Embedded Personal Physicalizations

Mathieu Le Goc, Charles Perin, and Sean Follmer

Abstract— With the emergence of quantified-self, smart devices, Internet of Things and ubiquitous robotics, we envision new opportunities to create dynamic embedded physicalizations. In particular, we see new challenges arising in the context of personal and casual physicalizations at home. In this paper, we discuss the research directions and potential benefits of dynamic embedded physicalizations in the residential context, or *Embedded Personal Physicalizations*.

Index Terms—Physicalization; Personal visualization; Casual visualization; Embedded visualizations.

1 Introduction and Motivations

The field of visualization is at a tipping point. As computers have transitioned from massive corporate calculators to personal computers to mobile devices, visualization is also becoming increasingly personal. Visualization has already moved from supercomputers for scientific visualization to desktop tools for information visualization, data science and data journalism.

Nowadays we generate massive amounts of personal data using devices and sensors such as "smart" meters and thermostats in our homes; personal devices such as Fitbit trackers, mobile phones, and smart watches on our bodies. However, this data is not readily available for the individuals to make sense of or get empowered for better decision making and behavior change. We argue that for visualizations to become personal, ubiquitous, and play a major role in our everyday lives, we need to explore new technologies and approaches to visualizing data, designed specifically for a personal usage context. There is a need to design interfaces so that this data is used to amplify people's cognition and help them make informed decisions.

In this paper we argue that *embedded personal physicalizations*, that can leverage multimodal interactions, ambient visualizations, peripheral attention, and social group discussions, are a promising approach to tackling this challenge. We start by discussing related work around ambient personal visualizations, ubiquitous interfaces and robotics, actuated physicalizations, and embedded visualization. Building on these bodies of work, we illustrate opportunities for physicalizations at home through a scenario. We further discuss the challenges and research directions of embedded personal physicalizations.

1.1 Ambient Personal Visualizations

There has been a growing interest in personal visualization and personal visual analytics, which brings forth the question: *"How can the power of visualization and visual analytics be made appropriate for use in personal contexts – including for people who have little experience with data, visualization, or statistical reasoning?"* [4]. There is also evidence that people can engage in the act of constructing personal visualization at home, promoting self-reflection [22]. One of the key aspects of these artifacts is their physical presence within people's intimate spaces, and how they can *"serendipitously spark reflection"* and facilitate *"continuous awareness"* [22].

In their discussion of casual information visualization [15], Pousman et al. argue that ambient visualizations produce *awareness insights* – insights that come from maintaining awareness of a data stream. For example, the act of linking information, such as an one's Fitbit activity levels with the visible health of one's house plant, amplifies awareness of one's overall health [1]. Such ambient visualizations can have a persuasive role in a personal context [13]. Displays are also becoming increasingly smaller thus better suited to personal use [13]. It is also important to convey information in a *"subjectively pleasant way"* in a personal context [13]. This aligns with the observation that people who craft personal visual narratives using visualization introduce subjective elements at all stages of the visualization creation process [23].

1.2 Ubiquitous Interfaces and Robotics

Zooids [11], small wheeled-robots capable of moving on horizontal surfaces and sensing user input. Zooids enable versatile creation of ubiquitous robotic interfaces [9]. These can move, manipulate, sense, display, and interact with both user and environment thus enabling to create rich interactive spaces. Similarly, Cellulo robots [14] allow to create tangible user interfaces for diverse learning applications. Each robot can accurately move in space and deliver haptic feedback to leverage kinesthetic learning.

1.3 Actuated Physicalizations

Data-in-Place [21] explores ambient dynamic physicalizations to better understand their impact and how it can be used to improve the life of communities, at street level. Building on shape-changing interfaces, Taher et al. [20] introduced Emerge, a dynamic physicalization of a 3D barchart alongside interaction techniques to support information exploration tasks. Dynamic composite physicalization [12] constitute a subclass of physicalizations made of multiple elements whose topology can be reconfigured, or can reconfigure itself. We presented our implementation of dynamic composite physicalizations using Zooids [11].

1.4 Personal Physicalizations

Stusak et al. [19] explored physicalizations as representations of personal data such as tracked running activity, and showed that the resulting sculptures engage users in reflective processes and trigger social interactions. Huron et al. [5] showed how physicalizations can help users with no prior experience in infovis create, use and explain visual representations of personal data.

1.5 Embedded Visualizations

In his talk "Seeing Spaces" [24], Victor depicts a maker space that allows makers to prototype and design using advanced *seeing tools*. This space contains the technology to capture and display information so that makers can observe and understand complex behaviors, keep track of the captured data, and compare parallel design variations in the resulting implementations. By capturing and representing information concurrently in context, makers have direct and easy access to large amounts of information, which would otherwise be complex to distill and cumbersome to acquire with traditional tools. Willett et al. [25] coin these as embedded data representations, representations that "are made up of multiple physical presentations that each independently display data related to their respective physical referent". Embedded physicalizations are precised as "consisting of materials or objects that are associated with the data referents".

