Understanding Physical Activity through 3D Printed Material Artifacts

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ABSTRACT
In this paper, we advocate a novel approach of representing physical activity in the form of material artifacts. By designing such material representations, we aim to understand what these artifacts might offer in terms of reflecting upon physical activity. For example, what types of affect do material artifacts, representing ones' physical activity create for the user? In order to advance this understanding, we designed a system called SweatAtoms that transforms the physical activity data based on heart rate into 3D printed material artifacts. We conducted an "in the wild study" by deploying our system in six households where participants were experiencing five different material representations of their physical activity for a period of two weeks each. We found that the material artifacts made participants more conscious about their involvement in physical activity and illustrated different levels of engagement with the artifacts. Along with reporting the gained insights from the deployments, we offer reflections on designing material representations for physical activity. We hope that our work will inspire designers to consider new possibilities afforded by digital fabrication to support user's experience with physical activity by utilizing interactive technologies at our disposal.

Author Keywords
Physical exercise; personal informatics; quantifiable self; 3D printing; digital fabrication; entertainment

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Studies have pointed out that a lack of awareness about physical activity may lead to a sedentary lifestyle [3,36]. In response, there has been a growing interest in building technologies that sense and collect personally relevant information such as bodily responses to physical activity and provide users with opportunities for self-monitoring and reflection [25]. For example, devices like heart rate monitors inform users about their exercise intensity by measuring the heart rate during a physical activity session while pedometers count the number of steps taken in a day. Studies suggest that regular use of these devices can increase the user's motivation towards physical activity [3,25,36]. However, the majority of the existing approaches mainly target the virtual medium (such as screen-based output) to provide a portrayal of physical activity [3,4,8,9,17,19]. On one hand, the virtual medium is beneficial for data visualization because of its interactive capabilities (such as allowing for zooming into data) and support for dynamic updates on the data. On the other hand, the virtual medium has some limitations as to what can be experienced with it, as argued by Vande Moere [39] and Victor [41]. For example, the virtual medium requires a flat display surface that is less perceivable in daylight and demands visual attention [40]. The "picture under the glass" effect [41] caused by a 2D display surface also makes the virtual medium mainly suitable for 2D representations of data since onscreen 3D visualization can suffer from problems such as occlusion, distortion and navigational issues [35]. Additionally, Ullmer and Ishii [37] worry that the virtual mode of information entirely focuses on the visual form and neglects other senses. Ishii [18] reminds us that "*our visual and auditory sense organs are steeped in the sea of digital information, but other bodies remain imprisoned in the physical world*". As being physically active happens in this physical world, we see an opportunity to explore complimentary design strategies beyond virtual visualizations to support physical activity.

Recently, with the rapid advancements in digital fabrication technology, devices like 3D printers are becoming more accessible for public use. Gershenfeld [11] envisions that 3D printers will soon be found in every home and people will regularly use them to create, share and copy material artifacts. As a result, design and HCI researchers are now increasingly considering the role of digital fabrication in HCI [28]. This has motivated us to advocate an innovative approach of representing physical activity data in the form of material artifacts. By material artifacts we mean physical objects that are constructed using a digital fabrication process [30]. By incorporating the digital fabrication

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process of 3D printing for constructing material artifacts based on physical activity, our research also aims to explore a "physical–digital–physical" mode of interaction, where physical energy is first invested in generating digital data such as heart rate, which is then converted back to a material form, re-entering the physical world. Vande Moere [39] argues that a material representation carries a meaning beyond the data itself as it "*can be touched, explored, carried and even possessed*" [39], thus potentially encouraging people to reflect on their behavior yielding more engaging and educational experiences. Additionally, a recent study by Jansen et al. [20] compared virtual and material visualizations of physical data and found that visualizations of data in material form can be easier to understand for the user because of the material's 3D features. In sum, material representation can offer many opportunities. However, it remains unclear how to design such material representations to support physical activity.

In order to contribute to an understanding of material representations of physical activity, we conducted an "in the wild" [33] study on our prototypal system "SweatAtoms" [21,22]. SweatAtoms transforms physical activity data based on heart rate into five different 3D printed material artifacts. We deployed SweatAtoms in 6 households to present findings from the system in use. Although invoking behavioral change was of general interest to us, we focused primarily on eliciting richer reflections on physical activity and understanding the affect material artifacts, representing one's physical activity, can have on users. Through the deployments, this research contributes the following: 1) Insights gained from the design and deployment of the SweatAtoms systems in households that illustrate various affects of material representations on individual's physical activity experiences. 2) An initial understanding of the interrelationship between material representations and physical activity.

