al. 2015; Sauvé, Bakker, and Houben 2020), our study findings suggest that they may not seamlessly integrate into a regular home environment. Although prior work states that smaller physicalizations are less suitable for group settings due to their limited visibility and interaction potential (López García and Hornecker 2021), our participants did not want to have smaller physicalizations as they may limit interaction and overall impact. Instead, our participants indicated that the ideal size should ensure visibility from a distance and establish its presence within the household. This suggests that future research should consider that the appropriateness of a physicalization's size is context-specific, with homes requiring a size that aids interaction and collaborative engagement while blending within the household setting.

5.3. Designing child-friendly data physicalizations: engaging children in sustainable practices

Our findings suggest that in family households, parents would seek to engage their children with physicalizations to engage in sustainable practices and gain an awareness of consumption. Designing child-friendly data physicalizations requires a thoughtful approach that considers children's unique needs, preferences, engagement factors (Bae et al. 2023), and cognitive development (Fleck et al. 2017). For instance, our participants mentioned that a child might be unable to interpret some information through numbers. However, to see the consumption data in a physicalization through a growing tree, hear a chirping bird or smell a cherry blossom (Wessman and Olsen 2015) could be better understood by a child. Using understandable visuals (Bae et al. 2023), and / or age-appropriate language could ensure children can comprehend the information presented (Hutchison, Ellsworth, and Yovich 2000).

5.4. Minimising the mental strain due to information overload through calm and comforting design

Our participants explained that looking at physicalizations may be more comforting and cause less anxiety in getting to know personal consumption information. Physicalizations have demonstrated the potential to reduce stress levels compared to screen-based displays (Eslambolchilar et al. 2023; Sauvé, Bakker, and Houben 2020; Stegers, Sauvé, and Houben 2022) through their

tangible and visual representations of data (Dumičić et al. 2022; Eslambolchilar et al. 2023; Jansen et al. 2015; Sauvé, Bakker, and Houben 2020). Supporting passive awareness of consumption data through physicalizations could reduce the need for individuals to actively seek out information on a screen, creating a more relaxed and less stressful approach to monitoring consumption (Eslambolchilar et al. 2023). As our findings suggest, utilising shape-changing objects (e.g. blooming flowers) to elicit intrinsic motivation through nature-based empathetic physical artefacts could minimise the anxiety of information overload. Future research could explore these insights to further investigate the stress-reduction potential of physicalizations in the context of sustainable practices.

6. Reflections on the study - limitations and future directions

While our study did not involve a large, representative sample of UK households, it is important to note that it is not uncommon for qualitative research to employ similar sample sizes (see Caine 2016; Gardner and Abraham 2007; Graham-Rowe, Jessop, and Sparks 2014; Mann and Abraham 2006). The participants in our study had diverse backgrounds, household sizes, locations, and socioeconomic statuses; however, future research could benefit from including a broader range of participants from various socioeconomic backgrounds, cultures, and perspectives. As we explored children's design preferences through their parents, future research may benefit from directly involving children to understand their choices and requirements for physicalization design. Future work could explore the textures, colours, and sustainability of materials (Lindrup, Menon, and Biørn-Hansen 2023) for the bag of items provided to participants for design creation. Although our participants were encouraged to create their own designs, most chose to explain their ideas verbally. Future research could employ methods that enhance participant engagement in design-related workshop activities (Gray, Brown, and Macanufo 2010; Pavelin, Pundir, and Cham 2014). Although the combination of low and medium-fidelity prototypes was useful for exploring the design space more comfortably, future research may benefit from considering artefacts that clearly depict the potential technology and aesthetic quality.

Furthermore, conducting these interviews in the households of the participants helped us to contextualise better, but it also made the process of research dependent on factors of the surroundings. For example, in certain situations, women who participated were observed to be silent when discussing technology-related issues (for example, the existing screen-based application of their energy providers). This was mostly because the men who participated had access to the mobile applications while other member(s) did not. In this case, the visual methods of data collection through sketches and prototypes were helpful in provoking interactions, enabling all members to participate actively even without having access to the said applications. However, when discussing household-related questions, all participants got involved.

There was a perception among a few households that their consumption data could be shared with energy providers through this research, which initially lead to careful answers from participants. The researchers were asked questions regarding the visibility and confidentiality of the studies, which served as a way to familiarise them and have open conversations, hence creating a safe space for discussion. Our ongoing and future work includes a series of design workshops with households to gain a deeper engagement with the aforementioned themes and ideas for physical artefacts, including figuring out ways to build and pilot-test them.

7. Conclusion

This paper explores the potential design of physical artefacts to encourage sustainable household practices. We conducted 15 design workshops to gather physicalization design ideas, and envision and receive suggestions in connection to five low to medium-fidelity prototypes aimed at enhancing user engagement in sustainable practices. Our findings revealed tradeoffs between aesthetics, abstraction, and communicating relevant information to cause less stress in the design of physicalizations. We found that incorporating tactile rewards, excitement, and challenges into these physical artefacts could sustain user engagement while considering their placement in various shared spaces within the household. We suggest considering the physicalization's size to seamlessly integrate it into the household and emphasise the importance of involving all household members, including children, in the design process to enhance household engagement.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Note

1. https://www.youtube.com/watch?v=0_QJWDRC6Rk

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