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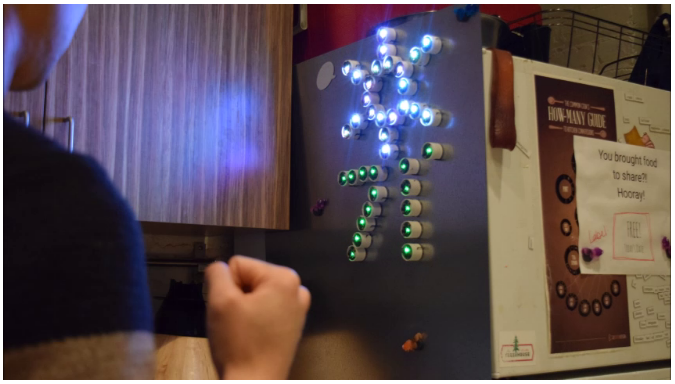

Fig. 1. An ambient physicalization representing the weather of the day.

We extend these with **embedded personal physicalizations**, that we define as *embedded visualizations that are physical representations of data in a personal context such as a home*. With embedded personal physicalizations, we aim to create pervasive and seamless representations of information in casual contexts, by leveraging the low spatial indirection of embedded physicalizations. While they come with new challenges, we envision that embedded personal physicalization will empower people by augmenting their awareness and understanding of their environment, and inform decision making.

2 Opportunities for Physicalizations at Home

With new technology come new opportunities for personal physicalizations at the junction of ubiquitous computing, robotics, and casual and personal visualizations. Recent advances in Internet of Things and ubiquitous computing, alongside with the widespread adoption of quantified self and smart devices, now facilitate the creation of large networks of sensors that collect data in a wide range of environments. This information can then feed embedded visualizations in real-time.

Traditional sensors can be distributed across the house as well as the power grid to collect, monitor, and provide information regarding utilities consumption (electricity, water, gas) [16], ambient air quality (e.g., presence of dangerous gases such as carbon monoxide), ambient temperature, illumination conditions, or human presence.

This collection of data can already provide residents with statistics and trends, to raise awareness regarding their own behavior. Yet in this personal context, phone applications or websites can seem intrusive or patronizing and raise privacy concerns. A relatively recent study also found that both the aesthetics of the representation and the context of use need to be considered when designing visualizations for environmental and resource consumption data in people's homes [17].

In this section we present situations depicting the daily life of a family whose house is equipped for data collection and embedded physicalizations. We illustrate this system with a potential variation of Zooids [11] (and thus not yet implemented), for which each robot, equipped with a variety of sensors, could move freely within the house.

2.1 Ubiquitous Sensor Network and Embedded Physicalizations

Saturday morning. The father decides to cook his specialty for the weekend family breakfast, an omelette. Looking at the physicalizations on the refrigerator of what is available in the fridge, he knows how many eggs there are, what vegetables he can incorporate into the dish, which ingredients are going bad and need to be used right away, etc.. Having access to all this information, he is able to serve up a delectable dish whilst using urgent ingredients. Zooids keep track of what has been used and what ought to be replenished, given the family habits when grocery shopping. As the children prepare to leave the kitchen to get dressed up, the father looks at the weather forecast for the day. He likes to keep a group of Zooids on the side of the fridge to display the forecast in the kitchen (see Fig. 1). As these indicate a sunny and warm day, the father tells his children to wear T-shirts and hats.

Meanwhile, the mother wants to install a new wall light in the living room. To help her find an appropriate location for the lamp, a group of Zooids climb on the walls and start scanning the surface to find the location of wall studs and electric cables in the wall. The Zooids align to create a line following electric cables, and synchronously flash their light in yellow to depict lightning and signify danger. Meanwhile, other Zooids detect the multiple studs to indicate potential locations for the new lamp. With these Zooids representations, the mother can now see in-situ the constraints and the potential spots for her new light fixture. From the multiple choices, she decides on an optimal location where the lamp will not only be supported by a stud while remaining close to electric cables, but also near her couch where she can do her evening reading. Happy with her choice, she starts drilling away safely.

Saturday afternoon. While working, the mother doesn't notice the dust building up and air quality degrading rapidly. Some of the Zooids measure the air composition at regular intervals, to help monitor the air quality in the house. As the Zooids detect increasing amounts of dust in the air, several Zooids bring a respirator mask within reach by the mother's toolbox. Meanwhile, another Zooid draws a sign in the dust on the floor, to create an additional representation of the poor quality of the air. As the mother finishes drilling, she notices the sign drawn by the Zooid in the dust and sees the respirator, and feels that her nose is starting to be itchy. Now aware of the poor quality of the air, she opens the window, put on the respirator and starts cleaning the room.