RELATED WORK

Li et al. [25] argued that visualization plays an important role in motivating users towards physical activity because it helps users to reflect upon their performance and to gain insights into their physical activity levels. However, Vande Moere [39] points out that physical activity data such as heart rate is often very abstract in nature, and "*has no natural counterpart that can be graphically reproduced*." Therefore, it becomes the designer's responsibility to create meaningful mappings of physical activity data for the user. We next discuss how designers have previously approached this issue.

Visualization using numbers and graphs

Most of the commercial applications built around sensing technologies such as heart rate monitors use numbers and graphs to show data from recent and past physical activities of users on screens[1]. Numbers and graphs take little screen space and can be easy to interpret, however there can be usability and interpretation issues when it comes to large data sets [16].

Visualization using virtual metaphors

Lin et al. [26] and Consolvo et al. [4] built systems in which physical activity is represented using virtual metaphors such as a virtual fish and garden flowers respectively. The designers believe that virtual metaphors can be more engaging, motivating and easy to glance at when compared to graphs and numbers. Moreover, the authors believe that such virtual metaphors can develop empathy in users motivating them to exercise more. However, living metaphors can sometimes discourage participants from doing the desired activity: for example, in the fish-based metaphor, people did not want to look at the fish when they were inactive because they knew their sedentary activity would make the fish sad [26].

Visualization using interactive art displays

Fan et al. [8] utilized a variety of abstract virtual visualization patterns to display the number of steps users have taken in a day. Their study revealed that people found abstract visualizations engaging. Some artists have also explored the use of physical activity data for artistic and musical performances [7]. George Khut [23] explored an interactive abstract visualization of heartbeat data while the Interactive Institute [17] created a Brainball game controlled by player's brain waves.

Visualization using physical metaphors

Similar to virtual metaphors, people have also looked at physical metaphors to make people aware of their sedentary lifestyle and prompt them to be physically active. For example, Breakaway is a sculpture-based metaphor system by Jafarinaimi et al. [19], where the sculpture starts to yawn if the user remains seated for a long time.

Visualization using playful systems

Prior work has also attempted to facilitate play experiences around the sensed bodily responses of physical activity. For example, Run Zombie Run [34] is a mobile app that prompts users to jog using a game-based narrative while Berkovsky et al. [2] have looked at virtual game rewards in exchange of physical activity, which suggests that rewards can be an important design consideration when building systems to support physical activity.

Rethinking visualization of physical activity

The above mentioned relevant literature suggests an emphasis on using a virtual medium to represent physical activity whereas non-virtual (material) representations have not been explored much, possibly because of the scarcity of

[1] E.g.: http://runkeeper.com, http://fitbit.com

resources that could support material visualizations. However, with the recent advancements in 3D printing technology, we see an opportunity to explore material representations of physical activity as an alternate design strategy. We believe the way energy is spent (subtracted) during physical activity is reversely analogous to the way a 3D printer works where a 3D model is constructed by adding up materials layer by layer on the print bed. This has motivated us to build a system called SweatAtoms that utilizes 3D printing to represent physical activity.

SWEATATOMS

SweatAtoms is a 3D modeling and printing system that transforms physical activity data into 3D printed material form (Figure 1). We utilize the constructive solid geometry technique [5] and preprogrammed patterns to generate 3D designs. These models are then printed, using a 3D printer, forming an aesthetic and informative expression of physical activity data in material form. Next, we discuss our design process to determine the material representations for our study.

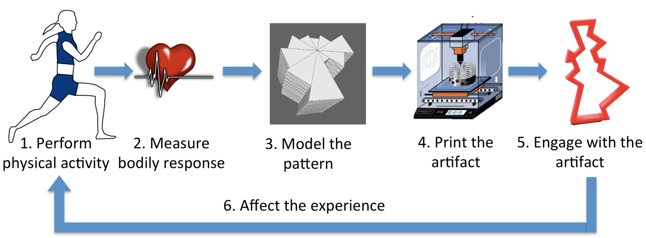

Figure 1: The SweatAtoms system in action: 1) User performs a physical activity 2) Her heart rate is measured 3) A 3D model is created based on the heart rate pattern 4) User prints the 3D model 5) User engages with the printed artifact 6) Engagement with the artifact affects her current (and possibly future) physical activity experience.

