Augmented-Reality Waste Accumulation Visualizations

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Fig. 1. A user looks at the amount of waste produced by his corporate restaurant in a week. The waste is represented by virtual trash bags, which are displayed directly in the restaurant using Augmented Reality (AR). 3D model by Wheelibin.

The negative impact humans have on the environment is partly caused by thoughtless consumption leading to unnecessary waste. A likely contributing factor is the relative invisibility of waste: waste produced by individuals is either out of their sight or quickly taken away. Nevertheless, waste disposal systems sometimes break down, creating natural information displays of waste production that can have educational value. We take inspiration from such natural displays and introduce a class of situated visualizations we call *augmented-reality waste accumulation visualizations* or ARWAVs, which are literal representations of waste data embedded in users' familiar environment. We implemented examples of ARWAVs and demonstrated them in feedback sessions with experts in pro-environmental behavior, and during a large tech exhibition event. We discuss general design considerations for ARWAVs. Finally, we conducted a study with 20 participants suggesting that ARWAVs yield stronger emotional responses than non-immersive waste accumulation visualizations and plain numbers.

CCS Concepts: • **Human-centered computing** → **Information visualization**; **Visualization design and evaluation methods**.

Additional Key Words and Phrases: Augmented Reality, Eco-Feedback, Embedded Visualizations, Concrete Scales.

1 INTRODUCTION

The adverse impact humans have on the environment (e.g., air pollution, plastic pollution, soil erosion, or damage to biodiversity) is one of the biggest challenges currently faced by our society. Although the causes are complex and numerous, individual behavior and lifestyles have been identified as among the key contributors [8, 43]. In particular,

current consumption habits in industrialized countries[1] far exceed what humans can sustainably manage without damaging the environment. A factor that likely contributes to the excessive consumption and unnecessary waste production in those countries is the *invisibility* of waste there [14]: when we buy a new smartphone, we do not see the metal mines that went into its construction [61]; Even when we directly create waste, it quickly goes away and becomes invisible: dirty water moves to the water treatment plant right after we showered or flushed our toilet, and the garbage we throw away in our homes is conveniently taken away to a landfill site every few days.

Modern society is organized in such a way that our waste is hidden from our view. However, accidents sometimes happen that cause waste to accumulate and unexpectedly come back to our attention: bathtubs and toilets get clogged; Garbage gets scattered in the streets during large public gatherings (Figure 2a) or piles up during garbage collector strikes (Figure 2b). In such cases, waste piles serve as visualizations of our waste production that are physical [28], literal [47], and situated [60]. Perhaps because such waste accumulations are so effective as displays of information, they are sometimes created and displayed on purpose. For example, some collective restaurants use transparent bread garbage cans to raise their customers' awareness about food waste (Figure 2c), and a designer has made a toilet with a transparent water tank to act as a preview of the amount of waste water that will be produced (Figure 2d). Waste accumulations like these act as situated information displays that are unique in their ability to convey waste production in a way that is immediately understandable by a large audience and can carry emotional impact. However, they also have a very narrow range of applicability: creating physical waste accumulations can be difficult in practice, typically requires space, and can cause sanitary issues. In this article, we propose to use augmented reality to re-create virtual versions of such information displays and embed them in users' physical environments (see Figure 1). We will refer to them as *augmented-reality waste accumulation visualizations*, or ARWAVs for short.

We go through different use cases to illustrate how ARWAVs can be useful in a range of situations. We also explain why ARWAVs go beyond what has been explored in research so far. In particular, they fill a gap in eco-feedback research [33], where most systems convey resource consumption and waste production using units and visual representations that are useful but often abstract and potentially difficult to grasp intuitively. Because ARWAVs use literal representations of waste amounts [23] (e.g., 300 litres of garbage can be represented with ten 30-litres trash bags), and embed those representations in the user's familiar surroundings, we expect them to give a more visceral sense of quantities and stand as more engaging representations. A user study with 20 participants, that we will describe later in this paper, outlines that indeed ARWAVs tend to elicit higher emotional intensities than other more classic visualisations. As such, we see them as a useful potential complement to more standard information displays in eco-feedback systems, and we hope they will inspire future research in this area.

Our contributions are:

(1) Identifying and naming a family of eco-feedback visualization techniques (ARWAVs) that have received very little attention so far, and presenting scenarios illustrating the different situations in which they can be useful;

(2) Describing prototypes that implement such visualizations techniques, and that were tested in initial feedback session, both with colleagues and with a larger public during a tech exhibition event;

(3) Introducing a terminology and a set design considerations for ARWAVs.

(4) Reporting a user study suggesting that ARWAVs are emotionally more engaging compared to less immersive display modalities (3D on screen) and simpler information representations (numerals).

[1]A developed country, or a sovereign state that has a high quality of life, developed economy and advanced technological infrastructure relative to other less industrialized nations (https://en.wikipedia.org/wiki/Developed_country)

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

Fig. 2. Examples of physical waste accumulations. (a) Street of London during the 2009 marathon (source: Paul Simpson, flickr.com) (b) Street of Marseille in 2010, during a garbage collector strike (credit: pxhere.com, public domain). (c) Transparent bread garbage can to raise waste awareness (source: https://www.chef-eco.fr/). (d) Toilet with transparent tank to raise awareness of water usage (photo taken in a Parisian restaurant).

2 BACKGROUND

In this section, we review previous work related to augmented-reality waste accumulation visualizations (ARWAVs). A highly relevant research area is the study of *eco-feedback* systems, i.e., "*technology that provides feedback on individual or group behaviors with a goal of reducing environmental impact*" [33]. Research on eco-feedback is vast and has been conducted both in psychology, with a focus on cognition and behavior, and Human-Computer Interaction (HCI), with a focus on technology [33]. We will cover both and will also review related work in information visualization.

2.1 Eco-Feedback Technologies

Simple eco-feedback displays have long been available. For example, in 2007, most UK residents with solar panels had a device that displays energy output and the total CO_2 mass saved since their installation [38]. Today, several eco-feedback apps are available on mobile devices to support self or group consumption awareness – for example, the MyImpact app[2] helps users log their plastic reducing and recycling actions, and displays the total amount of plastic reduced and recycled, which they can compare with friends.

While researchers in environmental psychology have mostly focused on the efficacy of simple eco-feedback displays like these, HCI researchers have emphasized exploring richer and less conventional information displays [33]. Examples include representing energy consumption as waves on a kitchen wall [15], or designing public trashcans that project their content and history of use on the sidewalk [48]. Researchers have also started to explore the use of virtual reality (VR) for eco-feedback, although mostly to test research hypotheses in experiments [11, 59]. We will discuss these experiments in subsection 2.2.

While there have been some explorations in VR, augmented reality (AR) has rarely been considered for eco-feedback. Several near-AR eco-feedback systems have been proposed or studied, including appliances (e.g., trashcans [48] and fridges [44]) augmented with sensors and displays, AR overlays of energy consumption on physical building models [29], and heat cameras to visualize thermal loss [18]. But as far as we know, enhancing real-world environments with AR for eco-feedback purposes has been only discussed mainly as opportunities (e.g., in [21, 32, 53]), and concrete implementations are very rare.

[2] www.myimpact.com

We only know of two examples of ARWAVs discussed in the past. The first one is an AR visualization of personal trash production designed during a research internship by Nic Stark [55]. In this prototype, which has directly inspired our work, users can use their smartphone to visualize a year worth of trash bags in front of them. The second piece of work is by Honee and al. [35]. In this work, conducted in parallel and independently from our work, a specific type of ARWAV is proposed that focuses on food waste, and a usability study is reported. Besides these two examples, we do not know of any academic work that discusses the general concept of ARWAVs. Our paper fills this gap by conceptualizing ARWAVs, presenting a range of examples, and providing design considerations. As far as we know, our paper is also the first to report a controlled user study of an ARWAV with non-AR comparison baselines.

2.2 Eco-Feedback Studies

Many studies have been carried out both in environmental psychology and in HCI to determine whether eco-feedback systems are effective and how to best design them. Directly relevant to this article is the question of how to display quantities, such as electricity consumed or amounts of water used. Pierce et al. proposed a taxonomy [50] that distinguish three types of eco-visualizations: pragmatic eco-visualization that aims to effectively communicate resource processes using scientific visualization elements such as numbers, charts, and graphs, artistic visualization that employs persuasive imagery to create meaningful representations such as metaphorical metrics and informative art that occupies an intermediate position between pragmatic and artistic approaches, characterized by its decorative nature and initial lack of recognition as data visualization. ARWAVs can easily convey information when presented as data visualization and foster immediate understanding simultaneously. Therefore, they fall in between two of the latter categories (i.e., pragmatic visualizations and informative art). Studies have found that units used by commercial eco-feedback monitors (e.g., kWh or tons of CO_2) are often not meaningful to users [56]. One study compared people's preference for simple quantitative displays (i.e., numbers or charts) vs. qualitative displays employing metaphors (e.g., a polar bear on a melting iceberg), and found that STEM[3] students tended to prefer the former, while non-technical students were more comfortable with the latter [13]. In contrast with metaphor-based or qualitative displays, the goal of ARWAVs is to offer faithful representations of quantities. However, such representations significantly differ from simple charts, and focus on efficiently communicating magnitude rather than precise numbers.