Saturday evening. Once dinner is over and the kids have put all the dishes away into the dishwasher, the Zooids remind the family that the compost bin is almost full and that it's trash pickup day tomorrow. The daughter, seeing the level of her contribution towards household chores as indicated by the Zooids, decides to take the compost out. As she is heading out with the compost bin, the Zooids near the garbage light up to indicate that it too is almost full. The daughter decides to take care of both the compost and the garbage at the same time.

Meanwhile, the older son looks at the physicalizations near the TV to choose the family's entertainment for the evening. He looks at the representations of which shows have been watched recently, how much each family member enjoyed it, how adventurous the family is feeling about what to watch, etc. He does not consider his younger brother's preferences tonight as the Zooids on the family schedule show that the younger son is away at a sleepover at his friend Ben's house.

Saturday night. After the father comes back from putting the kids to bed, both parents decide to take a closer look at the recent biometric measurements of their newborn daughter displayed on the ambient visualization in the living room (see Fig. 2). The recent evolution of the baby's weight, height, and other statistics indicate to the parents that the baby is very healthy and follows the national growth charts.

Checking the house before bed, the father finds that the compost and trash have been emptied, as indicated by the Zooids lights. The Zooids do one last final checkup of the house, and they confirm that all

Fig. 2. Parents looking at biometrics and statistics of their newborn baby on the in their living room.

the windows and doors are locked, the family dog is safe and sound in his little house in the garden, and the electronic appliances are turned off. The father climbs into bed next to his wife, ready to discuss the fantastic movie his older son had played for the family tonight.

By making information more available through multiplying and diversifying representations of data within the space, embedded personal physicalizations can increase people's cognition and awareness of their surroundings, and trigger reflection and associations of ideas.

2.2 Personal Physicalizations for Collaboration and Decision Making

In our most recent paper [12], we presented a scenario depicting how physicalizations composed of Zooids can support collaboration and decision-making. In this scenario (see Fig. 3), a family is planning their future summer holidays. They want to find a place that meets the expectations of each member of the family. To do this, they physicalize a dataset containing information about numerous attractive places. They can then explore the multiple dimensions of the dataset and isolate places of agreement, based on the result of queries. With this method, the whole family collaborates and participates in the decision-making process; they discuss and compromise to settle on a location. They also create an ambient physicalization that they attach to the kitchen wall. This physicalization represents the price of the flight for a few locations the family is interested in. Placing this on the kitchen wall allows them to keep track of the evolution of the projected costs, as they aim at buying tickets when prices would reach the threshold matching the budget set by the parents.

With this scenario, we conjecture that the tangible nature of the physicalization may better support collaboration by bringing the members of the family around a physicalization and providing them with a common ground, *i.e., Reference Space* [2]. This allows richer communication and thus can improve collaboration. Jansen et al. [8] speculate that physicalizations may better engage the audience, fostering our perception, skills, and experience to interact with the physical world [7]. Based on existing work in the fields of education and tangible user interfaces, studies have shown that physicality offers cognitive help using, for instance, epistemic actions [3, 10]. We believe that these benefits can contribute to better supported collaborations.

3 CHALLENGES

The space of embedded personal physicalizations is ripe for exploration. Not only is it an almost untouched area of research, but it can also potentially impact and empower every person, promote the widespread use of visualization, and help to develop visualization literacy. Many challenges emerge when designing embedded personal physicalizations. In this section we describe the most salient of these challenges.

3.1 Adapting Infovis Priorities in the Home

The golden rules of visualization most likely do not apply in a home, which is a personal environment. Most information visualization guidelines are about faithfully and accurately presenting data, for fast and efficient perception of trends, values, and relations. In a personal context, we argue that other factors such as aesthetics, relatability, persistence, natural integration into the home, and curiosity-triggering, are likely to be more important.

Embedded personal physicalizations are very well suited to this context that does not necessarily require accurate representations of data. Embedded personal physicalizations are also particularly appropriate for monitoring data streams in real-time, acting as constant reminders, and becoming ambient visualizations, as we are used to living surrounded by physical, tangible objects.

In addition, information visualization research often assumes that people interacting with visualizations are *fully dedicated* to the act of decoding, analyzing, and interpreting data. This situation is less likely to be the case in personal environments. Under such conditions, where people split their attention and distribute their cognition in the physical spaces they live in, what makes a visualization effective is yet to be determined.

Fig. 3. The family uses a dynamic composite physicalization system [12] to support collaboration and decision making.