Design process: Mapping heart rate to 3D design

Our design process involved investigation into the design space surrounding material representation, digital fabrication (3D printing) and physical activity. To help us explore each of these design spaces, we held regular meetings with available experts in each of the above-mentioned areas. For example, we had lengthy discussions with two junior level interaction designers (1 male and 1 female) and three senior contemporary artists (1 male and 2 female) on possible representation choices. We also talked to an expert (1 male), working on 3D printing from last two years, to identify current limitations and possibilities of state-of-the-art 3D printers. Finally, we also spoke to three designers of exertion games (3 male, 1 senior and 2 junior) as well as two physical activity trainers (2 male) to identify the aspects of physical activity that should be highlighted in a material form. Below we summarize the key aspects of each design space that we identified after the discussions.

Aspects of physical activity

We chose heart rate data as a first exploration to represent physical activity as the physical activity trainers suggested to us that heart rate data is commonly used to analyze physical activity performance and progress towards a set health goal [1]. We discussed with them the finer details of heart rate data such as six heart rate zones (resting, recovery, aerobic, anaerobic, speed and alarming) [1], and got an insight on how these zones can be utilized to convey varied information related to physical activity: for example, the resting heart rate is a good indicator of a user's physical inactivity (sedentary lifestyle). Exertion game designers also recommended us to look at the frequent changes in the heart rate data to uncover interesting patterns and insights on physical activity routine.

Aspects of material representations

We decided on the following design strategies suggested by Consolvo et al. [4] for creating material representations that could facilitate richer reflections on physical activity:

- **Abstract and reflective:** The material representation should not only reflect certain aspects of physical activity but should also be aesthetically pleasing.
- **Public:** Users should be able to wear the artifact or keep them on display in their home. However, care should be taken to conceal any personal information that a user might not want to share in the public space.
- **Unique:** Each artifact should appear unique and differentiable from the rest of the artifacts.
- **Positive:** The material artifact should be a positive reinforcement for doing physical activity.

Aspects of digital fabrication

After having a discussion with the digital fabrication practitioner, we gained an understanding of the limitations and capabilities of the current 3D printers. For example, we realized that the current printers are not capable of printing complex shapes, which limited our possible representation choices. Additionally, we also considered the printing time (which increases with the complexity and density of a selected shape) as well as the sustainability of the material (environmentally friendly). As a result, we chose to print small shapes using a biodegradable material called Polylactic acid (PLA) and selected the Cube 3D printer [6] for fabrication because of its polished look and its interface which we found easy to use.

Taking the above discussed aspects into account and after many design iterations and fabrication trials, we decided on five material representations of physical activity. The technical details and descriptions of the representations are provided in Table 1 and Figure 2 respectively. Below we briefly describe each of the representations.

Representation 1: Graph

"Graph" is an "abstract and reflective" representation where each recorded heartbeat per minute is mapped to a point in XY space. The plotted points are then extruded to achieve a suitable thickness for 3D printing. The idea behind this representation was to mimic a virtual graph and to offer detailed information on heart rate in a material form.

Representation 2: Flower

"Flower" is an "abstract and unique" representation where unlike the "graph" representation; we only capture significant changes (±20 beats per minute) to the heart rate and then represent them in a floral pattern. The length of the petal increases with the heart rate while the width of the petal captures the duration of that heart rate intensity. We intend it to serve as a wearable jewelry item that captures the variations in heart rate through a floral pattern and signifies how heartbeats have evolved over a day.

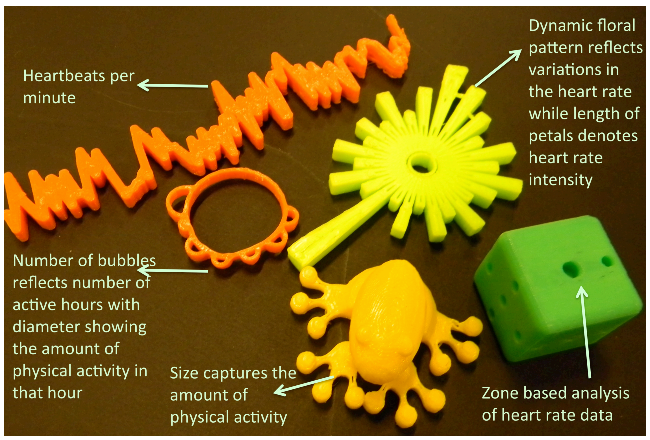

Figure 2: Five material representations of physical activity, each depicting a different aspect of physical activity.