Eco-feedback displays can either use a negative framing (e.g., show energy consumed) or a positive framing (e.g, show energy saved). Studies overall suggest that negative emotions such as regret and guilt lead consumers to choose sustainable products and services [39], and to engage in sustainable behaviors like recycling and using public transportation [22]. This confirms that negative framing, which is used in many eco-feedback designs, is effective. At the same time, an overly negative framing can backfire. For, example Bao et al. [12] showed different eco-feedback designs to participants, including one where a polar bear was pictured decapitated when the light switch was on; While some participants liked the design, most of them found it inappropriate, and some found it manipulative. Similarly, a study found that people preferred to see their CO_2 consumption expressed in terms of trees necessary to offset it than the number of polar bears whose habitat it will destroy or the number of Earths needed to support humanity if everyone consumed the same (i.e., more negative framings) [49]. While the types of designs we discuss in this paper (waste accumulations) naturally lend themselves to a negative framing, we also explore positive framing (e.g., waste avoided).

Two eco-feedback studies used a design similar to ARWAVs, but implemented in VR. In one study, participants were asked to take a virtual shower and were shown the amount of heating energy they used in terms of pieces of coal

[3]acronym of science, technology, engineering, and mathematics

(each piece stood for 100 watts or 15 sec. of a shower) [11]. After the experiment, participants used less hot water to wash their hands when they saw virtual renditions of actual piles of coals than when they saw the number of pieces of coals expressed as text. Another VR study asked participants to repeatedly use a water bottle to fill a tank with enough water for a toilet flush or a 1-minute shower, after which they were shown multiple water bottles representing that quantity [59]. They found a positive effect on self-reported attitudes towards water usage. Although both studies suggest that the kind of visual representations used in ARWAVs can be effective, they each only consider very specific instances and do not discuss how they can be employed in actual eco-feedback systems, for example using augmented reality.

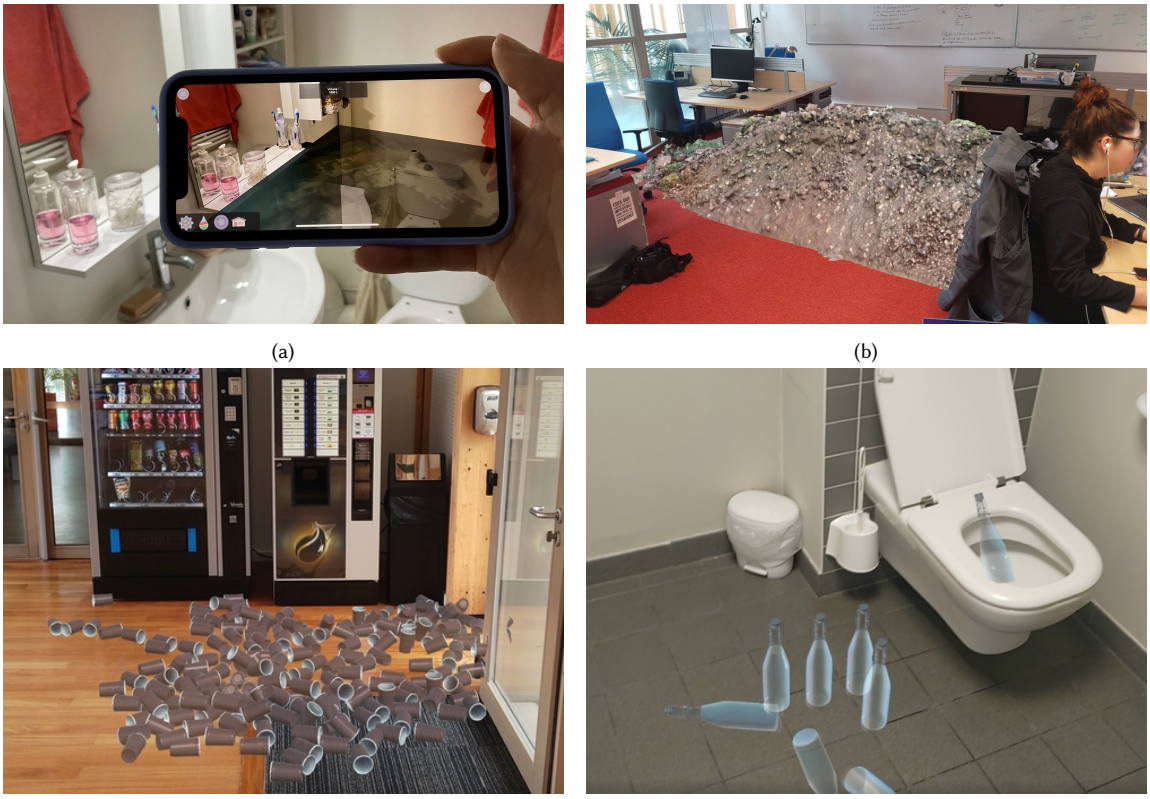
2.3 Information Visualization

Visualization researchers have investigated and explored many different ways of representing data to promote understanding and engagement among large audiences; one of them is the use of collections of icons or objects to convey numbers, a common practice in visualization and infographic design.[4] These has already been used in environmental communication in the web article "Drowning in Plastic" [54], showing computer-graphics renderings of gigantic heaps of plastic bottles situated next to prominent landmarks such as the Eiffel Tower. It conveys how many plastic bottles are purchased worldwide on different time scales, from a single day to the last 10 years. Strategies like these for representing large quantities or unfamiliar units have been formalized in information visualization under the *concrete scale* framework [23]. This framework describes the trade-offs behind several design decisions, including which object or container to choose to represent quantities; For example, the amount of sugar in a soft drink can be represented with a pile of sugar cubes next to the drink, while larger quantities can be represented by familiar containers (e.g., a shovel or a dumpster) filled with sugar [23]. However, the paper does not discuss how concrete-scale visualizations can be used for eco-feedback, nor how they can be used in AR.

Inspired by the concrete scale framework, Lee et al. [41] introduced the concept of *data visceralization* as "*a data-driven experience which evokes visceral feelings within a user to facilitate an intuitive understanding of physical measurements and quantities*". Immersion is a central component of data visceralization. For example, the authors propose to show the number of people in a protest by having users immersed in a virtual reconstruction of the protest or to convey US debt with a VR rendering of huge piles of dollar bills standing next to known landmarks. Again, the article does not discuss eco-feedback as a possible application and focuses on VR, but it does identify AR as a possible direction for future work.

Another relevant research area is *situated visualization*. Broadly speaking, situated visualizations are data visualizations that are integrated (or appear to be integrated, in the case of AR displays) into the physical environment meaningfully. Willett et al. [60] specifically refer to situated visualizations as data representations that are located close to the data's *physical referent(s)*, meaning close to the space, object, or person the data is about. For example, a visualization of data about a plant's health is not situated if it is shown on a desktop computer in another room but becomes situated if it is shown next to the plant. Other more general conceptions of situated visualizations have been discussed [20]. In general, situated visualizations are thought to facilitate data understanding, sense-making, and decision-making in some situations [57], especially in eco-feedback contexts where behavior may be easier to adjust when data is shown at the right place and at the right time [52]. Various techniques exist for situating data visualizations into the physical world. A straightforward approach is to place a screen close to physical referents [60]. Alternatively, physical data representations (also called data physicalizations [37]) can be used instead of regular displays and placed

[4]See, e.g., luizaugustomm.github.io/anthropographics and dataphys.org/list/tags/single-datum/.



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

Fig. 3. Illustrative examples of ARWAVs we prototyped. (a) Volume of consumed water visualized in a bathroom. (b) Approximate amount of material displaced and emitted to manufacture 8 smartphones (captured from Hololens, 3D model by SPLEEN VISION [1]). (c) Quantity of single-use plastic cups accumulated for a given period of time (captured from Hololens, 3D model by 3DHaupt [2]). (d) 9 Litres of water represented using water bottle (3D model by Unit Studio [3]) next to the toilets (average flush amount of water).

next to referents (e.g., placing a robotic plant next to garbage bins to convey data about recycling behavior [34]). The most common approach in academic research, however, has been to use AR to display visualizations in a way that makes them appear close to their physical referents or overlaid upon them. AR-based situated visualizations have been explored in various domains such as health – e.g., showing vital information about a patient during a surgery [9], and aviation – e.g., displaying flight information directly in front of the pilot [31]. We only know of two projects using AR-based situated visualization for eco-feedback, which we already discussed in section 2.1.

The natural waste accumulation displays we mentioned in the introduction section are inherently situated, and so are most of the eco-devices discussed in section 2.1. ARWAVs continue this stream of research by leveraging aspects of situated visualizations that have been recently presented as opportunities [20]; This includes *temporal relevance* – as ARWAVs represent an accumulation over time of recently produced waste, as well as *community* aspects, as ARWAVs can be used to reveal waste locally produced by a group.

3 ILLUSTRATIVE SCENARIOS

In this section, we present scenarios to illustrate and motivate ARWAVs. We will refer to these scenarios again in later sections, especially in our discussions of ARWAVs design considerations in section 5.

Augmented-reality waste accumulation visualizations or ARWAVs aim to help people better perceive the quantitative impact of their actions and decisions in order to inform them, raise their awareness, or encourage them to change their habits. The first one from Figure 1 illustrates a scenario where employees can perceive directly in their corporate restaurant a week of collective waste production represented with virtual trash bags. In the following sections we present additional scenarios that illustrate the same concept. An illustrative video is available in the OSF project repository[5].