In this particular context, we as a community need to question the efficiency and appropriateness of the visual encodings we employ to convey data. Some guidelines may not apply to embedded personal physicalizations. And perhaps some encodings that we quickly discard when designing visualizations are particularly relevant to embedded personal physicalizations. Rankings of encodings are based on perceptual studies that measure how fast and accurate people are at reading and comparing data values. But there is a growing discussion about how these rankings and guidelines can matter less, or even be meaningless, when factors like privacy, subjectivity, emotions and sharing of personal stories are more important than fast and accurate perception of data (e.g., [1, 4, 17, 23]).

3.2 Blending Streaming and Historical Physicalizations

Embedded personal physicalizations based on technologies such as swarm and robotic interfaces are particularly well-suited to providing real-time visualizations of streaming data, gathering insights, enhancing human awareness, and aiding collaborative decision-making activities. However, because they are more "things" than "stuff" [11], they are also ill-suited to visualizing large amounts or aggregations of data.

On one hand, highly dynamic visualizations that are well-suited to visualizing streaming data are likely to help people react immediately based on some data updates. On the other hand, visualizations that do not update much and are better-suited to comparisons and historical analysis, are likely to help people reflect and plan longer-term actions.

This tradeoff between highly dynamic, token-based visualizations and scalable, aggregated visualizations is not specific to physicalizations. For example, Visual Sedimentation [6] explores the challenge of transitioning from digital data tokens to aggregates of data over time, using the metaphor of the natural process sedimentation process. However, the challenge appears to be bigger in the physical world, subject to more constraints than its digital counterpart. While strategies for smoothly transforming token-based visualizations into aggregated ones are relatively easy to design, explore, and study in the digital world, this poses a difficulty in the physical world.

One of the main challenges in enabling embedded personal physicalizations to support both awareness insights, as well as reflective and analytical insights, is to blend visualizations of streaming data with visualizations of aggregated data. While the former provides real-time feedback, the latter delivers historical information for comparison and analysis, helping self-reflection and behaviour changes.

3.3 Evaluating Physicalization in the Wild

As technologies become more and more available, we see more systems emerging as research prototypes or potential products. Yet, we need to understand their usability and benefits in personal usage contexts. Very much like the Tenison Road project [21], longitudinal studies can help refine the new systems and most importantly, understand how they can inform and alter our behavior.

3.4 Requirements

The following are a few requirements that we deem important for an ideal embedded personal physicalization system from both implementation and design perspectives. Additional requirements may be identified with further development of implementation specifics.

Versatility. Embedded personal physicalizations should remain setup-agnostic, *i.e.,* they should not need a specific or localized setup to work. In personal spaces, one may want to be able to re-arrange and move things around freely, bring objects to the living room or to a friend's house. The system should be flexible to be context independent.

Scalability. The size of the personal physicalizations should remain a design variable, to accommodate different spaces as well as different resolutions.

Dynamicity and Interactivity. Embedded personal physicalizations should be dynamic to react to real-time feeds of data. Furthermore, interactions should be supported to react to users' manipulations, allowing collocated input and output.

Trust. When entering private and intimate spaces, users need to create a trust relationship with the system. To this end, the personal physicalization system should provide transparency regarding the data collection and processing, and ensure ethics in the design.

Non-Intrusiveness and Privacy. Embedded personal physicalizations should be designed with reflection and relatability in mind. Personal physicalizations are not recommendation systems, and thus should not provide users with conclusions, but rather with all the element to allow them to make their own decisions. Consequently, embedded personal physicalizations should not disrupt or trouble everyday life. One should be able to hide the physicalizations, or obscure what they represent.

3.5 Feasibility

To our knowledge, only few currently available technologies allow to implement embedded personal physicalizations meeting the aforementioned requirements of versatility, scalability and interactivity. Zooids [11] are one of these technologies that support embedded personal physicalizations. As a result, the physicalizations presented in the scenarios in Sect. 2 are largely inspired by Zooids and what they are capable of, as well as potential future improvements. Yet, Zooids show clear limitations that prevent creating embedded personal physicalizations as presented in the scenarios. In particular, restrictions due to tracking range and cost restrain the extent to which these scenarios can be readily implemented. Other technological approaches such as ubiquitous robotics [9] as well as shape changing interfaces [18] could allow for rich and diverse embedded personal physicalizations.

4 Conclusion

Embedded personal physicalizations have the potential to help people leverage the massive amounts of personal data that they collect in their everyday lives. They offer dynamic, actuated physical representations of data that can help families gain awareness insights, participate in collective decision-making activities, reflect on their behaviors, and change their habits. While embedded personal physicalizations offer some unique advantages, they also come with difficult challenges to tackle. We provide an initial discussion of these challenges as well as a first list of requirements for designing embedded personal physicalizations at home.

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