Shelfie: A Framework for Designing Material Representations of Physical Activity Data

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Self-monitoring devices are becoming increasingly popular in the support of physical activity experiences. These devices mostly represent on-screen data using numbers and graphs and in doing so, they may miss multi-sensorial methods for engaging with data. Embracing the opportunity for pleasurable interactions with one's own data through the use of different materials and digital fabrication technology, we designed and studied three systems that turn this data into 3D-printed plastic artifacts, sports drinks, and 3D-printed chocolate treats. We utilize the insights gained from associated studies, related literature, and our experiences in designing these systems to develop a conceptual framework, "*Shelfie.*" The "*Shelfie*" framework has 13 cards that convey key themes for creating material representations of physical activity data. Through this framework, we present a conceptual understanding of relationships between material representation and physical activity data and contribute guidelines to the design of meaningful material representations of physical activity data.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**;

Additional Key Words and Phrases: Physical exercise, personal informatics, 3D printing, physical visualization, self-monitoring, food printing, human food interaction

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1 INTRODUCTION

Rapid advancements in sensing and wearable technologies have given rise to a trend towards self-monitoring, where individuals are spending ample time observing and analyzing their own behaviors [Lupton 2016; Swan 2012]. A plethora of different self-monitoring devices exist today that help individuals by automatically tracking their data and offering them the opportunities to reflect and learn from their behavior. While the popularity of these devices is contributing to a

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wider availability of previously inaccessible physical activity data, such as an individual's heart rate, we know only a little about how, and for what purposes, this data could and should be used. Currently, these data are mainly used to increase awareness about physical activity levels and to support motivation for physical activity with a predominant use of numbers and graphs to achieve this goal [Choe et al. 2014]. To this end, self-monitoring is perceived as a eudemonic pursuit [Li et al. 2011; Rapp and Tirassa 2017] where the emphasis is on improving performance through rational self-analysis and the quantification of data.

However, in line with several recent studies [Clawson et al. 2015; Epstein et al. 2016; Rooksby et al. 2014; Etkin 2016; Lazar et al. 2015], we find the use of numbers and hence an emphasis on quantification, restrictive, and a rather one-dimensional view of representing the rich subjective experience of being physically active. For instance, although quantification is useful in bringing discipline and awareness to the physical act of exercise, this "number crunching" activity may not always lead to an enjoyable experience of looking back at collected data [Etkin 2016; Kay 2014]. Secondly, as Rooksby et al. [2014] note, not everyone approaches self-monitoring for the sole purpose of behavior change. People take interest in self-monitoring for a variety of reasons, for instance, for collecting rewards, knowing more about oneself and with an interest in exploring a new technology. For such users, quantified data in the form of numbers may offer little value over time [Kay 2014; Rind et al. 2013]. Existing works [Purpura et al. 2011; Fritz et al. 2014] criticize the long-term persuasive qualities of self-monitoring devices which may alienate individuals from their actual physical activity. They worry that instead of making the activity an end in itself, it could turn into a mere means for accumulating steps and satisfying metrics. Supporting this, Hassenzahl et al. [2016] raised concerns that numbers could make exercise feel like work, and it has been argued that we need better ways to represent this data [Rapp et al. 2016; Elsden et al. 2016]. In essence, we agree with Lupton's view [2016] that: "numbers and graphs as a source of knowledge serve to represent bodies and selves in a very limited, impoverished ways. Compare these flat forms of data materialization with the complexities of the affective embodied knowledge that is a response to a scent, taste, or the touch of skin."

Embracing the possibility of greater pleasurable interactions with the data, we seek to explore the role of new forms of media and their potential for representing physical activity data. Our aim is to go beyond screen-based quantified outputs while complementing the common notions of understanding the physical activity experience when supported by technology [Hook et al. 2016; Mentis et al. 2014]. We propose a complementary new perspective on representing physical activity data through material artifacts. By material artifacts, we refer to physical objects created from personal data using digital processes. By creating such material representations of physical activity data, our aim is to explore a "physical – digital – physical" mode of interaction where the physical energy of an individual is first invested to generate digital data such as heart rate. These data are converted into a physical form and then re-enters the physical world as a physical representation of the activity undertaken. This process is interesting to us because we believe closing this loop between the physical and the digitally captured through material representations could inform new ways of understanding and engaging with one's own physical activity data.

We ground our interest in creating material representations of data in the literature on material culture studies in human–computer interaction (HCI) [Kirk and Sellen 2010; van den Hoven 2004; Petrelli et al. 2008; Thudt et al. 2016; Mols et al. 2016] and anthropology [Miller 2010; Woodward 2007; Dant 1999; Kopytoff 1986] that signify a human fascination towards collecting and making material artifacts. Sennett [2008] refers to humans as "*homo faber,*" that is, a manufacturer and collector of objects who imbues sentiment in external artifacts. As Miller [2010] notes, people can glean great feelings of comfort through the meaningful role of material artifacts within their everyday lives, while Kopytoff [1986] observes that material objects, much like people, have their own distinct biographies. Furthermore, results of people's crafting activity are often displayed on fridge doors, walls, and shelves. Similarly, photographs of trips and events are often printed, framed, and displayed on the wall when in fact they could just as well be seen on a screen. Such an arrangement of artifacts is referred to as "autotopography" [Petrelli et al. 2008], a system of material representations that spatially denote the identity of an individual and trigger reminiscence of good moments at a later point in time [van den Hoven 2004]. The use of material representations can also be seen in the context of sports where individuals are rewarded with physical trophies and medals. This research draws on these insights to explore a new dimension of material rewards through an embodiment of personal digital data.

Our interest in creating material representations also stems from the rich multi-sensorial appeal of material artifacts [Jansen et al. 2015; Hogan and Hornecker 2013; Hogan et al. 2017; Thudt et al. 2017]. For instance, unlike digital representations, the three-dimensional (3D) nature of material artifacts allows embedded data to be "touched, explored, carried and even possessed" [Vande Moere 2008, p. 472]. Drawing on this, Jansen et al. [2015] argue that the tangible nature of material artifacts offer possibilities to convey meaning beyond the data by bringing data into real life; a process that might, in turn, encourage people to reflect on their behavior in new ways, while also contributing to the creation of an engaging experience. Finally, we are also inspired by rapid advancements in digital fabrication technology that allows for the creation of material artifacts from digital designs, a growing field of investigation for HCI researchers [Fuchsberger et al. 2016]. Investigating the opportunities inherent in digital fabrication offers potential for creating meaningful manifestations of personal data and is timely given the plethora of works surfacing on material representations of data [Lee et al. 2015; Nissen et al. 2015; Yu et al. 2016; Zhu et al. 2015; Häkkilä and Virtanen 2016; Stusak et al. 2014; Thudt et al. 2016]. Despite the growing interest, there exists only a limited understanding on how to design such representations for a specific dataset such as physical activity data. Designers can face both technical and conceptual challenges from perceptions of how the representations should look, to what they should convey and what processes to follow in order to construct them while aligning them with the context, goals, and characteristics of the underlying data. Although prior works exist that explore the impacts on material representations on learning [O'Malley and Fraser 2004] and professional data visualization tasks [Stusak et al. 2016; Taher et al. 2015] and personal visualization tasks [Huron et al. 2014; Huang et al. 2014], these offer little specific knowledge for the construction of material representations of personal data generated from one's physical activity, particularly where the focus is not just on analytical understanding but also sensory engagement.

Therefore, in order to contribute to this understanding, we created and studied a portfolio [Gaver 2012] of three systems, namely, *SweatAtoms* [Khot et al. 2014], *TastyBeats* [Khot et al. 2015], and *EdiPulse* [Khot et al. 2017], that explore material representations of physical activity data, in particular heart rate data from physical activity. We used three distinctive materials for constructing these artifacts: biodegradable plastic, drinkable fluids, and chocolate. We deployed these systems across different households following "in the wild" field deployments [Rogers 2011] and investigated how material representations could contribute to individuals' understanding of physical activity and the ways in which it could potentially support the experience of being physically active. We utilized the insights gained from the design and study of these systems to articulate a conceptual design framework, *Shelfie*. The *Shelfie* framework contains 13 design cards that convey key themes for the design of material representations. Rather than offering strict recommendations, we chose to use the deck of design cards as a catalyst to stimulate and support the divergent imaginations of designers during the ideation process. Through these cards, we unfold a rich design space [Hook et al. 2015] for creating engaging material representations from physical activity data and invite future design research to take this field forward. We, however, note that these design cards do not represent a complete set and are limited by the use of certain technologies such as 3D printing and heart rate monitors to create these representations. Despite these shortcomings, we believe that these cards serve as important starting pointers to inspire future investigations.

The rest of the article is organized as follows. We first discuss the key existing works on representing physical activity data using different media. We briefly describe the prior frameworks that are designed to support material engagement. We then discuss the challenges associated with creating material representations, outlining the three systems and design process behind *Shelfie*. Next, we present the *Shelfie* framework, articulating each of the 13 cards. We conclude with suggestions on how to use these cards in practice.

2 LEARNINGS FROM PRIOR WORKS

Below we have categorized the existing works into two categories: on-screen data visualizations and physical visualizations based on the use of media to represent the data. We describe these works to give readers an understanding of the diverse options available to represent data.

2.1 On-screen Visualizations of Physical Activity Data

In this mode of visualization, the data are mapped to pixels on a computer screen. The advantage of on-screen visualization is that it allows simultaneous representation of heterogeneous and multiple datasets. On-screen visualization methods support interactive explorations of the data such as dynamic filtering and precise searches. These methods are widely used in a variety of domains for interpreting complex data and their popularity in professional settings has also prompted their use in personal settings e.g., for visualizing personal data, described in the literature as personal visualization and personal visual analytics [Huang et al. 2014]. Following are some of the commonly used on-screen visualization methods for physical activity data (for the scope of this article, we concentrate only on data visualization works that involve physical activity data).

2.1.1 Representing Data Using Numbers and Graphs. The most commonly used method for representing physical activity data on screens is through the use of numbers, charts, and graphs. The advantage with numbers is that they require a small display space and are easy to interpret [Consolvo et al. 2014]. Graphs, on the other hand, are easier to glance at but identifying accurate values for specific intervals can become difficult to interpret in a large dataset and with multiple sources of data. As a remedy, some activity tracking apps like *RunKeeper*[1] display physical activity data using both numbers and graphs (the numbers appear when you hover over the graph). Existing research, however, outlines a bigger concern with numerical and graphical representation of data. Research suggests that most users are not very skilled at interpreting statistical data [Galesic and Garcia-Retamero 2011; Rind et al. 2013]. To them, the statistical depth of data might appear too overwhelming to generate new insights or actionable knowledge. To deal with these issues, Epstein et al. [2014] explored the concept of visual cuts, where the visual cut is a subset of the collected data. However, the study revealed that participants' interest in visual cuts of their data varies dramatically and designers should offer a variety of cuts to the users. On the other hand, Huang et al. [2016] aligned the recorded physical activity data with life events by integrating the data into personal digital calendars. They found that such calendar-based visualizations were non-disruptive and proved easy for users to understand. Existing research also explored the use of physical media to improve the engagement with graphical representations. For example, works by Stusak et al. [2016] and Taher et al. [2015] illustrated that users are better at grasping physical bar charts in comparison to their virtual counterparts. Drawing on this, two of our

[1] https://runkeeper.com/.

systems, *SweatAtoms* and *EdiPulse* explore 3D representation of a physical graph using plastic and chocolate as a material.

2.1.2 Representing Data Using Living Metaphors. HCI research has investigated the use of metaphors to represent physical activity data. Unlike charts or graphs, living metaphors are believed to be more engaging, motivating, and easy to interpret [Lin et al. 2006]. Moreover, it is believed that users might develop empathy with living metaphors, which would prompt them to exercise more. Drawing on this, Consolvo et al. [2008] created *Ubifit, a* garden that displays physical activity data in the form of a virtual garden on a smartphone screen, where the flowers in the garden grow when users perform different physical activities. The authors found that the garden-based display helped participants in maintaining their physical activity levels, because participants were motivated to make the virtual flowers grow. *Fish'n'Steps* [Lin et al. 2006] is a related system in which an individual's step count is mapped to the size and behavior of an animated fish. The animated fish grows in size and becomes happy or sad based on how many steps the user has taken throughout the day. On the similar lines, Tong et al. [2016] connected the health of a virtual pet with the owner's physical activity, while Taylor et al. [2013] created a mirror based interface to educate people about their posture. These works suggest to us the advantages of using metaphors to represent data but also inform us about the need for being careful while selecting them. Drawing on this, within our systems, we have used a variety of known metaphors such as *Flower, Emoji,* and *Frog* to represent physical activity data.