Representation 3: Frog

"Frog" is an "abstract and positive" representation, which serves as a playful reward for doing physical activity. The size of the frog is scaled based on the amount of physical activity done in a day.

Representation 4: Die

"Die" is an "abstract and reflective" representation where six faces of the die depict the amount of time spent in each of the six zones of heartbeat data. We intend the die model to serve as a playful object that can also be stacked together to support comparison between physical activities on different days.

Representation 5: Ring

"Ring" is a "reflective and public" representation where the circles around the ring denote the number of active hours in a day. We define an active hour as an hour where the heart rate is above the resting zone. The diameter of the circle increases with increase in the heart rate and the ring is designed to be a wearable item.

Table 1: Summary of the selected five designs

Representation	Max. dimensions (l × w × h) (mm)	Avg. print time (mins)
Graph	120 × 80 × 4	20
Flower	40 × 40 × 4	25
Frog	20 × 20 × 20	30
Die	16 ×16 × 16	35
Ring	20 × 20 × 4	10

SWEATATOMS IN ACTION: IN THE WILD STUDY

We conducted an "in the wild" study [38] to understand the impact of material artifacts on the behavior and experience of an individual engaged in everyday physical activity. Given the exploratory nature of our design work, we focused on gathering a rich set of opinions rather than a majority of opinion. As such, our work leans on the idea of cultural probing [9] and "in the wild" [33] studies that aim to encourage reflective thinking about a system.

Recruitment

We deployed the system in 6 households across a large metropolitan city for a period of 2 weeks. We recruited participants using the snowball method. We had one participant from every home except for the one where a couple (Frank and Kate as changed names) was interested to participate together in our study, which we welcomed. There were 4 male and 3 female participants with their age varying from 26 to 52 years (average 34). The sample size of 7 participants is in-line with the previous studies on cultural probing [9,10,13,15]. We asked the participants about their level of physical activity in a week (low 1-2 days, medium 3-4 days, high more than 4 days) and also about their most common physical activities (see table 2).

Table 2: Demographic details of the participants.

Name (changed) & Age (years)	Occupation	Level of physical activity	Common physical activities
Alicia (52)	Manager	Medium	Jogging, cycling
Alan (30)	Engineer	High	Gym training
Kelly (43)	Architect	Medium	Tennis, cycling
Frank (29)	Student	Medium	Karate, cycling
Kate (27)	Student	High	Yoga, cycling
Chad (32)	Consultant	Low	Gym training
Dave (26)	Teacher	Low	Cycling, walking

Setup

We supplied each participant with a heart rate monitor (Polar H7) [32], an iPod Touch (5th generation) with the installed Polar Beat application and a Cube 3D printer with 2-3 PLA plastic filament tubes as printing material. The heart rate monitor was paired up with the iPod using the Bluetooth low energy protocol. Following the cultural probing practice, we also provided diaries and asked participants to reflect upon their experience on our system.

Procedure

We installed the SweatAtoms system and 3D printer in every household. Then, we introduced the participants to the system, study procedure and how to understand each artifact. As our intention was to make the printer a part of the home, we placed the printer according to the participants' wishes (which we noted). We also went through the process of printing one object to make participants familiar with the printing process. We then interviewed participants about their daily routines in terms of physical activity. For quick reference, we provided every participant with an A3 poster detailing the study steps to be followed.

Tasks in the morning

We asked the participants to wear the heart rate monitor and start the Polar beat application on the provided iPod while starting their day (usually around 7-8 am). Participants were then asked to continue any usual routine including any physical exercise throughout the study's duration.

Tasks in the evening

We asked the participants to stop the Polar Beat application and to take off the heart rate monitor in the evening (usually around 5-7 pm). Once the heart rate monitoring was stopped, the recorded data was sent automatically to our SweatAtoms application. The SweatAtoms application then generated five material representations in the Stereo-Lithography (STL) format from the received heart rate data. We then converted the generated STL files into the required print file formats (.cube) and emailed them to the participants. (due to the taxing nature of the study, we did the conversions for the participants). To print the material representations, participants were required to copy these files on a USB stick and print them one by one by attaching the USB stick to the 3D printer. This process could have been simplified by wirelessly accessing the 3D printer; however, it would have required modifying the participants' personal Wi-Fi settings, which we chose not to interfere with. The printing time varied for every object based on the participants' level of physical activity (and thus the object size) every day, but typically it took around 90-120 minutes for printing all five objects.