Scenario 1: Personal motivation, water use. Water is a resource that many of us abundantly use at home when we take a shower, wash our hands, flush our toilets, or use appliances like washing machines. As water immediately disappears through the pipes, it can be hard to get a good impression of the amount we use over time. However, used water is waste that needs to be processed, and water can be scarce in lots of countries, where a drought can lead to a shortage with dramatic consequences. Knowing numbers is a good start, but is likely not enough. For instance, it might not seem a lot to consume 5 m^3 of water in a month, but it actually represents about 28 full bathtubs, or an average bathroom filled with water up to 2 m high. ARWAVs can literally show these volumes of water to make abstract numbers more concrete. A user could use their smartphone each time they get to a room of their apartment where water is used (e.g., bathroom, toilets, kitchen, garden). Figure 3a shows an example where they use it in their bathroom to see the amount of water they consume in a week, as a volume that fills the room. They can monitor this level occasionally when they get to the bathroom by looking at where the water stops on the wall, comparing their consumption across weeks (for instance, by recalling the level of water compared to furniture, e.g., from lower than the sink to higher than the mirror), and try to lower this level little by little. Figure 2a shows another way of representing wasted water with water bottles.

Scenario 2: Group dynamics, ecological rucksack. Computers and mobile devices are powerful tools with many useful applications, but they have a significant ecological footprint.[6] One way to capture this footprint is the concept of *ecological rucksack, which is the amount of matter displaced to build an object.*[7] *A smartphone requires an ecological rucksack of about 70kg, which includes the amount of soil mined to obtain the metals that go into its fabrication, and the amount of CO2 emitted during transportation and manufacturing.*[8] Since the metal mines and the CO2 emissions are typically situated far away from where the phone is purchased and used, it is hard for people to have a vivid picture of them in their mind, even when they hear about them. In addition, computing devices often look clean and beautiful, so looking at them does not bring about any association with mines, soil, or greenhouse gases. With ARWAVs, we can make those waste products more salient to users. For example, imagine a research team discussing whether to buy eight new smartphones for a project or use old ones. Here, an eco-conscious member of the team could book a room in their laboratory and set up a meeting in which they use a Hololens 2 to show the rest of the team the size of the ecological rucksack necessary to build the new phones, as a pile of soil (Figure 3b). Having this heap of soil appear as if it was in the room (as opposed to, e.g., on a computer screen or a magazine) could give the team members a more

[5] https://osf.io/v4yxs/?view_only=cd8b973f9df54d7590f8421be6b11098
[6] The ecological impact of ARWAVs is an important issue that will be discussed in subsection 7.1.
[7] https://www.gdrc.org/sustdev/concepts/27-rucksacks.html
[8] https://ec.europa.eu/environment/ecoap/about-eco-innovation/experts-interviews/friedrich-schmidt-bleek_en

visceral sense of quantity and size. It also adds a dramatic dimension, which can help make environmental issues more salient and more influential in the discussion. Showing ARWAVs is a way for the organizer of the meeting to initiate dialogue and share their concern about their common purchase habits.

Scenario 3: Support for policies, plastic cups. Single-use plastic cups have a negative repercussion on the planet. It is estimated that more than 50 billions are used in the US in one year.[9] Yet manufacturing them is costly in energy and resources, they are hard to recycle, and they are one of ten most commonly found waste items in European beaches[10]. However, plastic cups are still routinely given away in cafés, shops and companies, and thus it remains easier for many people to use them instead of bringing a reusable cup. In this third scenario, a company chooses to ban plastic cups as part of a program to reduce its ecological footprint but is afraid that not all of its employees will agree. The company has already communicated about the issue through figures and charts, but they were largely ignored. Therefore, the company decided to organize an event with a booth in front of the coffee machine, where employees can observe through an AR-HMD (Head-Mounted Display) an ARWAV composed of all plastic cups typically used over a week (see Figure 3c). With this immersive experience, most employees get a much better sense of the number of plastic cups accumulated over time, and many become more willing to make the effort to bring their own reusable cups. Afterwards, some employees keep thinking of the virtual pile of cups every time they go to the coffee machine and are happy that the policy was adopted.

Process. In order to elaborate these scenarios, we first designed and developed four ARWAV prototypes (further described in section 4). In designing these prototypes, we were inspired by the related concepts of concrete-scale visualization [23], and data visceralization [41], as well as by real waste accumulations and our own experience dealing with waste. We first discussed potential end-users of ARWAVs (e.g., individuals, small groups, communities) and their possible goals (e.g., self-motivation, decision-making, persuasion, support for policies). In imagining the prototypes, we sought to cover different types of visualizations (e.g., trash bags, cups, soil, water), different types of users, and different types of goals and tasks.

4 PROTOTYPES AND INITIAL TESTS

In order to test ARWAVs and get initial user feedback, we implemented four ARWAV prototypes. We first go through implementation details, and then describe findings from our feedback sessions. We then list the main lessons learned from our feedback sessions and how informed the subsequent stages of our research – i.e., the design considerations in section 5 and the experiment in section 6.

4.1 Implementation

The water use prototype (**Scenario 1**) was implemented with Unity 2020.3.2f1 on a smartphone, and used the AR-Foundation framework (handling most of ARKit and ARCore functionalities). We implemented mesh created from selected points on the real-world detected planes. This surface is extruded from the ground plane, matching the desired volume of water (predefined values include an average bath, shower, toilet flush, hand and dish washing and washing machine). On rendering, we applied a 3D shader on each volume face with a material using the URP pipeline. [11] The final rendering takes the physical surroundings to render an adequate water color.

[9] https://plastic.education/the-problem-with-disposable-cups/
[10] https://ec.europa.eu/environment/pdf/waste/single-use_plastics_factsheet.pdf
[11] https://docs.unity3d.com/Packages/com.unity.render-pipelines.universal@11.0/manual/

The trash bag prototype (shown in Figure 1) was previously implemented on a smartphone by Nic Stark[12] [55]. We re-implemented his prototype on a Microsoft Hololens 2, to be able to test and compare the two types of AR displays. The ARwavs described in **Scenario 2** and **Scenario 3** (ecological rucksack, plastic cups) were also implemented on Hololens. We developed with Unity 2020.3.18f1 and used the MRTK toolkit[13]. We enabled hands, head tracking, occlusion, and set the spatial awareness module to scan the environment at start (update interval of 3.5 seconds). The objects making up the ARwavs (trash, bottles, mud and plastic cups) were either found on the Unity Asset Store or download and adapted from 3D models browsers as CGTrader, Turbosquid or Free3D. For collision detection between the objects, in order to support numerous objects, we added an assembly of basic colliders that closely match the shape of the objects (instead of the more compute-intensive mesh colliders), and we set a discrete collision detection. We pre-created several prefabs (at run-time) to pile objects in a natural way, making them fall from a 1 to 2 meters height. Audio sources have been scripted to match collisions.

The source code for the ARwav used in our controlled experiment (section 6) is available in our OSF repository. More extensive source code covering a wider range of prototypes will be shared on gitlab upon publication.

4.2 Early User Feedback

In order to get initial feedback on our prototypes, gather impressions, and collect suggestions for improvement, we ran a testing session with five collaborators from different institutions. For all of them except one who tested the prototypes three weeks prior, this was their first experience with AR-HMDs. The testing session took place in a large meeting room, during a workshop. We demonstrated the ARwav prototypes (trash bags on HMD and smartphone, plastic cups on HMD, soil on HMD, and water with smartphone). Participants appeared overall quite engaged, qualifying the experience as *surprising* and *impressive*. When using the *Trash bags* HMD prototype, three participants stepped back when the trash bags started to fall, due to the impression that they may fall on them. In the *Plastic cups* prototype, one participant commented on how real the cups looked when they happened to roll under a physical chair (and disappeared due to occlusion management). Participants commented on the differences between the HMD and the smartphone. Overall, the HMD provided a stronger immersion and elicited more surprise, although the surprise factor may be largely due to a novelty effect. Participants also felt they could manipulate items more naturally using mid-air gestures on the HMD than using 2D gestures on the smartphone. On the other hand, one participant mentioned that the smartphone is the only option available to them if they want to share a visual, and it is already quite convincing. Among limitations, several participants mentioned the narrow field of view of the HMD (but also of the smartphone), especially for the *Trash bag* and the *Soil* prototypes. However, one participant emphasized that it was easier to overcome the narrow field of view by moving their arm with the smartphone than by moving their whole body and head with the HMD. Finally, several comments had to do with emotions induced by the experience – *guilt* was mentioned several times, as well as other negative emotions such as *anxiety*, *stress*, and *oppression*. Positive feelings were also mentioned: one participant reported feeling *satisfaction* when seeing the *Plastic cups* prototype, as they do not use plastic cups anymore and could see the approximate amount of plastic they save.

We also had the opportunity to demonstrate ARwavs in a large-scale tech exhibition ([Anonymized]], receiving more than 90K visitors). This allowed us to test the robustness of our prototypes and collect additional user feedback. Moreover, exhibitions are among possible real-world applications of ARwavs, as deploying ARwavs in such spaces can help raise the general public's awareness of environmental issues. We demonstrated our Hololens prototypes and added

[12]We are grateful to Nic Stark for sending us his code.
[13]https://docs.microsoft.com/fr-fr/windows/mixed-reality/develop/unreal/unreal-mrtk-introduction

a computer monitor for other people to see. We met approximately 40 people in our demo booth, who were highly diverse in terms of age and professional background. Most of them have already tried VR systems before, and a few have tried AR-HMDs. Viewers were generally impressed and sometimes surprised by the quantities: *"All this for one person! It's huge!"*. On several occasions, they mentioned that this type of tool can be useful to raise environmental awareness. A metal waste management professional was enthusiastic about the *ecological rucksack* demo: *"It's really great to be able to show this! In my daily life, I am confronted with large piles of metal and this has sharpened my environmental awareness. I have often said to myself that it is a public necessity to show this kind of place; with what you propose, there is no need to go there!"*. Two science communicators specialized in environmental issues and two teachers were also enthusiastic and argued that this tool could be useful in primary schools, at environmental awareness forums or fairs, or as a pedagogical tool for ecology courses in higher education. According to them, a novel user interface like this can be more playful and more impactful. The teachers also commented that it would be interesting to embed the visualization experience in learning spaces (e.g., classroom or amphitheater), where walls, screens, and tables are already occupied by physical or digital course materials Overall no negative feelings were reported.