2.1.3 Representing Data in Abstract Form. Few works also investigated the representation of data in more abstract forms. Anderson et al. [2007], for example, developed *Shakra*, a system that represents users' physical activity using a Global System for Mobile (GSM) cell signal icon. In a study of *Shakra*, the authors found that abstract visualizations can encourage reflection and increased motivation for achieving high physical activity levels. In other works, Fan et al. [2012] designed various abstract forms of visualizations of physical activity data inspired by informative art. They found that people have different tastes when it comes to appreciating and relating to abstract visualizations of their activities. In another system called *QS Spiral*, Larsen et al. [2013] developed spiral time-series based visualizations that allow recurring patterns to emerge. These works suggest that while designing abstract visualizations, it is important to pay attention to users' preferences. We build on these ideas to create the *TastyBeats* system that displays physical activity data in an abstract form using drinkable fluids.

2.1.4 Representing Data Using Text. The next category of on-screen visualization is text-based representation. Systems like *Health Mashup* [Bentley et al. 2013] and *Habito* [Gouveia et al. 2015] are two prominent examples of systems that offer textual feedback on self-monitored data. For example, text-based feedback could be offer information such as: "this weekend, you walked 30% further than your average walking on weekdays." Systems like *Houston* [Consolvo et al. 2006] congratulate users with gratifying text messages like "you broke your previous record." Accompanying studies of these systems illustrate that textual feedback on physical activity can increase awareness and motivation for physical activity. Taking inspiration from these works, we utilized textual feedback in the form of chocolate printed *slogan*s, in the third system *EdiPulse*.

2.1.5 Representing Data Using Play Elements. The final category of on-screen visualizations consists of works that explore the use of gamification techniques [Zuckerman and Gal-Oz 2014] in the context of physical activity data. Examples of such system include, *A Step Ahead*[2] and *Zombies,*

[2]http://www.astepaheadchallenge.com/.

Run![3] These are story-based jogging apps that encourage users to jog in order to escape a zombie apocalypse. Berkovsky et al. [2010] created a game called *Play, Mate!* where marbles move in the digital 3D world towards a goal as players move their body. *Heart Burn* [Stach et al. 2009] is a digital car racing game where heart rate values define the car's speed in the game. Finally, Walsh and Golback [2014] have converted user's steps into a currency, which can be spent within an online explorer game. Fogg [2002] also worked on a similar gamification idea, where a user's step count is turned into game points, which in turn help a virtual *Pikachu* to grow. These works highlight that introducing play elements can make exercise more enjoyable and engaging. Drawing on this, we utilized liquid fountains to playfully represent data in a fluid form in the *TastyBeats* systems, while in *EdiPulse*, we printed letters of the *Slogan* in an ad-hoc manner to involve users in a word guessing game. Next, we describe current explorations around physical visualizations of data.

2.2 Physical Visualizations of Physical Activity Data

Jansen et al. [2013, p. 2594] define physical visualizations as "visualizations that are made of physical matter." Physical visualizations benefit from the physical modality of the material, which makes the visualization easy to explore, handle, and manipulate in physical space. The use of physical media is motivated by their affordances towards facilitating haptic interactions and opportunities of embodiment [Vande Moere and Patel 2009]. For example, while traditional digital visualizations cater mainly to visual senses, physical media can also be touched and their physical properties such as shape, texture, temperature, or weight can all be utilized to represent different aspects of the received information. Physical visualizations are also popular in art installations and museums. Dragicevic and Jansen [2012] maintain a curated list of existing explorations in physical visualizations including art explorations, which suggest their potential to engage people for a longer duration and sustain their interest in exploring and understanding the captured data. We describe below some of the key works that utilize physical activity data.

2.2.1 Representing Data Using Data Sculptures. One popular type of physical visualizations is the data sculpture which Zhao et al. [2008, p. 343] define as "data based physical artifacts, possessing both artistic and functional qualities that aim to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it." *Breakaway* by Jafarinaimi et al. [2005] is one of the first works in which a data sculpture is used as an ambient visualization to provide feedback on the user's proper sitting posture. In a similar vein, Haller et al. [2011] and Hong et al. [2015] used *flower*-shaped physical ambient avatars to increase the awareness of incorrect body postures. Stusak et al. [2014] designed and studied 3D-printed *Activity sculptures* of running data while Lee et al. [2015] created a *Patina Engraving* system that represents physical activity data through engraved patina-like patterns on a wristband. *HeartPlotter* [Yu et al. 2016] is another system that represents heart rate data by the pen movements and its drawings on paper. These works report that physical visualizations can support an individual's self-expression [Stusak et al. 2014] and reminiscence [Thudt et al. 2016] besides increasing awareness of physical activity. The above physical visualization techniques focus on improving the user's understanding of data through the tactile experience of handling data presented in physical form. However, existing literature on material culture informs us of the polyvalent values of material artifacts within our everyday life, and how artifacts shape our identity within personal and social contexts [Dant 1999; Kopytoff 1986]. As such, material representations should not be considered purely as visualizations but also as substances to enrich our interaction with materials and their forms. Anthropologists like Miller [2010] view such interactions through the lens of "*Materiality*" and define them in terms of a broad

[3] https://zombiesrungame.com/.

range of values and affects that are elicited during the course of making and using the material artifacts. To this end, the topic of *Human–Material Interaction (HMI)* is an important consideration when representing data in a material form. Drawing on this, we refer to our work as material representations and not just physical visualizations. Below, we briefly summarize some of the existing works and frameworks that helped our understanding of HMI.

3 HUMAN–MATERIAL INTERACTION

The concept of materiality has gained considerable attention across many fields, including architecture, media and communication studies, materials engineering, material culture, and anthropology. Within HCI, interactions between humans and different materials have been explored using varied terms, for example as tangible bits [Ullmer and Ishii 2000], radical atoms [Ishii et al. 2012], computational composites [Vallgarda and Redstorm 2007], ephemeral user interfaces [Doring et al. 2013], and transitive materials [Coelho et al. 2009]. These explorations are partially driven by the emergence of Arduino, Raspberry Pi, and other microcontroller kits together with the rapid developments in sensors and smart material or e-textiles that contribute to the Weiser's vision of ubiquitous computing in the form of smart homes, internet of things, and electronic fashion. For instance, existing research has explored the use of tangible materials (e.g., shape memory polymers and thermochromic materials) as well as intangible materials (e.g., air, scent, and light) to represent digital data in a physical space [Robles and Wiberg 2011]. Besides, multiple processes also exist that include 3D printing, laser cutting, and vacuum forming for fabricating material artifacts. Given the wide variety of available options in terms of materials and processes, we turned to different HMI frameworks to guide us in the selection and to expand our understanding of materiality.

Several frameworks have been developed to establish an understanding of materials within interaction design. The framework "form-driven interaction design research" by Jung and Stolterman [2012] had a strong influence on our work. Jung and Stolterman proposed this framework that highlights the form and materiality aspects of digital artifacts going beyond their functionality. In relation to form, authors describe three properties: material, shape, and making; all of which concern aspects surroundings the chosen material, its appearance, and the processes used to create the artifacts respectively. With materiality, authors emphasize meaning and material ecology that focus on broader cultural and socio-technological contexts in which artifacts are being used. Similarly, Fuchsberger et al. [2014] offered an artifact oriented perspective on understanding the relationship between users and objects drawing on Actor-Network Theory. These two frameworks made us think and incorporate the broader ecology of artifacts going beyond their intended use of supporting motivations for physical activity.

Besides this framework, we also made use of other frameworks in this space. For example, Wiberg [2014] offered four dimensions of material-centered interaction design as materials, wholeness, texture, and details that helped us in identifying the right form for the material artifacts. The first dimension of materials points to their properties; the second dimension, wholeness, describes the meaning of the materials within their context of use; the third dimension is texture that highlights the importance of visual and tactile surface in the communication of meaning and; the fourth dimension, details, points to the finer design elements that shape the overall aesthetic and quality of the artifact. With goals of sustainability in mind, Blevis [2007] proposed a rubric for understanding the material effects of particular interaction design cases in terms of forms of use, reuse, and disposal. This framework made us think about the long-term use for material artifacts and ways to address sustainability issues, for instance, through the use of perishable materials as discussed in Section 4.4. The framework by Ashby and Johnson [2010] on the other hand, helped us to select appropriate materials by highlighting five dimensions of material information in engineering, usability, environment, aesthetics, and personality. We also looked into Karana et al.'s [2015] material-driven design method that is structured around "well-known materials, fully developed new materials as well as semi-developed new materials." This method involves four steps, understanding the material, creating a material experience vision, manifesting materials experience patterns, and creating material or product concepts. Similarly, Doring [2016] constructed "*the interaction material profile*" to support a structural analysis of our interactions with materials and to help build a catalogue of interaction materials. Giaccardi and Karana [2015] proposed a framework for material experience that highlights how interactions with materials influence our practices around four dimensions: sensorial, interpretive, affective, and performative levels. Finally, Wagner et al. [2010] offered a "*material-iconographic lexicon of artistic materials*" to describe unconventional and traditional uses of materials and how their selection adds meaning to the artwork. These frameworks inspired our choices of materials that could potentially evoke greater levels of sensory and affective engagement with physical activity data through its use. We discuss our choices in detail in Section 4.4.

Although these frameworks helped us to understand the theoretical foundation of material-centered interaction design, there remained a lack of understanding of how to apply this knowledge in practice, particularly for the context of physical activity and self-monitoring. According to us, designing material representations of physical activity data is challenged by a number of parameters including:

3.1 Key Challenge #1: Choosing the Right Mapping

Choosing the most appropriate mapping between data and the resultant material artifact is important because any feedback would require some level of user information processing. Sensors provide fine-grained data about physical activity, but designers must consider how, and which aspects of this data should be presented to the user using material representations. For example, should the mapping be informative to provide users with comprehensive details into their physical activity or should the mapping be more abstract, making users more curious and speculative about their physical activity? Should this mapping differ based on the individual and context of use? There is no definite answer in the literature to suggest an appropriate mapping [Jansen et al. 2015]. Davis et al. [2005] argue for direct and informative feedback as it offers opportunities to learn about the self and to improve the performance. Conversely, Consolvo et al. [2008], argue for a more abstract form of feedback to support positive engagement with data. The first challenge therefore revolves around identifying and understanding the appropriate mapping between data and the resultant material artifact.

3.2 Key Challenge #2: Choosing the Right Outcome

The outcome refers to the final artifact design in terms of its form and interface. A material representation affords many design possibilities—from the way it looks to what it should convey. Learning from digital metaphors for representing physical activity data, questions arise in terms of what values would a physical metaphor add to the overall experience? Should the constructed artifact be aesthetically pleasing and expressive to help users to talk about their active selves? Should the artifact serve additional utility besides offering data visualization? Should the utility and readability change with a change in context (public vs. private)?

According to Desmet [2003], a user will touch and engage with a product only if it looks good and feels good in the hand, thus making aesthetics is an important aspect of initial interactions. However, aesthetics alone is not sufficient to sustain user engagement [Forlizzi et al. 2004]. The aesthetics must complement a user's needs and intentions, which in this case would be to improve the understanding of physical activity. However, unlike a digital medium, a physical medium offers less flexibility when embedding information. Embedding too much data can render the material artifact less readable, whereas embedding too little data would prove inefficient in serving the intended purpose. The second challenge is therefore to understand the trade-off between aesthetics, utility, and readability.