Data source

To gain insights into the underlying motives and experiences of the participants, we asked the participants to maintain a daily diary. We visited each household two times (first and last day) and spent around 4-5 hours with each participant. Based on the participants' needs (such as difficulty in running the 3D printer), we visited some of them more frequently. Additionally, we were in contact with everyone through emails and phone calls. In the conversations, we focused on how they used the SweatAtoms system and gathered their thoughts and experiences with it. We also took notes and recorded audio, which was then coded and analyzed for common themes.

FINDINGS

Deployment of material artifacts representing physical activity not only led us to identify new insights and opportunities but also raised some questions. We describe below our key findings from the deployment of the system.

Intervention

Participants welcomed the system and the study setup in their home with excitement.

Accommodating the 3D printer

Participants usually placed the 3D printer in their living room space close to a window to nullify potential print smell, as seen in Figure 3.

Figure 3: Participants tried to make the printer fit into their home ambience.

Alan, being a technologically oriented person, kept the printer along with his other tech gadgets in a separate room. Kate was particularly happy with the size of the printer as it fitted into an empty window space. Frank and Kelly said that they would not have liked a bigger printer than this. Interestingly, Kelly felt the printer being a part of her household. For example, as the printer was kept near to an open window, she tried to conceal its appearance from the outside with cardboard to prevent someone stealing it. The printer worked smoothly for the entire study duration in all households except one. At Alan's house, we had to recalibrate the print offset and replace the print filament. There were no complaints about the printer smell; however, Frank and Kate commented that the printing noise is affecting their concentration when studying. As a result, they moved their study activity to a different room while the printing was taking place.

Accommodating the artifacts

Frank bought one box to keep all his objects together while Kelly utilized the envelopes of promotional campaigns to keep objects sorted according to each day. We found it noteworthy that a participant went out of his way and bought a box, as we had not previously seen such commitment in some of our prior work with participants.

Lessons learned

The size of the 3D printer is the key to finding an appropriate place in a household. Designers should also consider printer noise, as it could be an issue.

Engagement with the process

All the participants were enthusiastic about seeing their heart rate reflected in material artifacts despite the lengthy process of printing all five objects every day (Figure 4).

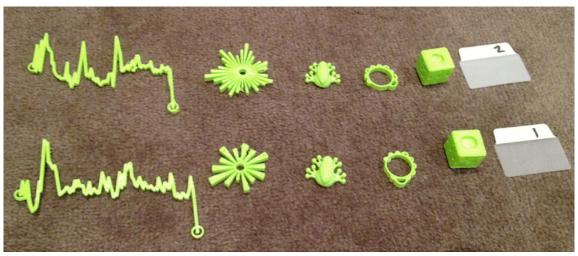

Figure 4: Participants were enthusiastic to see how their reflected heart rate evolved in different material forms as the study progressed. Participants arranged their objects according to day and used sticky notes for assigning days.

Engaging with the heart rate monitoring

Participants felt that heart rate was an appropriate measure of representing their physical activity. Five participants were curious to see how their physical activity was reflected in the artifacts at the end of day, while the remaining two participants tried to confirm whether the artifacts correctly portrayed their physical activity. Two participants had previous experiences of wearing a heart rate monitor but they never wore it continuously for 8 hours. Four participants felt a little uncomfortable in wearing the heart rate monitor continuously for 8 hours every day and they wished to have a strapless heart rate monitor instead. Three participants did not like the idea of continuous monitoring and suggested us to track heart rate only during an exercise.

Engaging with the 3D printing process

Most participants printed artifacts every night before going to bed, two participants skipped printing on a couple of days and then did bulk printing on the weekend to cover the backlog. All participants were excited initially to see the printing process, however, their interest in watching the print process faded over time. Frank mentioned, "*in the beginning, it was exciting to see objects printing small, big, like a recap of my physical activity... later it became time consuming.*" He further added that he would prefer to have objects delivered to him in a mailbox rather than doing the printing at home daily. Kelly and Chad also pitched a same idea. Alan on the other hand got excited about 3D printing and tried to learn more about the printer's capabilities and current trends in 3D printing. All participants enjoyed the opportunity of changing colors of the plastic filament and wished to have more colors in order to print everyday artifacts in different colors. Participants were also satisfied with the size of the artifacts. However, Kelly wanted to print a bigger "Flower" so that she can rest her wine glasses on them.