4.3 Lessons Learned

Importance of affect. Both our testers and visitors of the tech exhibition mentioned emotions elicited by ARwavs. This underlines the importance of the affective dimension and led us to reflect more on affect, such as whether ARwavs can be designed to elicit positive or negative emotions, a conept to which we will return in our section on design considerations (section 5). This also prompted us to study affect experimentally, as we will report in section 6.

Importance of AR equipment. People involved in prototype testing were highly sensitive to the type of AR display device used (Hololens or smartphone), and commented on the strengths and limitations of those devices. In particular, those who never used a Hololens before were astonished by how immersive the experience was, but they were also disappointed by the technical limitations of the device. This underlines the importance of the type of AR device used, which led us to include this dimension in our design considerations of section 5. Although we do not explicitly manipulate this factor in our experiment (section 6), we stress that it is important to test it in future experiments.

Importance of animations and interactions. We implemented basic support for animations and interactions in our ARwav prototypes, but did not expect they would be so salient to users during our testing session. This led us to include animation and interaction as important design considerations (section 5), and to implement animation (falling trash bags) in our experiment. We relied on this set of suggestions to build our study prototype. However, we did not include interaction in our experiment in order not to distract participants and keep the experiment simple.

5 DESIGNING ARWAVS

In this section, we present design recommendations. As presented in the previous section, we engaged in brainstorming sessions among the authors, drawing from existing literature, to generate multiple designs for testing in our early user feedback sessions. Our implementation of ARwavs in alignment with specific scenarios provided valuable insights. Subsequently, we consolidated the lessons learned from our initial testers and revised our list of suggestions accordingly. We acknowledge that these recommendations would benefit from an evaluation among experts (e.g., eco-feedback designers) to testify of its generative power. As we know that design considerations for ARwavs go way further than what we suggested below, we choose to convey our observations here and leave a deeper analysis of potentialities, one that would be assessable, for future work.

5.1 Type of representation

The visual representation of ARWAVs can vary from highly realistic depictions of actual waste products to slightly more symbolic representations.We categorize them into four groups.

1. Literal: The most straightforward way to represent waste material in ARWAVs is to use virtual representations that mimic the material itself. For example, wastewater can be represented by water (**Scenario 1**, Figure 3a), and used plastic cups can be represented by plastic cups (**Scenario 3**, Figure 3c). The main difference between the actual waste and its representation is in the layout: presumably, the plastic cups have never been arranged like in Figure 3c, and the water has never taken the shape of the bathroom like in Figure 3a. Nevertheless, the waste objects or material are represented literally and remain easily recognizable.

2. Transformed: This category corresponds to waste material that is represented as if the material underwent some processing or transformation, although the real waste material did not. For example, flushed water can be shown as if it has been put in bottles (Figure 3d), or soil like in Figure 3b can be shown packed in bags. Such quantity-preserving transformations, also called "unitizations" [23], can help people make sense of large quantities.

3. Materialized: Some waste material is difficult or impossible to perceive. For example, CO_2 is a common waste material but it is an invisible gas. For the purpose of ARWAVs, it could be useful to materialize CO_2 as, for example, a heap of coal or black smoke (as in [19]). Although this goes in the direction of metaphorical representations, it remains literal in the sense that coal is mostly made of carbon and smoke can contain a lot of CO_2. However, it is unclear if absolute volumes or masses are meaningful in these cases, and perhaps such ARWAVs would be mainly useful to assist comparisons (e.g., CO_2 emitted this year vs. last year).

4. Metaphorical: There are many ways waste can be communicated through symbols and metaphors. As an example, Ahn et al. [7] describe a VR application where trees are used to convey data about paper usage. However, using metaphors goes against the principle of ARWAVs, whose goal is to convey actual waste quantities with representations that resemble the waste itself. We include this category for completeness nonetheless, as the metaphorical distance is a continuum [62], and as we saw, *materialization* goes a bit towards metaphors.

5.2 Realism of the representation

Realism lies on a continuum and concerns all four types of representations we mentioned. In all types, the representations (water, bottles, smoke, etc.) can be modeled and rendered more or less realistically. Lee et al. [41] discuss realism in the context of data visceralization and came to the conclusion that *"realism is not important to understand the underlying data, but is still important for engagement"*. We identify several potential advantages of realism when it comes to designing ARWAVs. For example, the plastic cups in **Scenario 3** (Figure 3c) could be designed to be exact replica of the actual cups dispensed by the coffee machine. In that case, the cups would be immediately recognizable by people who regularly use them, which can contribute to making the ARWAV more plausible or more provoking. But in many cases, closely mimicking the physical waste material may be difficult, and not necessarily useful. For example, in **Scenario 2** (Figure 3b) the soil probably does not look like typical soil extracted from mines. Similarly, the trash bags in Figure 1 may not be of the same color and appearance as the trash bags actually thrown away by the person whose data is visualized. However, the objects are close enough to be recognized for what they are, and to give a reliable intuition of the waste quantity.

5.3 Animation and Interaction

Visual representations of waste in ARWAVs can be dynamic and even interactive. We distinguish between three levels:

1. Static: These are waste representations that maintain their shape and appearance over time. This is the case, for example, for our soil prototype (**Scenario 2**, Figure 3b). Users can walk around it but cannot interact with it. The main advantage is ease of implementation, especially for material whose physical behavior is challenging to replicate.

2. Animated: Adding physically plausible animations to waste representations can make them more realistic and increase the user's sense of immersion. For example, trash bags can fall down one by one to form a pile, or plastic cups can roll on the floor. This approach is easier for waste representations that consist of small to medium-sized collections of objects. Animations can be enhanced with sounds of objects colliding or crashing on the floor.

3. Interactive: Letting users interact with the waste representations may help enhance immersion and realism. For example, in our trash bag and plastic cup prototypes, users can pick and move objects; However, this is currently done through the standard Hololens pinch gesture and objects can only be moved one by one, which limits realism. Allowing physically more realistic interactions (e.g., shooting in plastic cups) would likely increase realism and immersion [36]. Besides aimlessly moving objects around, interaction opens up a range of possibilities, including in terms of gamification: VR systems already exist where users are invited to manually fill water tanks [59] or cut trees with chainsaws [7] to raise their awareness about water and paper usage. Similarly, it is possible to imagine ARWAVs where users are asked to spend energy to create, rearrange, or destroy waste accumulations. Interaction also opens up endless opportunities for data exploration, some of which will be discussed in subsection 7.4.

5.4 Framing

As we already saw in subsection 2.2, eco-feedback displays can be framed either positively or negatively, with possibly different impacts on users' emotions, attitudes, and behavior. Which framing is preferable is highly context-dependent and difficult to predict without user studies. Overall, framing is important to consider when designing ARWAVs.

1. Negative: Guilt or fear-tripping visualizations showing the negative impact of users' behavior can be effective ways of encouraging changes in attitudes and habits. As ARWAVs show waste accumulations, they have a naturally negative framing, which AR can be used to enhance: because people instinctively want to get rid of waste, showing it in their personal spaces (e.g., their living room) can elicit a sense of discomfort, whether their actual waste has been already disposed of (e.g., trash bags), or has been produced in a remote place (e.g., a heap of soil from a mine).

2. Positive: It is possible to use ARWAVs for positive framing, by having them represent waste saved rather than produced. For instance, our plastic cup prototype (**Scenario 3**, Figure 3c), could be used to show all plastic cups the user saved since they switched to a reusable cup. Such designs focusing on positive effects are more likely to elicit positive emotions such as pride and satisfaction.

Note that framing refers to the designer's intent to elicit specific interpretations or emotional responses, but the actual responses might not match the intent and might vary across people. For example, imagine an ARWAV showing plastic cups the user would hypothetically save if they changed their behavior. This visualization could be seen as either negative (especially if the behavior change is considered unlikely or too difficult) or positive (if the behavior change is easy to contemplate). Likewise, an ARWAV showing collective waste can be interpreted differently depending on the user's perceived contribution (e.g., a user might feel proud of having produced less, or ashamed of having produced more), and how important fairness and collective action are to them (e.g., a user might feel annoyed that others are not trying as hard as them).

5.5 AR Display Technologies

Different display technologies can be used to implement ARWAVs. We review them here, and the trade-offs involved.

1. Hand-held devices: Smartphones and tablets are widely used, and recent models provide sufficient capabilities to support AR applications. Hand-held devices are therefore a strong vector to provide ARWAVs to a vast majority of people nowadays. For instance, **Scenario 1** (Figure 3a) illustrates the use of a smartphone in a private bathroom, and can be extended to any place where water is consumed. Another important advantage of hand-held devices is that their content can be easily shared within small groups of colocated people to support collective experiences.

2. Head-mounted displays: Compared to smartphones, augmented-reality head-mounted displays (AR-HMDs) provide more immersive experiences [16]. Hence, they may enhance the visceral impression of quantities conveyed by ARWAVs. However, they are more expensive, they only support a single observer, and current versions are still heavy with a small field of view. AR-HMDs are more appropriate for educative demonstrations, as the one described in **Scenario 3**. In the future, AR-HMDs may become much lighter and may have a much larger field of view, which will extend the range of situations where they can be used.