3.3 Key Challenge #3: Choosing the Right Material

According to Ashby and Johnson [2013], the functionality of the artifact is dependent on the choice of material and process to meet the technical requirements of the design. In a physical space, the possibilities for choosing the material are numerous. A case in point would be that material artifacts do not have to be confined to solid-state materials like plastic or metal; other materials that are in a liquid state can also be explored as a potential material for creating these artifacts. Additionally, the use of certain materials could afford additional functionalities besides visualization. For example, a durable material like plastic affords use as a decorative piece within a home, while an edible material offers new opportunities for consumption and providing energy to the individual. While choosing the suitable material for representations, designers must consider underlying material properties so as to serve the intended purpose. For example, a material like plastic is more durable but may not be eco-sustainable (environmentally friendly) while edible materials like chocolate are tasty and tempting but are perishable and may not last long. Therefore, designers must strike a balance between material qualities and the intended purpose of serving as a material representation of data, which is thus the third key challenge.

3.4 Key Challenge #4: Choosing the Right Process

The final key challenge is to identify the means of creating material representations. Selecting the right process involves consideration about time and place, which according to Intille [2004] are essential for effective data communication. Patel et al. [2015] suggest that feedback on data should be presented at times when the user is most likely to notice it. In this regard, the following questions need to be answered. When and how should the material artifact be presented to the user? Should the process of creating material artifacts run in parallel with the physical activity or should it be delayed until the user finishes his/her physical activity? Should we involve users in the creation process of a material artifact or should we simply hand the artifacts over to the users?

Existing literature does not offer insights into whether or not to involve users in the creation process of the material artifact. In most works [Stusak et al. 2014], the resultant artifact is simply presented to the user, who has not contributed to its construction; a process which limits the experience and does not allow for what Gauntlett [2013] suggests, that is , that creating an artifact can also be an enjoyable experience.

To address these challenges, we followed a research through design approach [Zimmerman et al. 2007] to create and study a portfolio [Gaver 2012] of three systems that explore different materials as well as strategies to address the above challenges. We next describe the three systems.

4 THREE SYSTEMS

We designed and studied three systems that utilize three distinctive materials, namely, plastic, drinkable fluids, and chocolate to represent heart rate data of physical activity. We describe the three systems first and then detail the rationale behind our designs, specifically the rationale behind the choice of materials.

4.1 SweatAtoms

The first system is *SweatAtoms* [Khot et al. 2014] that transforms the heart rate data of physical activity into five unique 3D-printed plastic artifacts (Figure 1). We utilize constructive solid

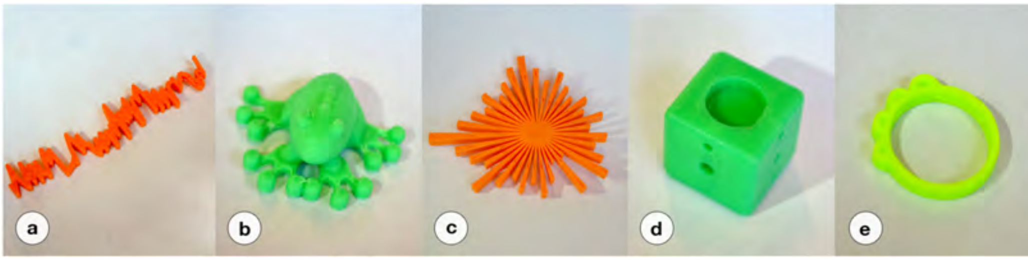

Fig. 1. *SweatAtoms* translates heart rate data of physical activity into five 3D-printed forms: (a) *Graph*, (b) *Frog*, (c) *Flower*, (d) *Dice*, and (e) *Ring*.

geometry technique and pre-programmed patterns to generate 3D designs from the captured heart rate data. These models are printed using a 3D printer forming an aesthetic and informative expression of heart rate data in material form. Each of these five representations captures a different aspect of physical activity in the following manner.

(a) ***Graph*:** The first representation is *Graph*, where recorded heartbeat per minute is mapped to a traditional two-dimensional (2D) graph. We then extrude the final result along the *z*-axis to create a 3D graph.
(b) ***Frog*:** The second representation is *Frog*, where the size of the *Frog* denotes the amount of physical activity undertaken in a day; the bigger the *Frog*, the more physical activity was completed in a day. We calculate the amount of physical activity based on the concept of "active time." An active time is the amount of time an individual spent exercising, where the heart rate was above the resting zone (60–75bpm)
(c) ***Flower*:** The third representation is *Flower*, which describes only the significant changes in the heart rate i.e., when the heart rate elevates or decreases by 20 beats per minute. We record these significant changes and map them to the length of petals, resulting in a floral-patterned piece of jewelry.
(d) ***Dice*:** The fourth representation is *Dice* where six faces of the *Dice* describe the amount of time spent in each of the six zones of heart rate data. Each face of the *Dice* has a center circle, which grows in size as the user spends more time in that particular heart rate zone.
(e) ***Ring*:** The final representation is *Ring*, which is a wearable ring with circles of different diameter on its periphery. The number and diameter of each circle define the number and duration of active hours in a day, that is, more circles equate to more active hours and a circle of bigger diameter means more activity performed in that particular hour.

4.2 TastyBeats

TastyBeats [Khot et al. 2015] explores interactive fluidic representations of physical activity data using drinkable fluids. We created an interactive water fountain installation that mixes different fluids in accordance with the measured heart rate data of physical activity to create a personalized drink.

The *TastyBeats* setup includes a central glass and four containers as shown in Figure 2. With each container fitted with a food graded water pump at the bottom. These Arduino operated pumps shoot drinks from the containers into the central glass. Each container contains a characteristic drink, representing a range of heart rate values; the first contains water representing the low activity zone (heart rate values: 60–95 beats per minute); the second contains lightly flavored water, representing the moderate activity zone (heart rate values: 96–130 beats per minute); the third represents the high activity zone (heart rate values: 131–165 beats per minute) and contains an

Fig. 2. *TastyBeats* is a fountain-based interactive system that creates a fluidic spectacle of mixing sport drinks based on heart rate data of physical activity.

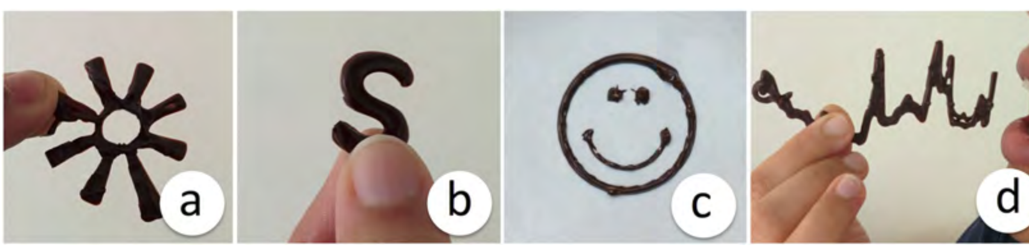

Fig. 3. *EdiPulse* creates 3D-printed chocolate treats from heart rate data in the form of: (a) *Flower*, (b) *Slogan*, (c) *Emoji*, and (d) *Graph*.

electrolyte drink and; the final contains a richly flavored and dark red drink representing the high intensity zone (heart rate values: >165 beats per minute).

The interaction begins by reading heart rate values from which the system identifies the corresponding heart rate zone and initiates the appropriate water pumps. The drink from the corresponding container is then pumped into the central glass for about 2 seconds. As long as the heart rate value stays in the same zone, no further drink is added to the central glass. When the activity zone shifts, a drink representing the new zone is pumped into the central glass (Figure 2) and continues until the central glass is full (in roughly 30 shoots). At the end of the interaction the user has a rich flavored personalized drink made from his/her data. The prepared drink also serves the additional benefit of replenishing the loss of body fluids due to physical activity.

4.3 EdiPulse

EdiPulse [Khot et al. 2017] explores an appealing food material, chocolate, to represent physical activity data. *EdiPulse* generates four different representations of physical activity from heart rate data in the form of 3D-printed chocolate treats. These chocolate treats bear the following four forms (refer Figure 3):

(a) ***Flower*** provides a summary of physical activity across each hour of recording. Each petal of the *Flower* corresponds to an hour and its length denotes the amount of physical activity in that particular hour without explicitly indicating the starting hour, as we wanted the *Flower* to be ambiguous, allowing participants to identify the starting hour on their own.

Fig. 4. The representations of how activity treats differ for (a) a sedentary day and (b) an active day.

(b) ***Slogan*** makes a cheerful comment about physical activity undertaken in a day. For example, if the user has been inactive during the day, *Slogan* will contain motivating words that communicate the benefits of an active lifestyle (Figure 4(b)). On the other hand, if the user has been active, *Slogan* will offer praise through gratifying words (Figure 4(a)).

(c) ***Emoji*** uses an emoticon to communicate an individual's progress towards a self-selected activity goal. At the start of the day, users enter their physical activity goal for the day into the *EdiPulse* application. This goal is a chosen duration for doing moderate to high level of physical activity and it could span over the day. The *Emoji* bears one of four faces: sad face, straight face, happy face, and super happy face based on how close the user gets to the goal. For example, achieving and exceeding the goal respectively results in a happy and super happy *Emoji*, while failing to meet the goal results in a sad or straight face *Emoji*.

(d) ***Graph*** shows recorded heart rate values over time. We map the recorded heartbeat per minute to a point in XY space and then extrude the resultant 2D shape along the z- axis to achieve a suitable thickness of 2 mm.

4.4 Design Process Behind Three Systems

The development and study of these three systems did not happen in parallel. Instead, they followed a sequential order, where the insights gained from the design and study of the first system, influenced the design of follow-up systems. The system we created and studied first was *SweatAtoms*. In the study of this system, we found that participants were initially engaged in the rather slow process of creating material artifacts using a 3D printer as it gave them time to reflect on their data as participants stand next to the printer while it prints out the artifacts. However, their interest in watching the print process slowly faded away because of the fixed and detached process of 3D printing. In the second system, *TastyBeats*, we attempted to improve the process by offering a drinkable artifact created from an individual's heartbeat and prepared as an interactive spectacle. In the *TastyBeats* study, participants found both the drink and the process of creating the drink engaging. This inspired us to explore whether the same results could be obtained through 3D printed edible artifacts through the use of an appealing material like chocolate, and with improvements to the printing process (e.g., printing letters in an ad-hoc manner rather than sequential) and whether participants find the process engaging as a result of it? In consequence, we decided to use chocolate to represent physical activity data for the final system, *EdiPulse*. We wanted a material that could add playfulness and intrigue to the idea of "self- monitoring and then eating the data based on the sensed activity"; hence, chocolate was our next choice. Here we reflect on some of the design decisions behind these three systems. The detailed design process is described in the individual papers of these three systems [Khot et al. 2014, 2015, 2017].

4.4.1 Selecting the Plastic as First Material. The synergy we observed between physical activity and 3D printing motivated the use of durable materials such as plastic. Physical activity involves the expenditure of energy without any material gain, whereas 3D printing follows an additive manufacturing process where a material artifact is created by additively depositing plastic layer by layer on a print bed. If we blend them to create a personalized data artifact, then it could serve as a physical souvenir or testimony to invested efforts in physical activity.

4.4.2 Selecting the Chocolate and Sports Drinks as Next Materials. We used consumable materials such as chocolate and sports drink fluids to provoke thinking about the significant relationship between physical activity and food, and the role of technology in supporting this relationship. For instance, self-monitoring technologies typically provide data about how much energy has been expended in physical activity (i.e., energy-out), while food printing technologies focus on ways of producing food meant for consumption (i.e., energy-in). As such, these representations contribute to the "human energy cycle," where the energy invested in physical activity is returned to the body though edible artifacts. Additionally, we attempt to explore related work around self-monitoring technologies and their representations seem to indicate a lack of exploration into "physical-digital-physical interaction" through an "energy cycle."