Four participants, however, did not like the idea of printing objects every day; rather, they wanted to make printing more flexible. For example, Chad added: "*I should be able to choose when and what data I can print*", while Frank and Kate inquired: "*Can we print an object representing heart rate from both of us?*"

Lessons learned

Designers should allow participants to customize their experience by letting them choose when and what information needs to be printed. Additionally, there might be an opportunity for designers to combine physical activity data from multiple people and represent them in one object. Similarly, designers should look into utilizing strapless heart rate monitors for a study.

Engaging with the artifacts

The "Frog" was the favorite artifact, as all participants got affectionate with it immediately. Participants particularly adored the idea that the frog gets bigger if they exercise more. Kelly felt *"it is like burning your body fats and putting them on the frog".* The majority of the participants kept frogs stacked on top of their computer screens and near their working desks (Figure 5). Frank and Kate competed against each other by doing more exercise in order to get a bigger frog. Kate read from her diary (while holding the printed frogs from her and her husband's data): "*see, how little I am doing in comparison to my husband ☹*". Alan, being a very active person, liked the "Graph" artifact as it clearly displays his performance during various physical activities. He particularly enjoyed the frequent high and low peaks in the artifacts showing how dynamic his day was. Chad stacked the graphs from all days next to each other, which was helpful for him to monitor his progress. Interestingly, Frank and Kate had different views about the "Graph": Kate mentioned "*the graph is not very exciting as we can see the same on a virtual screen. It would be like printing something that we have already seen. I don't like that.*" Four participants found the "Flower" artifact aesthetically pleasing and mentioned various ways of using them in their everyday life: Alicia felt that she could wear them as earrings; Dave, on the other hand, was interested in a flower garden and stacked all flower artifacts next to each other on a desk. The "Ring" artifact was less appreciated as participants felt it does not convey much meaning to them.

Moreover, participants also questioned its utility. Dave replied, "*One has only 10 fingers, then how many rings can he wear?*" Three participants found the "Die" informative as it made them realize about their sedentary lifestyle. Kate was particularly unaware about the time she spends sitting each day and was glad that we included the "Die" artifact in the study communicating this information to her.

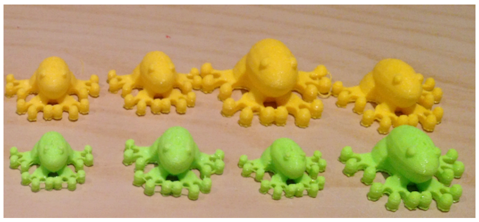

Figure 5: Participants liked the frog and the way it scales with their physical activity. It also became the object for public display and reflective conversations.

Cherishing artifacts

Participants had several ideas of using the printed artifacts in the future. Dave, for example, created a clock using all his printed artifacts as shown in Figure 6. He plans to hang it on the wall of his study room. Kate who liked the "Flower" model described: *"I would fill a glass bowl with water and then put candles on the printed flower and let it float on the water surface, it would make a great decoration for my house."* Chad had a great physical workout session on one day of the study. Looking at the printed artifacts of that day, he happily said: "*I am going to cherish today's graph...see how dynamic it is...I would put it on my shelf to remind me that I did well.*" It was heartening to see that participants took interest in correlating and arranging the objects together.

Figure 6: Dave created a wall clock using his printed objects to remind him about how his heart rate evolved over time.

Most participants were happy with the selected design choices for representing their physical activity, however, Kelly, Alicia and Dave were also willing to design their own objects.

Four participants raised issues of sustainability and pondered over the utility of objects in their life. For example, Kelly asked what would she do with so many of such artifacts, if she keeps on printing them each day. Frank and Chad had a common suggestion of making them all interlock with each other to create a bigger sculpture. Kelly put forward the idea of Lego bricks to construct a skyscraper of physical activity over time while Dave suggested printing of the objects only on selective or special days rather than everyday. Three participants wished for a provision to recycle the artifacts.