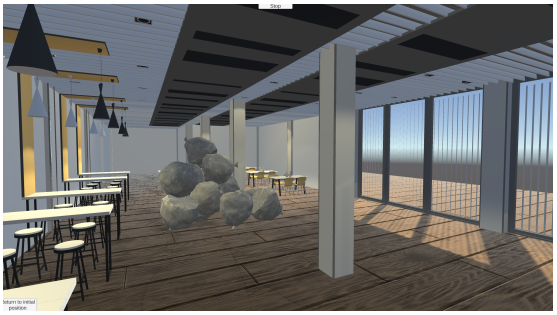
3. Spatial AR [17]: ARWAVs can also be implemented with video-projectors, which can allow them to be smoothly integrated in physical environments as in, e.g., JETSAM [48], a trashcan that records trash people put in it and projects it on the floor. Like hand-held displays, spatial AR can support shared experiences, but with even larger groups of people. However, virtual objects can only be displayed on 2D surfaces, which greatly limits possibilities. Nevertheless, research on 3D spatial AR is underway [42], and may open up unprecedented possibilities for ARWAVs in the future.

4. Tangible: The use of tangible and augmented objects can also be an interesting approach for creating ARWAVs experiences. For example, in the Erlen project [24] a physical object equipped with LEDs shows accumulated power consumption over the day. Such interfaces are however dedicated to very specific cases and currently lack versatility.

6 EXPERIMENT: ARE ARWAVS EMOTIONALLY MORE ENGAGING?

There are many possible ways ARWAVs can be evaluated. One important question is the choice of evaluation metrics. Broadly speaking, potential studies can look at the perceptual aspects of ARWAVs (e.g., whether people get a better sense of the quantities compared to alternative representations), the affective aspects of ARWAVs (e.g., whether people feel more emotions or feel more engaged), and the decision-making and behavioral aspects of ARWAVs (e.g., whether people adopt a more eco-friendly lifestyle). The behavioral aspects are arguably the most important but also by far the most difficult to evaluate. Motivated by our previous feedback sessions highlighting the importance of affect (see Section 4), we chose to focus on the affective aspects as a preliminary study.

Another important question to consider when evaluating ARWAVs is the choice of comparison baseline. Many baselines are possible, including the diverse representations of waste production used in eco-feedback research, ranging from simple digits to metaphorical depictions (see section 2). For this study, we chose two baselines of comparison: *(i)* a simple number conveyed in text form, and *(ii)* an interactive 3D representation similar to ARWAVs, but presented on a computer screen. The 3D condition is an intermediary condition that has some elements of ARWAVs but not all of them: like most concrete-scale visualizations [23], it uses a literal and realistic representation of data, but it is not displayed in augmented-reality. We included those two baselines to make it easier for us to entangle the effects of the presentation format (accumulation visualization vs. numerals) from the effects of the presentation medium (AR vs. screen). We now go through the experiment design in more detail.



(a) The **3D** condition, where a pile of trash bags is rendered in a generic 3D cafeteria and displayed on a computer screen.

(b) The **AR** condition, where the trash bags are rendered in the cafeteria where the experiment takes place and where most of the waste was produced.

Fig. 4. Two of the three experiment conditions.

6.1 Experiment Design

6.1.1 Visualized Data. We chose to show waste production data of a company building to their employees. We wanted the visualized data to be meaningful and to feel personal, in the sense that participants must have contributed – at least in small part – to the waste represented. This idea gathers themes discussed in the scenarios (see section 3). Each company member contributes to corporate waste production without necessarily taking responsibility for it, while the waste is partly due to lunch, office equipment usage, or other employees practices direct output. Working on prevention in the office is a way for companies to regulate their waste production, which is more and more strictly regulated by the government [6]. In effect, companies can communicate data about waste production to help employees identify with them, start discussions around their reduction, and promote good practices such as using fewer disposable cups or setting printers to two-sided mode by default. However, it is still unclear if the way of showing this type of data can have more or less impact on the audience. To find out, we ran a study in our lab building (about 400 employees), using building employees as participants, and showed them the average amount of waste produced by all employees in a week (5 working days). We reached out to the building management, which monitors waste output and estimates that an average of 2275 liters of waste is produced each week. This amount includes household waste (mostly from the cafeteria catering activity), cardboard, recyclables, paper, and glass. 2275 liters make up approximately 46 trash bags of 50 liters each. This is the datum we convey in our study.

6.1.2 Physical setup. The experiment took place in the cafeteria of the building (visible in Figure 4b), outside meal hours. A desktop computer (Dell Precision 3640 with Intel Core i9 processor) was installed on a table to administer the two baseline conditions, which will be explained in more detail in the next subsection. The ARwav condition was administered using a Hololens 2 AR headset.

6.1.3 Presentation formats. We convey the waste output information in three different ways:

Number shown on a screen. The number of trash bags produced is conveyed as numerals in a text sentence displayed on the desktop computer. The sentence is (translated from French): *"Each week, employees working in the Inria building produce 46 50-liter trash bags worth of waste (2021 data)"*. This condition will be referred to as **Text**.

Accumulation visualization shown on a screen. The same number is represented as a pile of 3D trash bags on the desktop computer (see figure 4a). The environment is a 3D model of a generic cafeteria, which is comparable to but

Table 1. The three experimental conditions according to the design considerations of section 5.

Condition	Description	Representation	Realism	Animation & Interaction	Framing	Display technology
Text	Number shown on a screen	Abstract	n/a	Static	Negative	Screen
3D	Accumulation visualization shown on a screen	Literal	High	Animated	Negative	Screen
AR	Accumulation visualization shown in AR	Literal	High	Animated	Negative	AR-HMD

different from the actual cafeteria. Before the 3D representation is shown, the screen displays the following prompt: *"Each week, employees working in the Inria building produce the amount of waste you will see (2021 data)"*. A 30-second animation first shows the 46 trash bags falling one by one from 3 meters above the camera's viewpoint. Participants are invited to navigate in the 3D scene with the keyboard and computer mouse. This condition will be referred as **3D**.

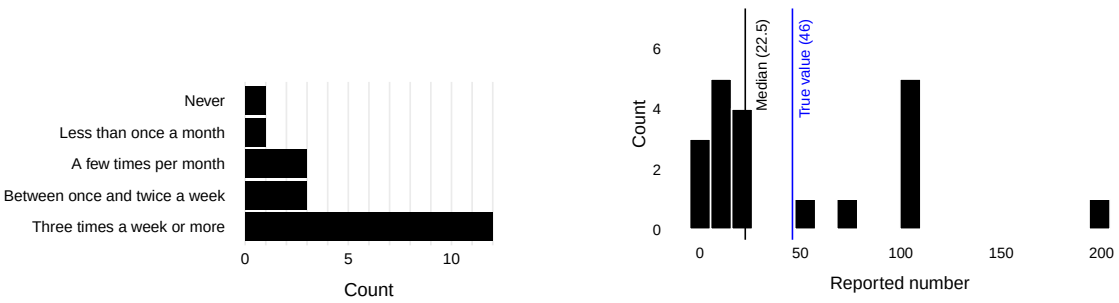
Accumulation visualization shown in AR. The same pile of trash bags as in the previous condition is shown, but this time in augmented reality (see figure 4b). The same text prompt is displayed as before. Then, participants saw the 46 trash bags fall one by one in the cafeteria. They are told that they are free to move in all the cafeteria areas with the head-mounted display on their head. This condition will be referred to as **AR**.

The three experimental conditions are summarized in Table 1 and characterized according to the design considerations of section 5. Since these considerations cover the design of ARWAVs and only one of our conditions is an ARWAV, some design options (shown in gray in Table 1) have not been discussed in section 5. Note that all three conditions are *situated* according to Willett et al.'s definition [60] because the representations are shown within the environment where the waste was produced. However, the AR condition is *more situated* than the other two because the representations (trash bags) appear to be integrated within the physical environment instead of being shown on a separate computer screen.

6.1.4 Design. We used a within-subject design where each participant sees all three conditions in order to reduce the impact of inter-participant variability and thus increase statistical power. The presentation order was fully randomized across participants, among four possible orderings: Text-AR-3D, Text-3D-AR, AR-3D-Text, and 3D-AR-Text. In other words, Text appeared either first or last. The reason is that we wanted to capture situations where people knew the exact figure before they saw the visualizations (3D and AR), as well as situations where they learned the figure only after having seen the visualizations. We did not include the orders AR-Text-3D and 3D-Text-AR to avoid situations where participants have asymmetric information between the 3D and the AR condition.

6.1.5 Procedure and Measurements. After having signed the consent form and indicated their age and gender, each participant was invited to read a text introducing them to the data they were about to see (waste output in their building over a week). The text provided context but without giving the actual number. The participant was then asked how often they eat at the cafeteria. This allowed us to assess the extent to which they were familiar with the place and were responsible for the waste output. Answering the question also likely prompted them to identify a bit more with the data and the place. The participant was then asked to provide a rough estimate of the number of 50-liter trash bags the building produces in a week. This question allowed us to assess the extent to which participants' prior beliefs were aligned with the information later shown to them and also likely increased their curiosity and engagement with the information.

The participant was then shown the three conditions in one of the four orderings mentioned before. After seeing each condition, the participant was asked to fill the PANAS questionnaire [58], a standard questionnaire for the self-reported affect that consists of 20 questions (10 about positive emotions, 10 about negative emotions). For example, the



(a) Cafeteria attendance.

(b) Estimated waste output.

Fig. 5. *Left:* Participants' reported attendance to the building cafeteria; *Right:* Participants' estimates of the number of 50-liter trash bags produced by the building every week; The blue line indicates the actual number.

questionnaire asks participants to report how much they feel interested, distressed, upset, etc., on a scale from 1 to 5. The participant was given the option to justify their responses using free-form text. The participant was allowed to review their responses to the previous conditions if they wished to, which we expected would further reduce random variability.