4.4.3 Selecting the Representations. We began by exploring the literature and considered findings from earlier studies to identify possible representations. We held regular focus group meetings with researchers from nearby research labs to help us refine our design choices. We drew on Nicolson's [2015] suggestion to provide a variety of representations to raise the chances that each participant can find something meaningful in the data. Drawing on goal-setting theory [Locke and Latham 2002], we also allowed individuals to set their activity goals and used activity treats to display progress towards it. The technical capabilities of digital fabrication technologies also influenced the selection. For example, during the time of the *EdiPulse* study, the food printer could not easily print tall structures. As a result, we restricted our design explorations to flat models. In *SweatAtoms* and *EdiPulse*, we also considered the printing time, the amount of material required for printing, and the size of the print bed (20cm × 22cm) for print efficiency. The final design choices are in line with Moles et al.'s [2016] three forms of reflection as follows:

(1) *Information-driven reflection:* This form of reflection represents data without any prescribed interpretation. We chose *Graph, Flower, Dice,* and *Ring* to help people understand how their activities change over time and how they progressed towards their goals.
(2) *Expression driven reflection:* This form of reflection adds a subtle interpretation of data using familiar metaphors and expressions. Drawing inspiration from this, we chose *Emoji* to give users the ability to reflect and identify themselves in alter egos, and we chose *Frog* to allow easy interpretation and comparison. Finally, we choose to use water fountains in the design of *TastyBeats*, drawing on the popularity of large-scale water fountain installations like Fountains of Bellagio[4]to create a public vista of someone's heart rate.
(3) *Dialogue-driven reflection:* This form of reflection offers textual feedback on data in the form of praise or positive encouragement. It is less ambiguous than the other two methods and directs attention to important information [Gouveia et al. 2015]. We chose the *Slogan* to acknowledge an individual's exercise efforts explicitly and to cheer them on towards their fitness goals.

[4]Fountains of Bellagio https://bellagio.mgmresorts.com/en/entertainment/fountains-of-bellagio.html.

Table 1. Comparisons of the *SweatAtoms, TastyBeats,* and *EdiPulse*

	SweatAtoms	***TastyBeats***	***EdiPulse***
Sensed physical activity data	Heart rate with Polar H7 heart rate monitor	Heart rate with Polar H7 heart rate monitor	Heart rate with Polar H7 heart rate monitor
Tracking period	9am to 5pm	9am to 5pm	9am to 5pm
Material used	Biodegradable plastic (PLA)	Water and sports drinks	Dark chocolate
Process used	3D printing	Arduino controlled water fountains	3D food printing
Printing time (on avg.)	1 hour	15 minutes	30 minutes
Number of representations	Five (Graph, *Flower, Dice*, Ring and *Frog*)	One	Four (*Flower, Slogan*, Graph and *Emoji*)
Received representations per day	Five	One	Four
Study method	Field study in participants' home	Field study in participants' home	Field study in participants' home
Number of participants	Seven	Seven	Thirteen
Study duration	2 weeks	2 weeks	2 weeks
Data collection method	Interviews and diaries	Interviews and diaries	Interviews and diaries

4.5 User Studies of the Three Systems

These three systems were studied individually through in the wild field deployments across different households in a large metropolitan city. Participants were not compensated for their participation. We used semi-structured interviews and diaries as the method for data collection and thematic analysis [Braun and Clarke 2006] as the method for analyzing participants' experiences with each of the systems.

During each interview, we carried a list of questions (topic guide) related to the research aims that helped us to remain on track, while leaving sufficient flexibility in the discussion. The questions revolved around the motivations, expectations, utility, and experiences of using these systems. We gathered participants' feedback on system design, the use of corresponding material and processes (water fountains and 3D printing) for representing data. We welcomed opportunities to discuss any photographs and recordings of interactions that voluntarily captured by participants during the course of study. This additional data helped us to investigate how people reacted to and integrated the systems and the material representations of their data into their everyday lives. All interviews were audio recorded. Following an inductive thematic analysis, we examined the interview notes to get an initial sense of recurring themes and then inductively coded the interview data by developing labels to describe the phenomena. After deriving the set of codes, we iteratively clustered related codes into higher-level groupings, representing the major themes as findings. The results from the user studies of these three systems were described in Khot et al. [2014, 2015, 2017].

Table 1 shows a comparison between the three systems.

These deployments and investigations have guided us to scaffold the first conceptual understanding of the interrelationship between material representations and physical activity, which we have articulated in the design framework, *Shelfie*. Before describing the framework, we briefly discuss the processes followed in arriving at this framework.

5 TOWARDS A DESIGN FRAMEWORK

We used an iterative approach [Ryan and Bernard 2003] towards designing the framework. The core strategy used to build this framework was to analyze findings from the studies of *SweatAtoms,*

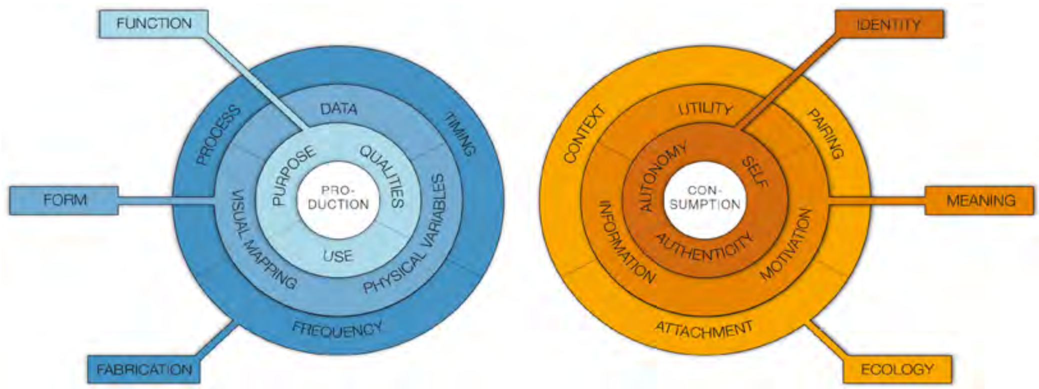

Fig. 5. The initial design of *Shelfie* framework had 18 design themes mapped across two broad lenses: production and consumption.

TastyBeats, and *EdiPulse* and supplement them with our understanding of the literature and gained experiences in designing these systems. We used affinity diagramming techniques to extract key findings from the three studies and recorded them on index cards. By sorting these cards into groups, we narrowed down the data to an initial draft of 18 important design concepts. We conducted multiple informal and focused group discussions with colleagues to strengthen and refine these concepts. We were also interested in developing a tangible framework as tangibility enables the physical manipulation of ideas and allows designers to focus on their mental processes in an actionable way [Antle et al. 2009]. Supporting this idea, we explored ways of representing the framework from the outset.

5.1 Initial Design of *Shelfie*

The initial design of the framework was based on 18 key design concepts mapped across the following two broad lenses: the production lens and the consumption lens. The production lens described how a designer could shape the physical appearance of a representation while the consumption lens offers understanding of the intrinsic cognitive relationship between the artifact and the user. Each lens had 9 design properties (18 in total), distributed equally across 3 nested layers as described in Table 2 and shown in Figure 5. We constructed a physical version of the framework using laser cut wood material as shown in Figure 6.

To represent the key concepts and three layers across two lenses, we made use of Lego bricks (that denote the concepts) and circular wooden tray (that represents the layers) as seen in Figure 6.

5.2 Evaluation of the Initial Design

To evaluate the effectiveness of the framework, we conducted a workshop with eight participants (6 males and 2 females aged between 21 and 45 years) from the nearby research community, comprising of academics and IT professionals with a design background. Participants were asked to use the framework to come up with ideas for edible representations for physical activity data (Figure 7).

The workshop highlighted that although participants found the framework useful in deriving different ideas for edible representations, they also felt it to be overwhelming, descriptive, and less intuitive to follow. Participants appreciated the tangible aspect of the framework as it supported a quick visual summary of the critical concepts of material representations and gave them a broad perspective on the variety of dimensions to consider during the ideation phase. Participants liked the idea of using Legos but had trouble addressing all the categories, and the separation

Table 2. The Initial Design of the Framework had 18 Design Concepts Mapped Across Two Lenses: Production and Consumption

Production lens		
Layer	***Property***	**Description**
Function	*Purpose*	Designer's intended purpose for the material representation, e.g., to enable richer reflection on physical activity.
	Qualities	Qualities of the material representation that go beyond the intended purpose, e.g., sustainability.
	Use	Values of the material representation concerning its use, e.g., decorative or practical object.
Form	*Data*	Aspects regarding the used data, e.g., data type.
	Physical Variables	Physical properties that can be used for representing data, e.g., size or texture.
	Visual Mapping	Process of mapping abstract data to a material form, e.g., mapping size to amount of physical activity.
Fabrication	*Process*	General process of 3D printing, e.g., manual or automatic.
	Timing	Duration and point in time the material representation is printed, e.g., during a physical activity.
	Frequency	How often the material representation is printed, e.g., every month or on special occasions.
Consumption lens		
Layer	***Property***	**Description**
Identity	*Self*	Extent to which a material representation is in line with the user's identity, thoughts and likes.
	Authenticity	Identification and mapping of distinctive characteristics of individuals in material form.
	Autonomy	Innate abilities to affect the design of material representation by experimenting with physical activity routines.
Meaning	*Information*	Perceived understanding of the material representation and the mapped data.
	Motivation	Incentives provided by the material representation for doing physical activity.
	Utility	Other imagined uses of the material artifact by users.
Ecology	*Context*	How situations and environment affect user interactions with material representations.
	Pairing	Association of material representation with other material artifacts and people.
	Attachment	Level of engagement with the artifact in terms of time.

of consumption and production lenses was confusing. One participant said, "working with Legos is intuitive, but I must first need to learn the categories. I also had doubts about the consumption and production divide." Another concern was the lack of order, which made participants wonder how to move across different design concepts, e.g., should the designer start with the production lens and then move to consumption lens or vice versa. One participant suggested using Lego bricks of different sizes to signal priority in terms of the design choice. Similarly, it was also not clear if participants should incorporate all design concepts in their design, or they could omit some depending on their requirements.

Participants preferred a well-defined description of each design concept with illustrations on how to use it in their design. A couple of participants suggested placing descriptive cards alongside

Fig. 6. Physical manifestation of the initial design of *Shelfie* framework using circular wooden tray and Lego bricks to represent concepts.

Fig. 7. Participants interacting with the initial design of the framework during a workshop.

the Lego bricks to offer supplementary information about those design concepts. Considering participant feedback, we revised this framework by using design cards that carry descriptive text and a visual illustration of the design theme. We decided not to use layers and stopped using the circular wooden tray opting for a flat Lego sheet instead. At the same time, we updated the textual content for each card in order to make the cards simpler. We refined and reduced the number of the themes to 13 from the initial design of 18 and removed the overarching categories of "production" and "consumption." We considered the feedback regarding the names of some of the themes, for example, one was initially named "attachment" to signify long-term engagement with the artifacts and was later renamed to "lifetime" to broadens its scope and highlight the importance of the ageing of materials. Finally, we altered the physical manifestation of the framework from the initial concentric layers (Figures 5 and 6) and began using design cards to describe the concepts of the framework, drawing inspiration from existing literature within HCI [Deng et al. 2014; Mueller et al. 2014; Hornecker 2010; Antle et al. 2009].

A deck of design cards is a useful tool for discovering ideas and for capturing a diverse set of possibilities for designing in a specific context [Bekker and Antle 2011]. Rather than offering strict guidelines or strategies, the cards act as a catalyst to stimulate and support divergent designs during the ideation process. Design cards do not follow any particular order—thus providing more flexibility and freedom for designers to come up with different theme sequences. Design cards also provide designers with a common vocabulary about a specific context during the ideation phase. The tangibility of design cards acts as a "physical anchor" and helps to generate concrete design knowledge [Bekker and Antle 2011; Deng et al. 2014]. Cards assist in the refinement and iteration of ideas by keeping the discussion centered on a given design task—making the ideation phase productive [Halskov and Dalsgaard 2006; Hornecker 2010]. To this end, cards offer a fun tactile experience of ideating and discussing ideas collaboratively.

Numerous works in the past have explored card-based design tools to support brainstorming and ideation processes during the early stages of design research. For example, Halskov and Dalsgaard [2006] created two sets of inspiration cards—domain cards and application cards—to support the ideation of new concepts for design. IDEO [2002] created a deck of 51 cards, where each card illustrates a user-centered design process and provides ways of empathizing with users in design projects. Design cards have also been designed with specific application context in mind. For instance, Mueller et al. [2014] created exertion cards that allow the creation of exertion games, while Lucero and Arrasvuori [2010] created PLEX cards for creating playful experiences. Hornecker [2010] created ideation cards for creating physical interactions. Tango Cards by Deng et al. [2014] enable the creation of tangible learning games. Finally, Lockton's "design with intent" toolkit [Lockton et al. 2008] aids designers creating systems that influence behavioral change. Wolfel and Merritt's work [2013] and Roy and Warren's work [2019] offer a comprehensive survey of design cards used in academia and practice, whereas Deckaholic[5] is an online library that curates a list of design cards used in practice. Each of these card-based design tools allows different perspectives to emerge to support designing for a specific context.