Conversations around artifacts

Many participants showed their printed artifacts to neighbors and visitors to their home. These artifacts generated a sense of curiosity and conversations among the visitors who did not know what the design actually meant. Participants were enthusiastic to explain the meaning to them. Kate on weekends does voluntary work for young girls at a school. At an annual science and technology event, which happened during the first week of the study, she enthusiastically spoke about the system to the girls. She plans to give some artifacts to the girls "*as a token of her heart*". Chad similarly gave a few of his artifacts to his mom and sister who came to visit him one day during the study. Alicia is planning to incorporate the system in her IT services office. She says: *"I would like to use an approach like this for a reward and recognition program that we are starting. We were thinking about giving out big stars but that is lame in comparison with letting them print out 3d trinkets and the more they need to be rewarded the bigger they are - plus the more they can print."*

Lessons learned

Although people's interest in the printing process faded over time, their interest in the artifacts appeared to be more persistent over time. Designers can learn from the "Frog" design and should map a similar reward structure into their design. For example, the participants welcomed scaling the size of an artifact as a reward to the invested efforts in physical activity. Participants took interest in decorating their homes with the artifacts, and these artifacts also became a topic of conversion. The "Frog" also prompted healthy competition among participants for getting bigger frog. These narratives suggest that personalized artifacts if designed carefully, have an ability to extend engagement with physical activity. For example, although participants appreciated the aesthetics of artifacts, their utility as well as sustainability was equally important to participants.

Relating to physical activity

Most participants became more conscious about their physical activity routines and started to take their heart rate data more seriously with time. Alan said: "*I used to see my heart rate data on my mobile, but this is different, now I can not only touch and feel my data, but I can also show it to the world, I care more about my heart rate now.*" Alicia confirmed, "*My trainer was so happy to see my progress, thanks for letting me participate.*" This supports findings from previous research where participants gained awareness about themselves from a visualization method [21]. Besides physical activity, participants also tried to understand their daily routines from the printed material artifacts. Frank said: "*It was great to know about the self and my activities throughout the day from the printed artifact (graph): when I went to university, when I came back (by looking at large peaks in the graph), when I sat idle (by looking at lower peaks)*". However, Frank and Alicia initially had difficulties in interpreting the "Flower". Alicia thought Flower is like clock that shows her physical activity of the entire day around the clock. Referring to a large petal in Flower, she said, "*see I was most active around 2 pm, when I had to rush twice to office for work.*" After discovering that Flower is not clocklike timely representation of physical activity, she felt slightly disappointed and suggested to make such alternations to Flower design. Kelly and Chad expressed the need of designing artifacts that are easier to interpret similar to the "Graph" and "Frog" artifacts.

Although we did not target an immediate behavioral change with the artifacts among the participants, there was anecdotal evidence of increased physical activity amongst them. For example, Alicia confirmed her increased physical activity to us in an email (Figure 7). She added, *"but the main thing is I am out on my bike and am aware of my heart. In the past, if I exercised on Saturday I would have said that I deserve to rest on Sunday :)"* Dave resumed his weight training after a long time to see its reflection on the artifacts. He mentioned: "*It's been ages since I did that […] but now this study prompted me to start weight training again*". We find these examples illustrative of people's rekindled interest in physical activity. Kelly emphasized that "*it's the Frog, that makes me jog more*", while Frank and Kate said that they did more physical activity to get a bigger frog at the end of the day.

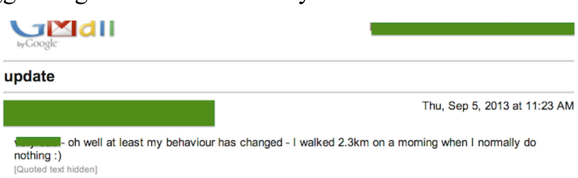

Figure 7: Engagement with the artifacts encouraged a participant to go for a walk.

Significance of personalized material artifacts

During the follow-up interviews, we asked the participants what difference a material artifact made over the virtual counterpart. Most participants answered affirmatively that the physical form and the support for sensory capabilities like touch and feel makes the material artifacts more special than the virtual ones. Kate added that "*[on a mobile phone] you look at your heart rate and then forget about it, here [addressing the material artifact] you cannot, it is more persistent*".

During the follow-up interviews, participants also mentioned that they care more about these artifacts because they contain their personal data and are printed by them at home. Referring to the "Flower" and "Graph" artifacts, Kate mentioned, "*this is me and my data, you cannot get this in the market*."

Lessons learnt

3D printing was new for all the participants, although all of them had heard about it. We worked with the vision that in 10 years time, most people will have a 3D printer in their home just like a 2D printer today, and therefore, we intend to explore the future interactions associated with today's technology. Although further studies are needed to eliminate any doubts about novelty effects, our interview data suggests that participants' interest in the printing process faded over time; however, participants' interest in the artifacts appeared to have persisted over time. Participants mentioned that the objects matter to them because they reflect their personal data and activities, making them unique, as they cannot be "bought at a shop", as mentioned by Kate. Furthermore, the statement made by three participants that they would rather get the objects delivered to them in the mail rather than printing them at home (to avoid the printing noise), further suggests that the participants were able to differentiate between the appeal of 3D printing and personalized 3D artifacts. Therefore, we argue that giving a physical form to the ephemeral experience of physical activity can facilitate a deeper engagement with the data. Secondly, personalized material rewards also prompted physical activity amongst people who otherwise was spending time sedentary.