At the end of the experiment, the participant was asked to rank the three techniques depending on *(i)* each technique's ability to elicit emotions, and *(ii)* how much each technique helped them to understand the data presented. Finally, they were given the option to provide general comments about the study. This study was approved by the ethics committee of Inria.

6.1.6 Hypotheses. We expected that participants would report feeling stronger emotions overall in **AR** than in the other conditions and would report feeling stronger emotions in **3D** than in **Text**. The overall strength of reported emotions was operationalized by averaging the responses to all 20 PANAS questions, yielding an aggregate measurement on a scale between 1 and 5.

6.1.7 Participants. We recruited 20 participants (15 male, 5 female, mean age 27, SD = 10) using the lab's mailing list and word of mouth. As a selection criterion, participants had to be working in the building for more than three weeks. This allowed us to make sure that participants were familiar enough with the building and were responsible for its waste output, at least to some extent.

6.2 Results

6.2.1 Planned Analysis. All analyses reported in this section were prepared and registered [25] with the Open Science Framework (OSF) before the data was collected (see [14]). Experimental data and the final analyses are also available on OSF (see footnote 5). We report and interpret all our inferential results using interval estimation [26, 27].

Complementary demographics. In addition to age and gender, we asked participants to report how often they eat at the building cafeteria, with responses shown in Figure 5a. The other question asked them to estimate the amount of

[14] https://osf.io/v78ay

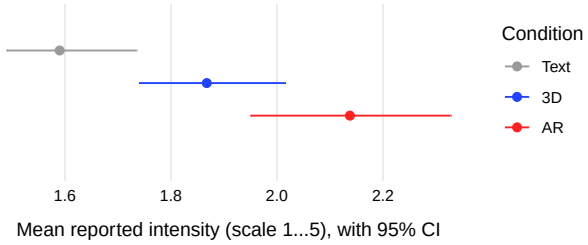


Fig. 6. Overall emotion intensity for each of the three techniques.

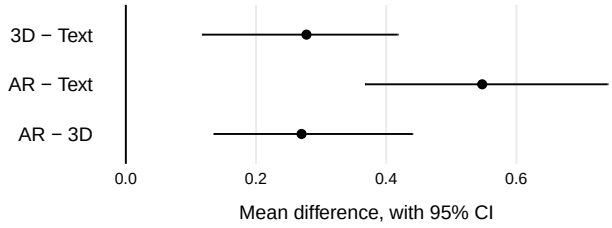


Fig. 7. Within-subject differences in overall emotion intensity.

produced waste, with responses reported in Figure 5b. Overall, the data suggests that most of our participants are regular cafeteria users (and therefore contribute to the building's household waste), and many underestimate the amount of waste produced by the building employees (with the median response being half the true value).

Overall emotion intensity. Again, overall emotion intensity is the mean response to the 20 questions of the PANAS questionnaire. Figure 6 shows the value of this aggregate metric averaged across all participants for each of the three conditions, with 95% confidence intervals (CIs). All CIs reported here are BCa bootstrap confidence intervals [40] unless specified otherwise. Overall, participants report higher emotion intensities after having seen the AR condition than after having seen the 3D condition, followed by the Text condition. These trends are confirmed by estimating within-subject differences in overall emotion intensity, shown in Figure 7. All intervals are located far from zero, providing strong evidence and support for our hypothesis that people tend to report stronger emotions with AR than with 3D, and with 3D than with Text.

Positive vs. negative emotions. We broke down overall emotion intensity into positive emotions (10 questions in the PANAS questionnaire) and negative emotions (10 questions). The results are shown in Figure 8. Whether we consider only positive or only negative emotions, the trends are the same as before. However, negative emotions are overall less intense than positive emotions.

Individual emotions. Figure 9 shows mean responses for each of the 20 questions of the PANAS questionnaire. For context, possible responses were labelled: 1 – "very slightly or not at all", 2 – "a little", 3 – "moderately", 4 – "quite a bit", and 5 – "extremely". If we only look at the point estimates, the trend we observed before (AR > 3D > Text) seems to hold for each emotion separately, except for emotions that most participants did not feel, namely *irritable*, *hostile* and *proud*. Among the positive emotions, those that participants reported feeling the most intensely are (in decreasing value of point estimate for the AR condition):

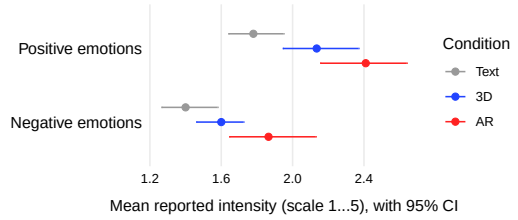


Fig. 8. Overall intensity of positive and negative emotions.

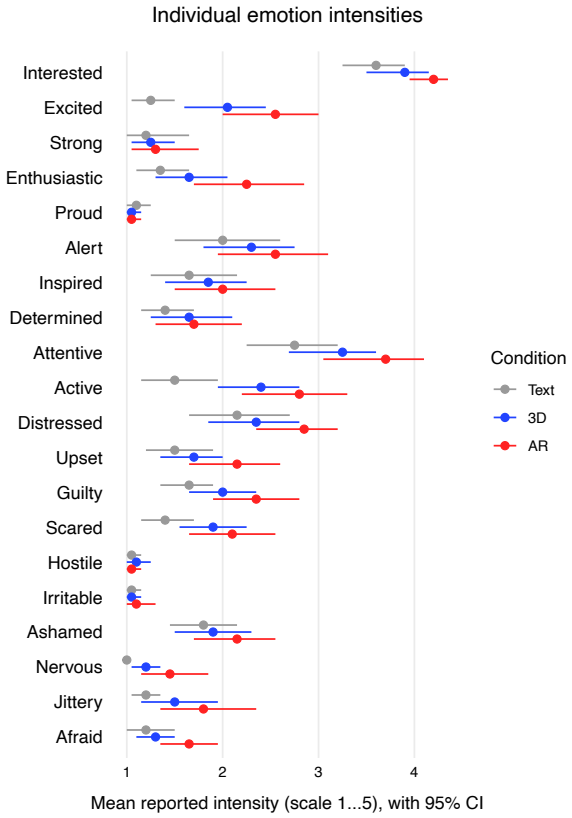
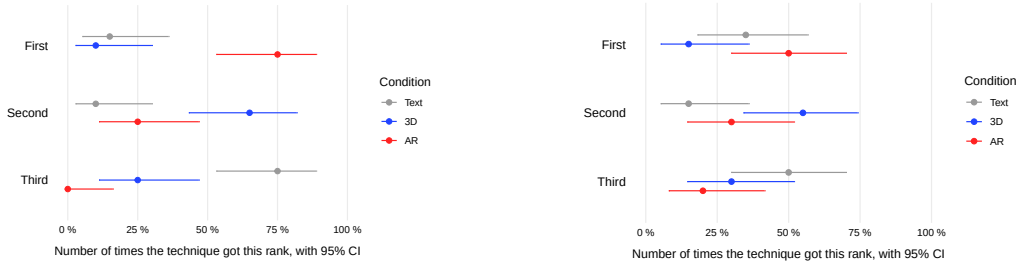


Fig. 9. Reported intensity for all 20 emotions of the PANAS questionnaire.

- *Interest.* On average, participants reported feeling "quite a bit" of interest. Responses are high across all three conditions, suggesting that interest was mostly intrinsic to the information presented. This confirms that our participants identified with and engaged with the information presented to them.
- *Attentive.* Participants also reported being attentive (on average, between "moderately" and "quite a bit"). Attention is similar to interest but implies perhaps an even deeper cognitive engagement. There seem to be differences between conditions, which would mean that the degree of attention may depend on the presentation technique.



(a) Ranking of techniques according to their ability to elicit emotions.

(b) Ranking of techniques according to their ability to make information clear.

Fig. 10. Technique rankings.

- *Active.* Participants reported feeling reasonably active for 3D and AR (on average, between "a little" and "moderately"), but substantially less so for Text. This is likely because the Text condition is non-interactive, while in the 3D and AR conditions, participants were invited to move virtually or physically.
- *Excited.* Participants reported being reasonably excited but less so with Text, probably due in part to the interactive and entertaining nature of the 3D and AR conditions. In addition, there was likely a novelty effect at play with the AR condition.
- *Alert.* Similarly, participants reported feeling somehow alert but without large differences between conditions.
- *Enthusiastic.* Overall, participants felt slightly enthusiastic, but more so in the AR condition.

Among the negative emotions, those that participants reported feeling the most are (in decreasing value of point estimate for the AR condition):

- *Distressed.* No strong negative emotion was reported, but distress was clearly on top, with an average rating between "a little" and "moderately". This is likely due to the negative nature of the information conveyed and the fact that most participants did not think that the waste output was so high (see again Figure 5b).
- *Guilty.* Many participants reported feeling some degree of guilt (typically "a little"), with possible differences between techniques. This emotion is likely due to participants' awareness of their contribution to the waste represented.
- *Upset.* This emotion yielded similar responses to the previous one, with likely higher responses for AR.
- *Ashamed.* Responses were comparable to the similar emotion *Guilty*.
- *Scared.* Finally, participants reported being a bit scared but substantially less so in the Text condition.