We took these works as an inspiration to guide us in the redesign of the *Shelfie* framework as design cards. The refined framework *Shelfie* has 13 key design concepts defined through design cards. We have grouped them into four categories based on the commonalities found in its features.

6 *SHELFIE* FRAMEWORK

Shelfie stands for "on-shelf material representations of the self." The aim of *Shelfie* is to assist designers in designing material representations of physical activity data. *Shelfie* consists of a deck of 13 cards divided into four categories: *Mapping, Outcome, Material*, and *Process*. Each card represents a key design aspect that designers should consider while designing material representations.

The final deck of 13 design cards (Figure 8) is the result of a process of carefully sorting, synthesizing, and discussing each card with four interaction designers. We paid special attention to the content and layout of the cards such that the cards are easy to understand and applicable in practice. Previous research on design cards suggests that accompanying pictures play an important role in representing the card, as it provides a visual summary of the content [Deng et al. 2014]. To this end, images need not be too specific to restrict the ideation space to a particular context; while not being so general that designers find it hard to relate to the design task at hand. Drawing on this, we chose the majority of the images from the three case studies. The other sources of images include Pexels[6] and Unsplash,[7] which are repositories of royalty-free images.

[5]http://deckoholic.com.
[6]http://pexels.com.
[7]htttp://unsplash.com.

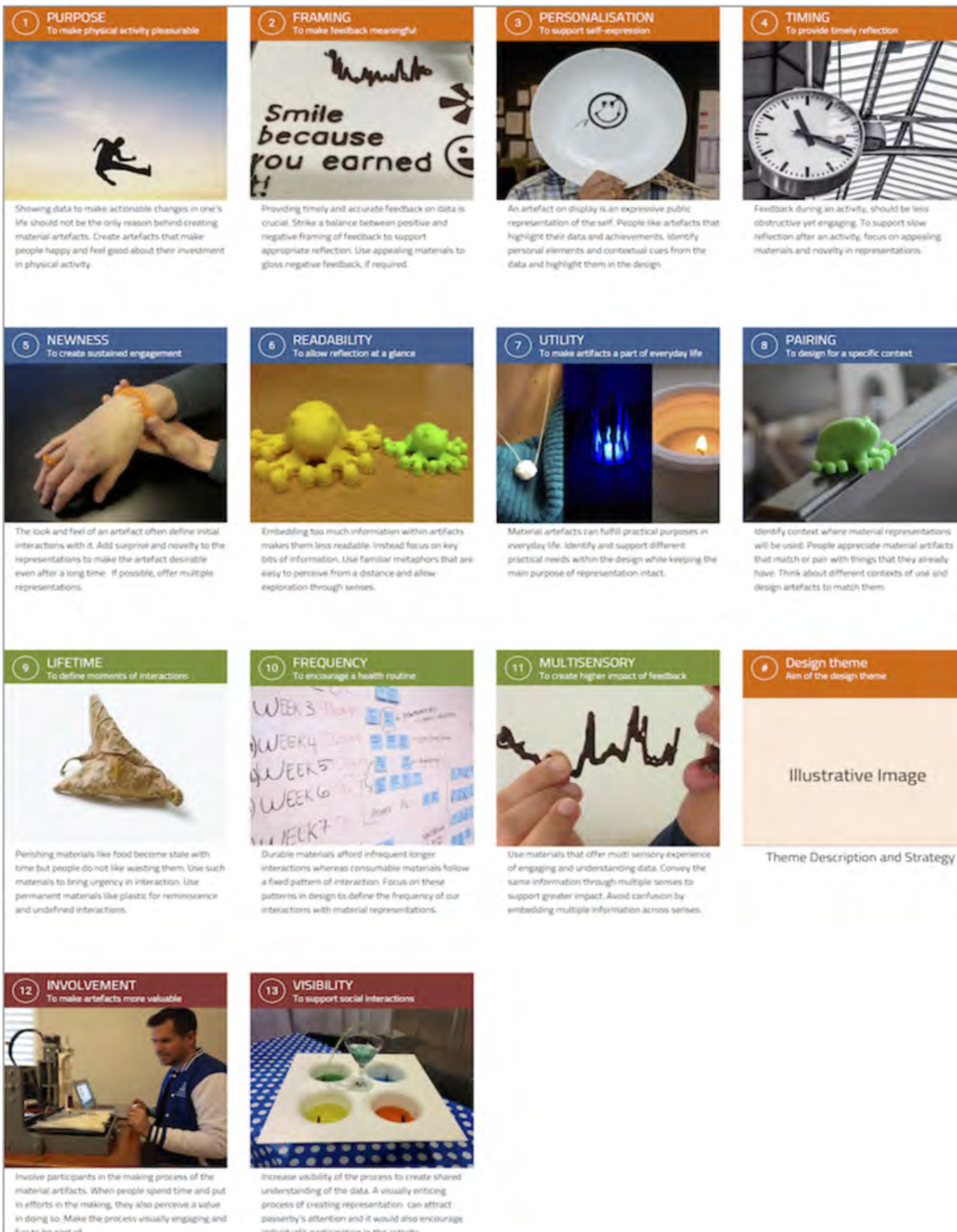

Fig. 8. Each *Shelfie* card contains four pieces of information: (1) name of the design theme, (2) aim of the design theme, (3) illustrative image; and (4) theme description and strategy.

Fig. 9. Each *Shelfie* card contains four pieces of information: (1) name of the design theme, (2) aim of the design theme, (3) illustrative image, and (4) theme description and strategy.

Extending the existing design card space, introduced a new way of interacting with the cards. The framework utilizes Lego bricks and flat Lego sheet as physical props to arrange the design cards, facing up, drawing inspiration from the game of "Guess Who!" There are five Lego bricks for each design themes. These physical props aim to enhance the ideation phase with the physicality of Lego bricks, allowing designers to manipulate different design themes as per their needs.

The Lego board is utilized to make the ideation phase quick and more visible ensuring that once cards have been chosen, they remain visible for the rest of the game. For example, a designer draws a card from a deck, uses it in some way and would normally return the card to the deck, whereas in the *Shelfie* framework, we instead opt for a visual and spread-out display of cards on the Lego board, where the used cards are visible and quickly accessible at all times. Such an arrangement is partially inspired by a popular board game "Guess Who?" Allowing all cards to be visible offers the designer an easily accessible view of the chosen design concepts, thus ensuring a broad overview of the design throughout the ideation process. This allows designers to change their mind about specific design themes quickly and to move them around until their desired design concept is realized. The potential advantages of this system have yet to be studied formally through a comparative study and it is a part of our future work.

6.1 Layout of *Shelfie* Cards

Each design card is 64 mm × 100 mm and color-coded by category, displaying the following five sets of information related to the design theme. A blueprint card is shown in Figure 9.

(1) **Design theme:** The first piece of information is the name of the design theme. The design theme describes the key aspect of designing material representations for physical activity data. If the name of the design theme is X, then the designer should read the card as, "*Consider X in the design.*"
(2) **Aim:** The second piece of information, written just beneath the design theme, is the aim. The aim describes the resultant outcome of the given design theme. For instance, if X is the design theme and Y is the prescribed aim, then the card should be read as, "*Consider X in the design to achieve Y.*"
(3) **Illustrative image:** The third piece of information is an example image of the design theme. The intention of displaying an image is to support the design theme with a visual cue.
(4) **Theme description and strategy:** The final piece of information is the "theme description" that resides underneath the picture and describes "the design theme" in a couple of

Fig. 10. The four cards from the *Mapping* category are: (1) Purpose, (2) Framing, (3) Personalization, and (4) Timing.

lines. The theme description also mentions a "strategy," which suggests possible ways of implementing the design theme in real-world context. These suggestions are formulated from the findings of the three case studies as well as from the design of these systems.

7 *SHELFIE* CARDS IN DETAILS

Each of the 13 design cards is next described in detail. These *Shelfie* cards are mapped across the following four categories: *Mapping, Outcome, Material,* and *Process.*

(1) **Mapping:** The first category assists designers in identifying different ways of translating physical activity data into a material form. This category includes four design themes: *Purpose, Framing, Personalization,* and *Timing*, which are illustrated through four design cards represented by the color orange.
(2) **Outcome:** The second category aids designers in choosing the look and feel of a material artifact. This category includes four design themes: *Newness, Readability, Utility,* and *Pairing*, and the corresponding four design cards are colored blue.
(3) **Material:** The third category helps designers in choosing the right material for representing physical activity data. This category includes three design themes: *Lifetime, Frequency*, and *Multisensory,* represented through green colored design cards.
(4) **Process:** The final category places an emphasis on the selection of an appropriate manufacturing process for creating material artifacts of personal data. This category includes cards belonging to two design themes: *Involvement* and *Visibility*. These cards are colored red.

We note here that these categories originated through our design experiences as we progressed with our work in designing and studying these systems in situ. For example, we started the work on *SweatAtoms* with challenges around *Mapping* and *Outcome*. The challenges around *Material* and *Processes* emerged after the *SweatAtoms* study and when we began working on *TastyBeats* and *EdiPulse* study. For clarity, instead of writing them separately, we have combined them together to offer a unified view on challenges. We start by describing the four cards from *Mapping* category (as shown in Figure 10).

7.1 Mapping: Purpose

The first card in the *Mapping* category is *Purpose*, which defines the overall aim behind creating material representations of physical activity data. In many cases, the *Purpose* is most likely to help people begin or maintain a physically active lifestyle. However, this rather broad purpose can be

Fig. 11. Participants stacked artifacts from different days to keep track of their progress.

fulfilled in a variety of different ways based on the individual's needs and preferences. Here, we discuss two possible ways of supporting *Purpose* as identified by the study insights: eudaimonic pursuits and hedonic pursuits.

Eudaimonic pursuit: The *Purpose* could be framed as a pursuit of virtue where individuals can identify and develop character strengths from the collected data to achieve their fitness related goals [Li et al. 2011; Lupton 2016]. Psychologists termed such activities as eudaimonic pursuits [Henderson et al. 2013]. Material representations can help individuals in this regard by presenting users with data in a clear and understandable manner, exploiting the tangible properties (as discussed in the *Readability* theme). Within the three studies, we found that few participants used the material representation to keep track of their physical activity levels. In the *SweatAtoms* study, participants stacked different sized *Frog*s and *Graphs* from different days next to each other to track their progress and understand changes in their performance as seen in Figure 11.

Participants also admired the tangible qualities and selection of the representations such as *Graph* and *Flower* as they offered insights into one's activity at a glance. Although the material representations often serve as an extrinsic motivation, they proved to be a form of supplementary motivation to support the intrinsic motivations that several users already had. In *EdiPulse*, most participants worked towards achieving the happy *emoji* on every day of the study (achieved when one surpassed one's physical activity goal for the day). We found that participants with predefined targets (such as losing weight or going back to their old active routine) were more willing to take advantage of the motivational features provided by the representations. They often adjusted their routines to incorporate different forms of physical activity and in doing so, became more physically active. Drawing on this, we argue that for such users (i.e., who have an intrinsic motivation for being physically active), setting *Purpose* as an eudaimonic pursuit might be appropriate where the artifacts would assist them to track their progress and support self-expression of their consistency in pursuing physical activity.