DISCUSSION

We discuss below the experiences that the material representations of physical activity elicited for our participants.

Material artifacts as an autotopography

Miller [29] argued that individuals like to express themselves with material artifacts that embody their lives, personalities, emotions and achievements. Our participants expressed themselves by placing the "Frogs" on their computer monitors and decorating their home with "Flowers". Such an arrangement of material artifacts as physical signs to spatially represent the identity of an individual is called "*autotopography*" [14]. This autotopographical collection of material artifacts put on display not only becomes the public representation of the self and craftsmanship [12] but also serves as a memory landscape to the owner triggering reminiscence [38]. As such, our study supports the theory of autotopography. Interestingly, the autotopography was driven mainly by the aesthetic rather than the embodied information in the artifacts. For example, the "Frog" was readily displayed in the home ambience despite containing very little and abstract information about an individual's activity; in contrast, other more informative models like "Graph" and "Die" did not become a part of people's home ambience except for Chad, he placed his "Graph" on the living room wall for public display to cherish his best workout day. Designers therefore should consider building artifacts that are easy to interpret, although the embodied information can be as little as "*I did more physical activity*".

Material artifacts as personalized rewards

According to the Goal Setting Theory [27], incentives are important to sustain a user's interest in an activity. Participants liked getting artifacts at the end of the day as a reward and a testimony to their invested physical efforts. It seemed that material rewards could contribute to an increase in physical activity for some participants. Participants enjoyed how the "Frog" scaled based on their physical activity and they did more physical activity to get a bigger "Frog". Participants appreciated this scaling, even though a bigger "Frog" required more printing time. We believe that the perceived value of the artifact among the participants also increased with the time they waited for it to get printed. Therefore, in future works, it could be interesting to examine the relationship between printing time and size of the reward.

Previous research on archiving and souvenirs suggests that material artifacts can be cherished more than virtual objects because of their higher visibility in the surroundings and low replication possibilities [13,24]. Our findings support this argument, as participants liked the fact that these artifacts are unique and cannot be purchased elsewhere. Additionally, they also liked that these artifacts embodied their personal heart rate data. As a result, we see further opportunities for using material artifacts as personalized rewards to physical activity that can readily be displayed and consider it an interesting design space for designers to explore in the future.

Material artifacts for reflection and reminiscence

Participants mentioned that the material artifacts prompted reflection and reminiscence on past physical activities. Sometimes participants encountered difficulties in understanding the meaning conveyed by these artifacts (the "Flower" in particular). These issues however encouraged conversations and fuelled recall about past activities. We believe that ambiguity in meaning encourages participants to expand their interpretation of physical activity data and thus could facilitate a richer reflection about the self and past activities [15].

Material artifacts have a tendency to disappear into the background, which Miller calls as the "humility of things" [29]. For example, unlike a virtual representation that calls for instant user attention, a material artifact can sit quietly in the surroundings and may not seek attention. We believe this property can be harnessed as an alternative design strategy to provide passive tracking of physical activity and to encourage delayed feedback on data. For example, material artifacts can be built that passively monitor user's physical activity and which are seen only when the user is looking for them. We see an opportunity for designers by engaging with these notions to provide users with additional opportunities for reflection on their physical activity.

CONCLUSION

The contribution of this work is the first conceptual understanding of the relationship between material representations and physical activity. With the deployment of our system SweatAtoms through an "in the wild" study, we explored how participants' relationship to physical activity can be affected through design. We hope that our work inspires different ways of reflecting upon embodiment and material representations, especially, in the context of physical activity and sensing technology. We also encourage design researchers to consider and incorporate digital fabrication in their HCI design practice: in particular, designers should consider not only trying to print things that already exist in the material world, but rather consider that there is an opportunity to print things from data that exists only in the digital world, such as heart rate. We also foresee an opportunity of having personal 3D printers at home, as these printers can produce unique material artifacts that are never as good as coming from large fabrication houses, but are more personal representations of one's life. In the future, we envision people crafting their world with moments from their lives, using data that was previously only seen in digital form but now re-entering their physical world in an embodied material form.

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