Technique ranking. Again, at the end of the experiment, participants were invited to rank techniques according to two criteria, the first one being their ability to elicit emotions. Responses are shown in Figure 10a: the three dots and CIs on top indicate the percentage of participants who ranked each technique first (the 95% CIs are computed using Wilson's score method for independent proportions). The AR technique was ranked first by most participants (around 75%). The three CIs on the next row indicate that 3D was ranked second by most participants, while the last row indicates that Text was ranked last by most. The second-ranking was according to the techniques' ability to make the information understandable, with results in Figure 10b. AR was ranked first more often than 3D, but Text was also ranked first by many participants, almost as many as AR. Overall, there is much more variability in the rankings for this criterion.

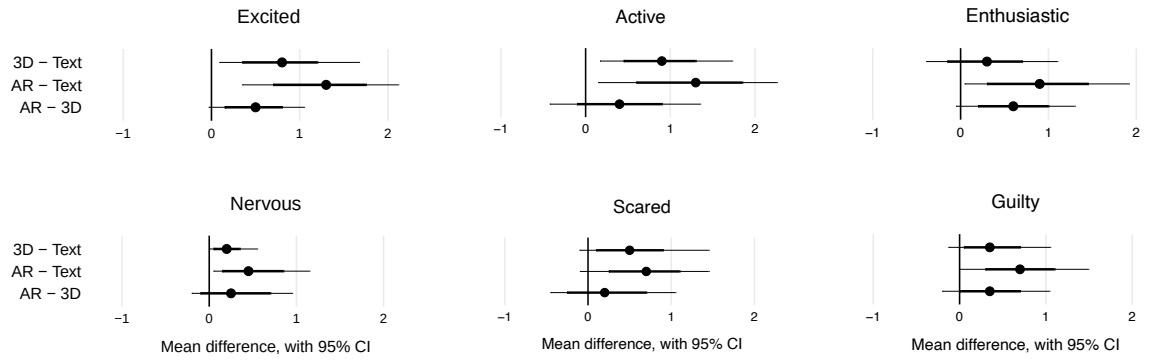


Fig. 11. Mean within-subject differences between techniques for the three positive emotions (top) and the three negative emotions (bottom) for which evidence of an effect of technique is the strongest. The thin error bars are corrected for multiple comparisons.

6.2.2 Additional Analyses. Analyses in this subsection were not preregistered. As part of our post-hoc analyses, we estimated pairwise differences between the three techniques for all of the 20 emotions reported in Figure 9. Doing so allowed us to better examine the strength of evidence of differences between techniques. For space reasons, we only report results for the three positive emotions and the three negative emotions for which we found the strongest evidence of differences between techniques. We operationalized the strength of evidence as the p-value obtained by a one-way ANOVA omnibus test. The full results (20 plots) are available in the supplementary material on OSF.

Figure 11 shows the pairwise differences for the six emotions we selected. Error bars are two-tier confidence intervals where the thick interval is a regular 95% CI, and the thin interval is a Bonferroni-corrected 95% CI for 3×20 = 60 comparisons.

Concerning positive emotions (top row on Figure 11), we can be reasonably confident that people report feeling more *excited* and *active* with 3D and AR than with Text. On top of that, people may report feeling more *excited* and *enthusiastic* with AR than with 3D, but the evidence is weaker.

The bottom row of Figure 11 shows the pairwise comparisons for the three negative emotions selected. There is some evidence that people report feeling more *nervous*, *scared* and *guilty* with 3D and AR than with Text. It is possible that those emotions are slightly stronger in AR than in 3D, but the evidence in our data is weak.

6.3 Discussion and Qualitative Feedback

In this section, we put our results in perspective using open comments from participants. Participants are numbered P1 to P20 and all quotes are translated from French.

As suggested by our quantitative analysis (Figures 6–11), participants did not experience particularly strong emotions when shown waste output data but reported slightly more intense emotions with ARwavs than with the two alternative formats. ARwavs seem to have boosted both positive emotions, such as engagement, and negative emotions, like guilt. This suggests that ARwavs may be effective if the goal is to leverage people's affect and that both the visual representation (literal visualizations of waste accumulation) and the medium (AR) may play a role.

The possible double role of visual representation and medium is consistent with comments from participants. In terms of representation, P9 reported that plain text was insufficient for them to *"realize what [the number] meant"*,

and P4 mentioned that it was *"hard to imagine this quantity"*. Participants commented on the benefits of having a 1:1 scale representation, with an environment (physical or virtual) that acts as a visual anchor: P5 and P9 mentioned that surrounding objects helped them get a sense of the size of the individual trash bags, while P1 and P4 reported they helped them get a sense of the total volume of waste. These comments are consistent with previous speculations about the benefits of literal, object-based visualizations for conveying unfamiliar quantities [23, 41]. However, participants reported that the numeric format was useful too: P15 mentioned that it is *"more accurate on the precise amount of waste"*, P12 reported that it *"provides the clearest data, which I may be able to memorize"*, while P13 commented that it is the best tool to support understanding. Overall, participants had different opinions about which representation best-supported understanding, which can also be seen in the technique ranking data Figure 10b.

In terms of presentation medium, participants commented on the increased immersion and realism provided by AR. P4 and P18 referred to the trash bags in AR as if there were *"in real life"*, P2 mentioned that their amount was *"enormous"*, and P13 mentioned that the animation was impressive and gave a good feeling of the volume. Meanwhile, P4 reported that *"being immersed in the simulation enhances emotions"*. Participants also commented on the possible benefits of having a visualization that is situated, i.e., embedded in an environment that is relevant to the data presented [60]. Although all three conditions were administered in the cafeteria (where a lot of the waste originates from), only in the AR condition was the visualization directly embedded in the cafeteria itself. P15 reported that *"concerning emotions, AR is more striking because it is the most concrete, the most real, and in a familiar place. 3D on a screen is less striking because it is less immersive and represents a generic cafeteria that is not the one at Inria"*.

6.4 Limitations of this Experiment

This is only an initial experiment and there are many possible directions for future work. One is to design experiments that disentangle the effects of immersion from the effects of situatedness – this would allow us to understand better if ARWAVs carry advantages compared to, e.g., data visceralizations that are immersive but not situated [41]. Another possible direction is to design experiments that dive deeper into the causes of emotions. In particular, it is hard with the present experiments to know whether the reported feelings were reactions to the information presented, reactions to the technology itself, or a combination of both. For example, P2 reported being frustrated by the narrow field of view of AR and found that the natural light made it hard to see the trash bags. Such usability issues could have contributed to some of the negative feelings. Conversely, a novelty effect could have contributed to some of the positive emotions reported with AR. It remains to be seen whether the seemingly increased engagement provided by ARWAVs can be sustained or wear out as users become familiar with AR.

Other possible limitations lie in the design choices we made for the intermediary (desktop) condition. In particular, we chose to render the 3D trash bags within a virtual cafeteria for consistency with the AR condition (e.g., in both conditions, participants can use elements of the environment for visual size comparison), but we decided against replicating the real cafeteria to be able to test the difference between an ordinary concrete-scale visualization [23] (3D condition) and a visualization that is integrated within the relevant environment (AR condition). Choices could have been to replicate the real cafeteria in the desktop condition (and possibly show it at a different location), or to show the waste accumulation on a neutral background. But all choices would have suffered from confounds – with only two baseline conditions, it is impossible to disentangle the effect of all factors, and more experiments are needed.

One more limitation of the experiments is that it measure self-reported emotions, not actual emotions. The two may differ for several reasons, including social desirability bias [30] and good-subject effects [46]. Objective measurement

methods such as skin conductance exist, but they are unlikely to be sufficiently sensitive to detect changes in low-intensity emotions. Another approach is to use a between-subject experiment design, which would require many more participants but would reduce possible good-subject effects. Finally, as we already mentioned, it is important to study aspects other than affect, such as perception and behavior.

7 GENERAL DISCUSSION

In this section, we discuss other important aspects of ARWAVs to consider, as well as the limitations of our initial explorations and directions for future work.

7.1 The Ecological Impact of ARWAVs

A seeming paradox with ARWAVs is that they are meant to promote eco-friendly behavior, but they themselves are costly to the environment due to their reliance on AR hardware. However, it is possible that at least some forms of ARWAVs are so effective at changing behavior that their benefits outweigh the environmental costs of the hardware necessary to run them. The net ecological benefit of an ARWAV likely depends on a range of factors, including the type of AR display technology it uses. For example, most people in industrialized countries already own AR-ready smartphones, so running ARWAVs like the one in Figure 3a is possible at almost no extra environmental cost. In contrast, AR-HMD devices and spatial AR installations are uncommon and require lots of hardware components. Nevertheless, a single device can be shared across people, and can reach hundreds of people in exhibitions and other public events (see, e.g., **Scenario 3**). In addition, the enhanced sense of immersion brought by AR-HMDs and spatial AR installations may make ARWAVs more effective than smartphones, which could justify their use. Doing cost-benefit analyses like these will be crucial but will require empirical knowledge from user studies. It is possible that some ARWAV designs (software and hardware) have a net ecological cost while others have a net ecological benefit, so not studying ARWAVs just because of the environmental cost of AR hardware could cause us to miss important opportunities.

7.2 Exploring More Design Options for ARWAVs

We discussed design considerations for ARWAVs and started to explore them by building prototypes, but many areas remain to be explored. Regarding the type of visual representation for the waste material (see section 5), we mostly focused on literal representations, and only started to explore transformed ones (Figure 3d). It would be useful to explore transformed representations further, for example by trying other unitization approaches [23]. More work is also needed on materialization, i.e., ways of representing quantities without an obvious literal representation, such as electricity or greenhouse gases. Concerning metaphorical representations (e.g., using trees to convey paper saved), they are somehow outside the scope of ARWAVs as we defined them, but it could be interesting to see how they compare with literal representations. Another promising area is the physically-realistic behavior of waste representations: our feedback session already suggested that animations and sounds (e.g., trash bags falling from the sky) can increase immersion and induce emotions. It could be interesting to explore other physical behaviors and ways people can interact more realistically with the waste representations.