Hedonic pursuit: Conversely, the purpose can also be framed as a hedonic pursuit, where the emphasis is on highlighting the pleasures, joy, and satisfaction associated with being physically active and having a positive outlook towards exercise. Mueller et al. [2017] highlighted various virtues of exertion beyond eudaimonic pursuits. Henderson et al. [2013] on the other hand suggest that offering pleasurable rewards is important because they serve a revitalizing function and encourage people to pursue their goals. Drawing on this, material representations can act as incentives or positive reinforcements. We found that participants' inclinations towards material representations were not just the result of an interest in self-knowledge, but part of a broader positive outlook on exercise and encouragements for these pursuits. For instance, participants of the *EdiPulse* study mentioned that the urge to receive a smiling *Emoji* served as a motivational factor, leading them to exercise more. In *SweatAtoms* study, we found that four participants did more exercise specifically to receive a bigger *Frog* as a reward. Similar results were observed in *TastyBeats*, where participants exercised more so as to receive a rich-flavored drink. We found that participants treasured receiving a physical reward as a testimony to their invested physical efforts. In line with earlier study findings [Munson and Consolvo 2012], physical rewards felt satisfying with one of the key contributing factors being the choice of material used to create these representations for example, the chocolate and sports drink, which we will discuss further under the "*Multisensory*" theme. Drawing on these findings, setting *Purpose* as a hedonic pursuit could provide users with a desired initial push towards leading an active lifestyle. However, material representations should not simply be treated as external rewards, but should be considered a commodity that could support a joint pursuit for both "hedonic and eudaimonic" experience.

7.2 Mapping: Framing

The second card in the *Mapping* category is *Framing*. This describes the way of structuring the feedback on one's physical activity through material representations. This theme is important to consider because raw unexplained data can lead to discouragement among users [Gockley et al. 2006]. We classify *Framing* under the following two categories: positive and negative framing. Positive framing presents the feedback in an encouraging way, giving more emphasis on what the user has achieved. Negative framing, on the other hand, highlights unachieved goals and any losses associated with it. As an example, missing an exercise session in the gym can be framed as: "No worries mate! Tomorrow is another day!" (Positive framing); and "Don't miss the session again. You seem to be bit lazy lately!" (Negative framing). Earlier research suggests that positive framing of data can be more persuasive towards achieving goals [Consolvo et al. 2008]. For example, a study by Choe et al. [2013] showed that displaying achieved steps (positive framing) compared to remaining steps, contributed positively to user's self-efficacy. Furthermore, Lyubomirsky et al. [2005] highlighted that positively framed feedback can support self-esteem, health, growth, and perseverance. However, an overly positive framing could create an illusion of the self, which is dangerous in the long run and as a result, individuals may fail to critically reflect on their activity goals [Robins and Beer 2001]. Therefore, positive framing may need to be supplemented with occasional negative framing to keep individuals on track and convey information about certain aspects of one's life that needs attention. Negative framing has proven useful in helping people quit smoking and reduce substance abuse [Pfau 1995]. However, the disadvantage with negative framing is that the user can feel guilty of not achieving their goals, leading to disinterest in physical activity, as identified in the study by Lin et al. [2006], where individuals were not keen to look at the animated fish-based visualization of their sedentary lifestyle, because they knew that because of their inactivity, the fish would have been sad (negative framing).

Golden and Alpert's work [1987] on marketing campaigns suggest that a successful communication strategy should include two-sided communication containing both positive and negative framing. Following on this, we have utilized a mix of positive and mildly negative framing across all three studies, although, in the majority, material representations that we created were aimed at positively reinforcing participants in achieving their goals. An important aspect of these systems was that participants were never punished for not doing physical exercise and they always received material representations of their data, irrespective of their physical activity levels. For example, Figure 4(a) shows edible representations received by participants on a less active day in the *EdiPulse* study, where we used positive encouraging words to motivate people to exercise.

However, we rewarded the efforts by improving the quality of representations with an increase in physical activity. For instance, when the participant was active throughout the day, the *Frog* became bigger in size, the sports drinks in *TastyBeats* had more flavor, *Emoji* was smiling, and *Slogan* had congratulatory message in *EdiPulse* as seen in Figure 4(b). The act of getting bigger representations had a positive and encouraging impact on study participants as explained in *Purpose* theme.

The use of materials such as chocolate and sports drinks also played an important role in allowing the participants to digest even the negatively framed feedback. For instance, receiving a small quantity of drink from the *TastyBeats* system, or a sad *Emoji* printed with the *EdiPulse* system, did not discourage participants rather such negative framing became a motivational anchor that prompted more determination and effort to achieve the desired physical activity goal on the following day. This relates to the theory of inoculation [McGuire 1961], which describes a strategy to strengthen one's belief in health behavior by mildly attacking the belief with a counterargument. This strategy has been applied previously in *Monster Appetite* game [Hwang and Mamykina 2017], a persuasive game that encourages healthy nutritional behavior through an animated display of the effects of both healthy and unhealthy nutritional choices to the users.

Another key strategy that designers might apply is to keep the framing open and speculative. For example, within the three studies, even though the participants were aware of their sedentary hours in a day, they did not know what kind of material representations they would get or how the drink prepared by the *TastyBeats* would taste until they consumed it. As such, there was always an element of surprise of not knowing what the representations may look like and whether they would be positively or negatively framed. This feature not only contributed extra physical activity among participants, but also generated and persisted their interest in seeing these representations even in situations where the feedback was "negatively framed."

Negative framing became challenging when interactions with the system took place in social settings, that is, in the presence of other people. Participants did not want to expose themselves as inactive and felt the pressure to partake in greater amounts of physical activity. For instance, in the *TastyBeats* study, a couple of participants felt sad to receive a weak flavored drink for being less physically active than their partner who was also participating in the study. One participant tried to cheat by creating a drink based on the data of his partner's physical activity but drinking the prepared drink felt even worse because he felt that he do not deserve the drink as he was not physically active. Balancing the positive and negative aspects of the data is a key in social context, especially when personalization becomes part of the broader design considerations, as we describe in the next design theme.

7.3 Mapping: Personalization

The third card in the *Mapping* category is *Personalization,* which looks at expressive qualities of material representations, synonymous with the individual's understanding of the self [Li et al. 2011; Thudt et al. 2017]. Since the constructed material artifact serves as another manifestation of the self, its relationship with the individual can be dependent on how reflective the representation is of an individual's identity.

Personalization can be achieved by exploring the differences in individual's health-based goals and ways of achieving them in accordance with their lifestyle. For example, within the design of the three systems, we utilized the fact that heart rate responses to physical activity are not only different for each individual, but also vary based on different types of physical activity. Drawing on this, the *Flower* artifact in *SweatAtoms* and *EdiPulse* was designed to capture and signify unique patterns of an individual's heart rate. Significant increases or decreases in the heart rate were mapped to

Fig. 12. A distinct heart rate response was highlighted through the evolving floral patterns.

an evolving floral pattern. Since these shifts in heart rate differed from person to person and also from one day to another (refer Figure 12), the resulting floral pattern in the *Flower* artifact varied for each participant every day. The design of other representations such as *Graph, Slogan, Frog*, and *Emoji* were also dependent on an individual's physical activity. For example, happy and super happy *Emoji* were displayed on days when the user was active whereas sedentary days resulted in display of a sad or straight face *Emoji.* Most importantly, each day, participants received four (in *EdiPulse*) and five (in *SweatAtoms*) representations of their activities, which are personalized to their activities on that particular day, which participants liked.

The studies of the three systems showed that participants' responses were based not only on the visceral aspects of the artifacts, but also on reflective and expressive qualities of the artifacts. As such, participants appreciated the artifacts not only because of their aesthetics or their materiality (i.e., the use of appealing materials such as chocolate in case of *EdiPulse*), but participants appreciated these artifacts because they embodied their personal data and represented their activities. As one participant of the *SweatAtoms* study said, "[these artifacts] cannot be bought at a shop."

The personalization highlighted an interesting aspect that participants generally did not want to "trick" the system and when they did trick the system, it felt bad. An interesting example of this happened in the *TastyBeats* study, where one participant tried to trick the *TastyBeats* system by using data from his more active day to create a drink. Interestingly, however, he described how cheating in this way felt bad and that he considered himself as undeserving of the created sports drink. Similar traits were also found in the *EdiPulse* system, where participants refrained from eating their chocolate treats on days when they were inactive. Drawing on this, we encourage designers to consider ways of ensuring the artifacts are perceived as "their own" by utilizing unique characteristics of the data. This, however, may require deeper access to a participant's everyday life such as Global Positioning System from their smartphone, or access to their personal or social life through applications like Facebook or digital calendars. Such additional tracking practices obviously raises greater privacy concerns and can affect the ambiguous nature of the artifacts (i.e., a *Flower* artifact means nothing to someone who does not themselves have one, but a *Graph* may indicate to an observer that the individual has been really inactive, or active at times they should have been working). Special attention must be paid in abstracting the personal aspects of the data so that it offers meaning to the individuals but remains esoteric to bystanders, as discussed under the *Visibility* and *Readability* theme.

Involving participation in the design process: Finally, designers can also support *Personalization* by including participants in the design process. For instance, most participants in all three studies were vocal and enthusiastic about designing representations for themselves. Participants often altered the way in which they printed and used their representation, not only to improve their understanding but also to reflect their personality. Anthropologists refer to such behavior as singularization [Kopytoff 1986] highlighting people's tendency for adding something new to the artifact in order to differentiate it from others. For example, decorating garments to one's liking, adjusting the seasoning to suit one's taste and adjusting the visual setting of the computer in order to make the artifacts more identifiable and familiar. In the *SweatAtoms* study, some participants chose to print artifacts using material filaments of their favorite color. Three participants wanted to change the filaments color every day to achieve a distinctive feel and order to the representation once assembled together. In *TastyBeats*, participants wanted to use their favorite flavors to create drinks, and in *EdiPulse*, participants enjoyed receiving activity treats made of their favorite food. Although participants can alter color and other dimensions of on-screen representations, doing this in a physical space, seemed more personal as they could choose the color and pattern to match the ambience and improve the visibility to bystanders.

7.4 Mapping: Timing

The fourth and final design card under the *Mapping* category is *Timing*. This theme emphasizes the timing of feedback, that is, the timing of creating and delivering the material representations. Patel et al. [2015] suggest that feedback on data should be presented at times when the user is most likely to notice it. As such, timing considerations for the feedback would be: "before," "during," and "after" a physical activity.

To begin with, the "before" option seems impractical, as there would be no data available to create material representations. The second *Timing* option "during" allows the user to receive feedback on their ongoing performance. The advantage of such a strategy is that it enables users to think ahead to their next action and adjust the activity as it unfolds based on the feedback. This has, for example, been suggested as beneficial for physical activity in the "Jogging over a distance" project, where joggers receive real-time feedback while they jog through an audio channel [Mueller et al. 2010]. Drawing on this, if material representations are created "during" physical activity, then a user could directly change their activity based on the material representation. However, this is often (a) technically challenging (as 3D printing takes time) and (b) restricts the user to remaining indoors or near a machine, although recent development in mobile fabrication technologies [Bader et al. 2018] might offer a solution to this problem.

The "during" option of *Timing* would work in custom-made systems like *TastyBeats*, where data can be displayed in real time through interactive fountains. Using a visceral process has the advantage of making the interaction more performative and engaging even for the bystanders. This was particularly visible during the public demonstration of *TastyBeats* where the interactive fountains invited social interactions [Khot et al. 2015]. Bystanders were shouting and cheering the person who was doing different exercises to influence the water shoots in real-time. To individuals, the feedback through water fountains felt more vivid and playful. Drawing on this, there are advantages in exploring the "during" option: to invite social participation and to further incentivize participation in physical activity.

The final option "after" allows users to think and reflect on their physical activity performance and to consequently make different choices the next time. Within our systems, we chose to follow this option. We intentionally delayed the construction of material representations until the end of the day. This allowed participants to focus on their physical activities and altered their habit of frequently checking their phone for feedback on the data.