In most of the ARWAV examples we considered, the waste accumulations are situated in the sense of Willett et al. [60] as they are displayed where the waste was produced, or in other terms, where the waste accumulation would have really taken place if the waste had not been carried away. Although this seems to be the most straightforward design choice, it is possible to imagine ARWAVs that are shown in places unrelated to the data – for example, in museums or exhibition halls (see subsection 4.2). Such ARWAVs could still help users understand waste data and make informed

decisions, and could therefore be considered situated in the broader sense of Bressa et al. [20]. By the same reasoning, waste-accumulation visualizations could be displayed in virtual spaces while retaining some of their utility: such designs would be very similar to the data visceralizations proposed by Lee et al. [41].

Another interesting medium for waste-accumulation visualizations is data physicalizations [37]. Real waste accumulations that are deliberately created for information purposes – such as illustrated in Figure 3-c and Figure 3-d, can be considered as existing examples. Other examples could include installations where physical objects (e.g., fake trash bags) stand for real waste. Such installations could help overcome some of the inconveniences of real waste accumulations (e.g., sanitary issues), but they would generally still be more time-consuming to build, replicate, and update than augmented-reality representations. On the other hand, physical waste representations could carry more emotional power than virtual representations and could reach larger audiences, as they can be displayed in strategic places, they are always visible, and they do not require people to wear special equipment [37].

In all these cases, there is still a lot of research to be done not only in designing and implementing novel systems but also in empirical evaluation and comparison. Studies can be centered around psychophysics experiments focusing on waste quantity perception, or like we did with emotions, they can focus on other psychological impacts (e.g., attitude, engagement, or memorability), or they can be dedicated to the assessment of behavior change through the design of behavioral experiments.

7.3 Scale Issues with ARWAVs

The testers in our initial feedback session reported that viewing our larger ARWAVs was uncomfortable because they could only see a small portion of them at a time, and they had to scan them as if they were looking at it through a peephole. This was likely caused by a combination of two factors. One was the relatively small field of view of the AR displays (52° diagonal for the Hololens 2, and about 20° diagonal for the smartphone if held at 40 cm), which is an important limitation of many current AR display technologies. The second factor was the relatively small distance of the ARWAVs to the user. To address this, one solution is scaling down; Based on the feedback session with colleagues, we implemented a miniature view, consisting of a 1:10 scale model of the ARWAV with a human silhouette and a car standing next to it (see Figure 12). As Lee et al. already discussed [41], it is impossible to get any direct notion of the true size of extreme-scale objects (e.g., planets), but a scaled-down version can show their relative sizes.

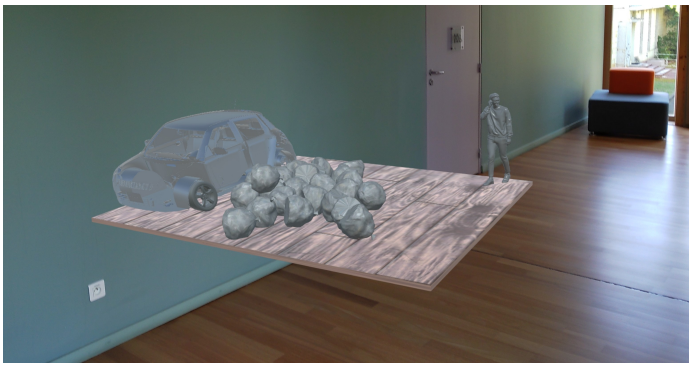


Fig. 12. Miniature view of an ARWAV, with a car [4] (3D model by CasacadeOperations) and standing man [5] (3D model by NumikPopulate) as reference points.

In the tech exhibition event, as before, when experiencing HMD ARWAVs, several observers commented the narrow field of view and expressed the need to step back. With them, we activated the miniature view. They found it useful to be able to walk around the ARWAV and get a global overview of the volume. One observer made the point that the two objects of reference (the man and the car) were very important to get a correct idea of the size of the individual objects (trash bags and cups) and therefore, of the entire volume. It was also mentioned that the two views can be complementary: the miniature gives a better overview, while the 1:1 visualization presents objects on a familiar scale. This kind of solutions sure needs refinements and comparative evaluation.

Another solution could have been to invite our testers to move to a larger room or outside and position the waste accumulation visualizations further away from them. However, supporting AR in large spaces is difficult due to limitations in scanning technologies [10]. The Hololens 2, for example, needs to scan its physical surroundings to properly anchor virtual content and manage occlusion, and the depth spatial mapping is currently limited to 3.1 meters. More research is needed to develop techniques that can realistically integrate virtual objects in the physical world far away from the user. But in principle, even very large-scale ARWAVs should be possible using computer vision, 3D maps, and/or spatial anchors (e.g., Microsoft Azure Spatial Anchors[15]). Once this becomes possible, we will be able to design ARWAVs that convey massive amounts of waste (see Figure 13). At present, we can explore fresh options in the design and implementation of novel systems that explore trade-offs for adapting to these current technical limitations.

Fig. 13. Photomontage giving a rough idea of the amount of material displaced and emitted to manufacture the smartphones for the entire population of Paris, placed next to the Notre-Dame cathedral. Credit : Léana Petiot https://www.leanapetiot.com/

[15] https://docs.microsoft.com/fr-fr/azure/spatial-anchors/overview

7.4 Exploratory Data Analysis with ARWAVs

In this paper, we have mostly focused on how to convey waste quantities when the data consists of a single quantity to be conveyed. However, waste data is dynamic in nature and can have rich attributes associated to it, such as the nature of the waste, where it was produced, and by whom. This opens up a vast array of possibilities for interactive data exploration. Interaction techniques used in traditional computer-based visualizations could be mapped to AR gestures involving remote or direct touch. For example, an ARWAV could support zooming through a pinch gesture, and let users go back and forth between a 1:1 view and a miniature view. Gestures could also be used to change the time scale of an ARWAV, e.g., to see the amount of trash produced in a week, a month or a year; To facet the data by sub-categories, e.g., see the trash amount recycled or not, or the amount produced per person; Or to make comparisons, assess trends and distributions (e.g., see twelve piles of trash bags next to each other, one for each month – also see the device in Figure 2c, which supports comparison between two periods). Such interactions could help users understand patterns in their waste consumption, and perhaps help them find ways to reduce their waste output. As augmented-reality visualizations, ARWAVs could support interactions that make smart use of the physical environment and go beyond what is possible on desktop or virtual-reality displays. For example, an ARWAV system like in Figure 3a could first show an overview of total water consumption in the house, and let the user break down this data by consumption source (e.g., bathroom shower, bathroom sink, toilet, kitchen sink, etc.). This transition could be shown with an animation of a large volume of water splitting into smaller volumes, each moving next to its respective source. Such a feature could help users identify activities for which changes in behavior are likely to be the most impactful.

We have also mostly explored the use of ARWAVs made of collections of simple and identically-looking objects, but object appearance (color, shape) can be used to encode richer information. For example, a pile of plastic cups could be composed of crushed cups representing cups that have been used and disposed of, green cups representing the part that will be recycled, and new cups for the cups that have not been thrown away. Finally, the prototypes we have presented only implement basic audio effects, but work in immersive analytics has already demonstrated the use of haptics [51] and sound [45] to encode richer data and enhance data exploration.

7.5 Generalizations of ARWAVs

Although ARWAVs focus on representing waste, similar techniques can be used for other purposes than waste representation. For example, ARWAVs could be repurposed to show the personal consumption of unhealthy substances which, just like waste production, tends to disappear and leave no trace. For example, a person may struggle to understand how much alcohol they consume over time. Although mobile apps exist to log this information, showing cumulative consumption as numbers or bar charts can lack impact for users who seek motivation to improve their behavior. Showing the same numbers using literal AR accumulations (e.g., piles of alcohol bottles in the kitchen) could help raise users' awareness of their consumption, make it more salient, and help them change their behavior. Similar ideas can be applied to other unhealthy habits such as smoking or eating sugar. Alternatively, ARWAVs could be used to show the cumulative consumption of healthy substances like vegetables or water, and provide positive feedback. Finally, ARWAVs could be used to improve people's understanding of personal material consumption more generally. For example, when buying clothes (leaving aside the environmental concerns associated with it), it can be difficult to assess the amount of clothes bought, thrown away, and sold over a period of time. Seeing them accumulated and organized in such a way as to have visibility of their life cycle may be interesting in the scope of personal behavior analysis.

8 CONCLUSION

In this paper, we presented *augmented-reality waste accumulation visualizations* or ARwavs, which are literal representations of accumulated waste embedded in users' physical environments. We went through several examples of ARwavs to illustrate the variety of situations where they can be useful, and we discussed general design principles and trade-offs. Initial feedback sessions with experts and exhibition visitors suggested that ARwavs can successfully engage observers. A controlled user study involving 20 participants provided further evidence that ARwavs can increase emotional response compared to more standard ways of representing waste output. Further research is necessary to determine whether this could in turn promote pro-environmental behavior. This research would benefit from a multidisciplinary collaboration with environmental scientists, behavioral economists, psychologists, sociologists, and science communicators.

Minimizing the negative impact of humans on the environment is an incredibly complex problem, and the issue tackled by ARwavs (giving individuals a better sense of the magnitude of their waste production) only represents a tiny subset of all problems that will need to be addressed. Nevertheless, ARwavs could play a useful role if some designs prove to have a high net ecological benefit, or if they usefully inspire future research.

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