In *EdiPulse* and *TastyBeats*, the feedback also came in a material that appeals to their taste buds. The delay between the activity and the printing of material representations was beneficial, as it

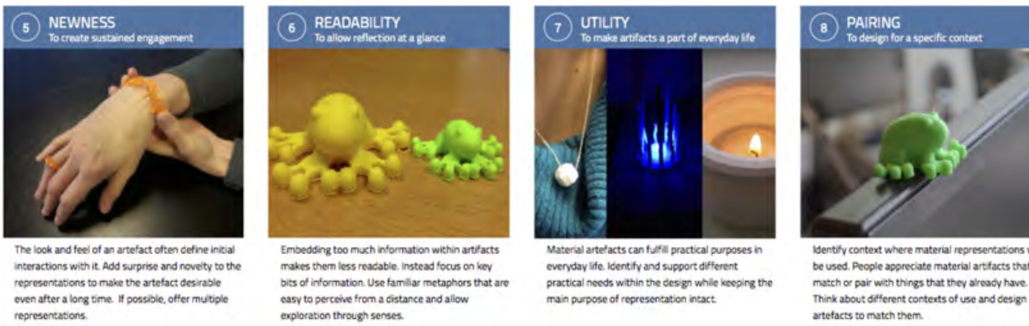

Fig. 13. The four cards from the *Outcome* category are: (1) Newness, (2) Readability, (3) Utility, and (4) Pairing.

allowed users to speculate how the activities would be reflected in the artifacts. As explained in the *Framing* theme, there was also an element of surprise as to the final material representations. This behavior can be explained in terms of "Anticipatory Savoring," which is defined as a process of psychologically looking forward to a positive experience [Black and Areni 2016], which in this case was to enjoy well-deserved material representations. In *SweatAtoms*, participants wanted to get a bigger *Frog*. Since there was uncertainty in accurately predicting whether they had done enough activity to receive better looking physical representations, participants continued to remain active throughout the day and unknowingly contributed opportunistic physical activity [Consolvo et al. 2014] among participants.

We encourage designers to carefully evaluate the benefits of two forms of feedback, "during" and "after." The "during" strategy of feedback supports reflection on the go and is suitable when the individual is interested in improving upon specific parts of exercise. Therefore, they need to see the emerging process of exercise. This is the case with the majority of existing self-monitoring devices where users can see the continuous stream of physiological data through a mobile app or on the small screen embedded on the device. On the other hand, the "after" strategy offers the capacity to support slow reflection [Odom et al. 2014]. Interestingly, recovering and gaining personal health is also a slow and steady process, which demands time and consistency [Benson and Connolly 2011] and while efforts are being made to tackle the slowness of 3D printing [Bader et al. 2018], we suggest designers embrace the slowness as a useful design resource to support anticipatory savoring and delayed feedback on physical activity data.

Next, we describe the four cards from the *Outcome* category (Figure 13).

7.5 Outcome: Newness

The first theme in the *Outcome* category is *Newness*. This design theme invites designers to incorporate novel form factors in the design of material representations. Earlier studies highlight the importance of the look and feel of an artifact in grabbing the user's attention and driving its initial use [Desmet 2003]. Newness of an artifact therefore plays a crucial role in driving the initial appeal and making it desirable. One might argue how newness is different from novelty. Novelty such as the thrill of owning a new possession often lends short-term value to the artifact. However, we believe newness is different to novelty as it places emphasis on continual relationship through elements of surprise. The embodiment of personal data as explained under the *Personalization* theme would allow the creation of newer artifacts and should help in creating a sustained engagement with the artifact.

According to Dinnin [2009], three factors create the perception of newness in an artifact: situational product involvement, a sense that the product is pristine, and the physical possession.

Govers and Mugge [2004] on the other hand, suggest four ways of creating *Newness*: (1) self-expression, where one expresses themselves through the artifact; (2) group affinity, where ownership communicates membership of a group; (3) pleasure, which is derived through ownership and sustained use; and (4) memories, which are built over time with the use of the artifact. The immediate value of a new artifact is derived from the hedonic experience of being its first user. Importantly, if the artifact only had novelty, the thrill of possessing the new artifact would fade [Dinnin 2009], whereas artifacts that continue to have newness may move to the background after a certain period of time. This does not mean that the artifact has lost its value, but rather it is adopted into daily routine [Kirk and Salen 2010].

In all three systems, *Newness* of material representations played an important part in sustaining participant's engagement. Participants liked the fact that they were getting not just one kind of representation each day but rather a variety of representations (four in case of *EdiPulse* and five in case of *SweatAtoms*) that depict and inform different aspect of their physical activity. Some of the representations such as *Frog*s, *Flower*s, and the drinks were new to participants, while other representations such as *Graph* and *Slogan* were familiar to the participants. Despite the familiarity, its embodiments in a physical and edible form were new to the participants. Interestingly, participants appreciated the representations, which resemble a living creature, such as the *Frog* from *SweatAtoms*, which every participant adored; and the chocolate printed *Emoji* that was compared to a human smiling on their achievements. Representations such as the Graph and *Flower* offered visible changes in its form with changes in participant's daily activity (as explained in *Personalization* theme) and as a result, participants found something new to learn, admire and understand. As such, these systems offered an emergent way of representing data where the forms or content of representation changed daily, thus adding a sense of serendipity to the overall experience.

Newness with material representations can also be achieved through novel technologies like 3D printing that afford the possibility of creating new forms from digital data, as explored in the *SweatAtoms* and *EdiPulse* study. At the start of the study, some participants were very excited with the opportunity of having a 3D printer at home and being able to use it daily. However, their interest in the printing process faded over time, while their interest in the constructed artifacts persisted throughout the study period, possibly because, as explained, the material artifacts embodied their personal data and were new every day, whereas the 3D printing was mechanical and redundant. However, in the case of *TastyBeats*, participants' interest in seeing the fountain interaction was sustained throughout the study. The fluidic display of the data was not only "eye candy" to them, but also shaped a social understanding of the data and allowing even bystanders to pay attention to what it is revealing (what information it is displaying). Similar results were also found for *EdiPulse* where the sweet aroma of printed chocolate and ad-hoc printing of representations kept participants engaged in the entire printing process. This suggests the importance of *Newness* and ways of achieving it could be by using appealing materials to create a variety of different representations and also by using serendipitous representation strategies to help in sustaining user's interests in the created material representations.

Newness can also be supported by choosing different interesting materials to construct the representations and exploring its properties, for example, experimenting with smell as well as the taste of the edible material. However, these aspects of newness must be validated through long-term empirical studies. We will discuss these multi-sensorial aspects of engagement under *Multisensory* theme.

7.6 Outcome: Readability

The second card in the *Outcome* category is *Readability*, which describes strategies for representing data in a material form to improve its understanding. Representing data in a material form includes

Fig. 14. The frogs in *SweatAtoms* were printed in bigger size with increase in physical activity.

both technical and cognitive challenges as one has to mentally interpret the interrelationship between the artifact (representation) and its referent (the physical activity). For example, embedding too much information within artifacts might make them illegible [Koutsomichalis 2018], while embedding too little data might make the artifact less meaningful.

Let us first look into the cognitive challenges. Although earlier work Stusak et al. [2016] suggest that individuals can grasp data presented as physical 3D-printed bar charts, designers can also consider other methods, in particular using metaphors for representing data. A study conducted by Sun et al. [2017] on different ways of representing heart rate data highlight that metaphors help viewers make a connection between themselves and what they see and affords a "deeper impression." According to Ham and Midden [2010], such subtle and ambient representations of data requires less conscious attention, as well as less cognitive effort from user once they understand what they mean. However, choosing metaphors are also not easy as designers must also consider the metaphorical distance [Clevenger and Edwards 1988] between a chosen metaphor and underlying data, as it can affect interpretive qualities. Secondly, if 3D printing is used to create artifacts, designers should consider the required print time. For instance, in case of *SweatAtoms*, the average print time for printing bigger shapes like *Frog* and *Dice* was 25 minutes whereas Graph and Ring took 10 minutes.

In *SweatAtoms*, we used known metaphors such as *Flower, Dice*, and *Frog* and opted for a simple mapping. In the case of the *Frog*, it became bigger with an increase of physical activity (refer Figure 14), whereas in case of the *Graph* and *Flower*, more dynamic patterns were exhibited in response to user's physical activity. In *EdiPulse*, instead of scaling the representations, we chose to alter its "tone." We chose to print a smiling *Emoji* when users achieved their physical activity goal and a sad face *Emoji* if they did not (refer Figure 4).

The studies of *SweatAtoms* and *EdiPulse* demonstrate that participants were happy with the choice of metaphors that offer abstract information about their activity but in an aesthetically pleasing way. In the beginning of the study, some participants had some difficulties in understanding all bits of captured information and the ways in which different shapes represent different pieces of information. However, these difficulties diminished as participants received more representations of a similar shape. It led participants to engage with the artifacts, by observing them, stacking them, and comparing them. The fact that these representations required personal knowledge to be interpreted also fostered reflection on data. Drawing on this, the designers could consider adding some level of ambiguity and abstractness in design to support "personal narrative visualization" [Thudt et al. 2017], where individuals could narrate their data stories from their own point of view.

Participants could display them freely without feeling as if they were over-exposing themselves. For example, the *Frog* from *SweatAtoms* was the favorite of all representations despite the fact that it contained very little information about physical activity. It was readily displayed in people's surroundings and became a talking point within the households. It also facilitated healthy competition among participants as they sought to receive a bigger *Frog*. More informative models such as *Graph* and *Dice* did not achieve the same level of appeal, possibly because they were familiar (as explained in *Newness* theme) and required more interpretation effort. The representations like the *Frog* or the *Emoji* or the *Slogan* from the *EdiPulse* study were much easier to understand as they offered a good glanceable summary of the participant's day. In line with earlier studies [Lazar et al. 2015], participants thus preferred intuitiveness with a possibility of quickly gaining insights into their activities in comparison to exploring graphical data that require numerical literacy and interpretive abilities.

This suggests to us that the material representations should be easy to read and interpret. The embodied information could be as subtle as "I did more physical activity today than I did yesterday." as explored through the scaling of *Frog* or via altering the *Emoji* facial expression from sad to happy. However, the abstract representations might initially require a little effort from participants, as we found in the studies, in terms of (1) understanding which representations relay what information, and (2) how their representations alter their shape with a change in data. Besides shapes, legibility can also be supported through different properties of a material such as color, and texture.

While deciding the legibility of material representations, it is also crucial to understand the context in which the material representation will be placed. An individual might desire more abstraction and privacy in a public setting, whereas the same individual might appreciate a more detailed mapping between the data and material representation to enable an in-depth understanding of the self in a private setting. We will discuss this further under the *Pairing* theme.

7.7 Outcome: Utility

The third card in the *Outcome* category is *Utility*. This card relates to the additional utility value that material representations offer besides serving the main purpose of providing feedback on physical activity. The hypothesis here is that if the material artifact affords different purposes in everyday life, such as serving as a decoration piece, or a domestic appliance, or a personalized gift, it would then offer more avenues for the user to interact and engage with them. We agree with Verbeek [2005, p. 226] when he suggests, "Products to which people develop an attachment are not generally as emotionally charged and irreplaceably present as heirlooms, but neither are they as anonymous as a throw-away item...what distinguishes these goods from our most loved possessions is that they are used rather than cherished." Brown [2001] similarly proposed Thing Theory as a way to examine human–object relationship, highlighting the fact that insignificant objects can become objects of significance from their misuse or repurposed use. An interesting point to note here is that the user may not necessarily utilize the material artifact in accordance with the use expected by the designer. Our studies identified that users often bring their creativity and imagination into play when adopting material artifacts into their life.

While designing material representations, we had practical utility in mind for most of the representations. In *SweatAtoms*, we designed the *Frog* to serve as a decorative object, while we designed the Ring and *Flower* to serve as fashionable jewelry. The use of sports drinks and chocolate in the *TastyBeats* and *EdiPulse* studies naturally served the purpose of drinking and eating, respectively. Interestingly, their use as a representation of data also altered participants' snacking habits, where participants refrained from eating other foods and the prepared sports drink and chocolate treats became their first source of post-exercise energy. We found that participants appreciated artifacts that had an explicit purpose. For instance, the *Flower* and *Frog* were displayed in the surroundings as adorable decorative pieces. Some participants also wore the *Flower* as jewelry and gifted some of their artifacts to others as "a token of their heart."

Participants also invented new uses for the artifacts in accordance with their needs and creative abilities. One participant turned the *Flower* model into a floating candle holder, which would allow candles to float on water, whereas another participant stacked his entire set of *Dice* models in the form of a skyscraper, publicly advertising his physical activity performance. One participant even transformed all of the constructed artifacts into a clock to be used as a decoration. However, for representations such as the *Dice* and *Graph*, participants had a difficult time identifying use beyond visualization, suggesting that their relatively fixed design did not leave many opportunities to come up with alternative use scenarios. For instance, one participant said that, "although the Graph looks pretty and gives me insights into my activities, it's quite hard to know where I could possibly use it, maybe if the Graph had some form of locking mechanism on its ends, then it could have been used as a bracelet."

Participants' reactions to material representations created with consumable materials like food were quite unexpected. Since food is something that is generally shared, we thought that participants would share their drinks and chocolate treats with other family members. As we explained in the *Personalization* theme, the embodiment of personal data in these artifacts allowed participants to treat these representations as their own personal, well "earned" treats and most participants refrained from sharing them with others. In a few instances, chocolate treats were eaten by participants' family members, but the main reason was so that participants did not wanted chocolate to go to waste.

The chosen design of the material representations is also important in defining its use. The chocolate treats from the *EdiPulse* study were very thin and followed a spread out layout on a baking paper. If these chocolate treats were thicker in size, participants could have thought of wrapping them in paper without breaking and possibly sharing them with others as gifts, similar to what we observed in the *SweatAtoms* study. However, thinner, spread out patterns of chocolate meant they are easier to consume than to share.

We also draw designers' attention towards inherent needs and how we could utilize material artifacts to support them. For example, fluid materials composed of electrolytes can help in replenishing loss of bodily fluids from prolonged physical activity, whereas materials like wool or cotton sportswear [Genc et al. 2018] can support persistence in physical activity under different weather conditions (hot or cold weather). A representation constructed from such materials that serve a certain use thus could offer an extra support to the user in achieving their goals.

To conclude, designers should consider additional utility for the material representations. Having these additional uses prescribed in the design could increase user's interaction with the artifacts and thus support the main purpose and overall engagement with the material representations. However, care needs to be taken since the additional utility should not overcome the main purpose of the representations. For instance, printing thicker chocolate treats to serve the purpose of personalized gift is fine but making chocolate thicker would mean an increase in amount of chocolate and thus calories.

7.8 Outcome: Pairing

The final card in the *Outcome* category is *Pairing*. This design theme is concerned with the context in which the artifact resides and highlights the importance of designing artifacts that can easily participate or complement the existing schema of things. Jung and Stolterman [2012] emphasized that the use and ownership of artifacts is interleaved with the underlying context and surrounding in which they are placed. In keeping with the previous theme "utility," this theme identifies how individual's interactions with material artifacts and their creation process differ in different environments. It also draws parallel with the concepts of "space" and "place." Dourish [2006, p. 299] explains, "space" is a geometrical arrangement that might structure, constrain, and enable certain forms of movement and interaction whereas "place" denotes the ways in which settings acquire recognizable and persistent social meaning in the course of interaction.

Goffman [1959] attributes humans as actors that take on various identities for different audiences, and where the goal of social interaction is to seek approval from these audiences. Borrowing Goffman's analogy of the public and private stage (ibid), there is a clear distinction in terms of how an individual presents himself to others in a public or private setting. A material representation, similarly, has a different role to play in a public and private context. According to Verbeek [2005], artifacts adjust and act according to the environment in which they were situated. Similarly, Latour [1999] suggests that artifacts work in close relationship with people and other artifacts, creating networks that shape each other. It is therefore essential to customize and design such representations that can cater to a particular context of use and participate in existing schemas. For example, placing a material representation within a home must satisfy existing aesthetic details and surroundings, while an object that has been designed to be worn should complement the personality, body type, and dressing style of an individual. The findings of the *SweatAtoms* study revealed that one of the reasons why participants appreciated the *Frog* and *Flower* over other representations was that participants found immediate applications and places where they could place these representations. For example, the *Frog* was placed on the top of a computer screen and the *Flower* was used as a coaster on the dining table. Participants expressed this was because the color, design, and shapes of these artifacts complemented their homes. As such, the suitability of the material representations, in pairing with existing decorations, was strongly dependent on the physical characteristics and the type of material used. For example, participants did not appreciate the *Ring* model mainly because they did not enjoy wearing plastic rings.

When considering the pairing, it is not just the material representations that need to be considered, but the systems that create them must also match the existing environment. For instance, while *SweatAtoms* resided in the lounge room of participants, *EdiPulse* and *TastyBeats* found their place in participants' kitchens. Participants expressed interest in making the 3D printers appear less mechanical so as to fit in with the ambiance of the home. For *TastyBeats*, participants wanted to make it a part of their refrigerator, allowing them to receive their sports drinks when needed, and keep all the drinks fresh and tasty. Interestingly, *TastyBeats* grabbed different levels of attention in private and public settings. For instance, when *TastyBeats* was used in a public setting [Khot et al. 2015], with several viewers watching the user interacting with the system, spilling of water was considered fun because it did not require any cleaning up from the users afterwards. By contrast, when *TastyBeats* was placed in the home setting, spilling was an annoyance, as it required extra time and effort to clean. To this end, we encourage designers to think carefully about the environment and the process they use to create material representations.

The final point to discuss in *Pairing* is the difference in the level of abstraction required to map the data into material form. For instance, in a public context, an individual would desire more abstraction to maintain privacy of their data whereas in private setting, an individual might be inclined towards more of an informative representation. In order to create varied levels of abstraction, designers can explore different properties of a material such as color, shape, texture, and design. Additionally, abstraction can be explored through multiple layers where multiple material artifacts, each carrying a different dataset, can be joined together to reveal more insights about an individual's active life [Khot et al. 2016].

Next, we describe the three cards from the *Material* category as shown in Figure 15.

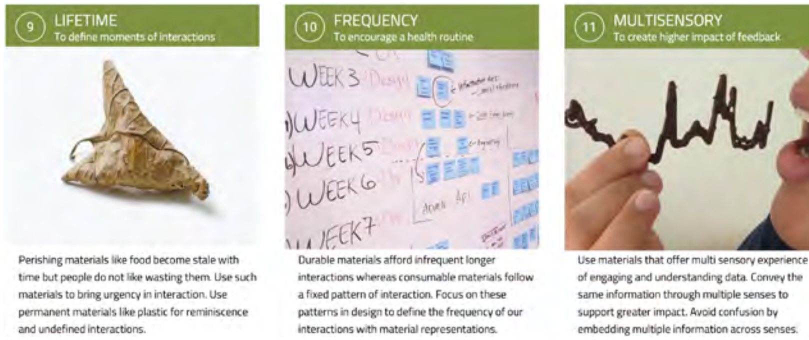

Fig. 15. The three cards from the *Material* category are: (1) Lifetime, (2) Frequency, and (3) Multisensory.

7.9 Material: Lifetime

The first card in the *Material* category is *Lifetime*. This design theme draws designers' attention to the ageing property of the material artifacts and its effect on an individual's relationship with them. Previous literature on archiving suggests that material artifacts have a longer life and are more valuable in personal life than their digital counterparts [Petrelli et al. 2008; Kirk and Sellen 2010]. These artifacts can gain value by progressive appropriations, that is, their value increases over time and even if they become worn or cracked, they continue to be the prized possession of owners [Lee et al. 2015].

The study of *SweatAtoms* highlighted that users appreciated the use of durable material such as plastic that could resist wear and tear. They treated these artifacts as a token of embodied memory of their physical efforts and because of the durability, these artifacts were easily carried and displayed. However, with physical artifacts, there is also a fear of wear and tear, breakage or spill (as identified in case of *TastyBeats*). Technologies like 3D printing are advantageous here so as to create a new copy or a patch for the broken one. Such technologies also allow creation of replicas, giving the artifact a sense of "placelessness" [Odom et al. 2011]. In other words, the possession of a physical artifact is not limited to a physical place in which it is created and used, rather one can create a replica of a beloved material artifact at a newer place or in situations of breakage, theft, and where the owner forgot to bring the artifact with them. However, this act also raises questions of identity and authenticity. One could relate this to "Theseus's paradox," which discusses the paradox of body vs. soul, i.e., it is questioned whether the ship that all its part had replaced over time was still the same ship or not. Secondly, this act raises concerns around sustainability. For instance, a durable material artifact works well as a souvenir of a precious moment or achievement, such as competing in a marathon. Since these material artifacts stay with participants for longer, they afford a greater chance of reminiscence and reflection upon their efforts. However, if material artifacts are made daily for all forms of activities, then there is a question of responsibility in creating and destroying them properly, since not all materials are biodegradable.

One of the main benefits of using digital media for representations lies in its dynamic properties: most data visualizations work supports runtime updates whenever new data are received. These visualizations allow users to manipulate the view to match their interest. Material representations that are created using durable materials are different in that they are static and hard to update once they have been printed, meaning that one must print a new representation whenever new data are generated.

For the *SweatAtoms* project, we made use of biodegradable materials like polylactide for the 3D printing of material artifacts. This compostable plastic material is certified to European Standard

EN13432 and shown to break down in less than 12 weeks under industrial composting conditions. However, this material's ability to break down quickly in a natural environment is not yet known and not thoroughly studied [Thomlinson 2019]. As such, its use could be problematic if care is not taken to recycle it correctly. A solution to this could be to use more sustainable materials for printing and to offer clear guidelines on not only how to use the material but also how to recycle the material correctly.

Selective printing is also an option to address environmental sustainability. For example, designers can choose one type of material representation for a specified goal and once this goal has been achieved, a new representation could be unlocked, following well-known gamification principles, e.g., unlocking new levels or badges after attaining specific achievements. Designers could consider creating dynamic material representations that augment themselves over time rather than printing new artifacts each time.

Using perishable materials like food can also tackle some of the problems associated with sustainability. However, artifacts created using perishable materials like chocolate or energy drinks exhibit interactions of an ephemeral nature, i.e., once material representations are consumed, they can no longer be accessed. In a way, the "prize" for activity fades from sight. This dynamic works well in situations where users do not want to keep a record of the data, possibly of a sedentary day, when they were unable to achieve their fitness goals.

While using food as a material to represent data, designers can also leverage the fact that people do not like to waste food. In the *EdiPulse* and *TastyBeats* study, we found that the prepared drink and created chocolate treats were almost always consumed, if not they were preserved for later consumption. Participants were very careful to use the supplied food ingredients (different flavors of juice and chocolate bars) and made certain to use the leftover materials the following day. Designers might harness these qualities to allow individuals to pay attention to their data.

Designers could also mix and match different types of materials to enhance the user experience. One possible option could be that participants print plastic-based representations on successful completion of major milestones (e.g., a marathon) in order to preserve the memories whereas perishable materials may be used to encourage participation and to reward progress towards goals.

7.10 Material: Frequency

The second card in the *Material* category is *Frequency*. It describes how often the material representation should be constructed. Identifying the correct frequency of feedback is challenging because although frequent feedback is considered ideal to support behavioral change (if behavior change is the goal) [Hermsen et al. 2016], earlier research highlighted that constant feedback and repeated emphasis on achieving health goals can reduce user's motivation for physical activity [Berry and Latimer-Cheung 2013].

A digital representation on a smartphone, for example, affords multiple moments of engagement as most users carry such devices with them and frequently interact with them. By contrast, an individual's interaction with durable physical artifacts is often ad-hoc, as these artifacts tend to disappear in their surroundings [Miller 2010]; however, once noticed, these interactions with physical artifacts may last longer. This was observed in the *SweatAtoms* study, where the material representations remained mostly in the background (in places where users preferred to keep them) and came to foreground when visitors noticed them. They then became conversation pieces and participants were happy to explain their meaning to curious visitors and relatives.

Perishable materials like food on the other hand inhibit a scheduled pattern of interaction, for example, most cultures consume three meals a day. Once the satiety level is reached (i.e., people are satisfied and full), food is no longer consumed. As a result, there is lesser interaction with the material. For example, a couple of participants in the *TastyBeats* study mentioned that receiving a flavorful drink is ideal mostly when one is thirsty. Receiving a drink or other foods when one is already full might not be that tempting. In such situations, designers must pay attention to the amount so as to cater to satiety levels. Besides satiety, people follow and adopt different patterns of consumption based on social and cultural preferences [Cialdini 1998]. For instance, many people drink two cups of coffee in a day, some drink tea before going to bed. Consumption of food comes with a recommended set of guidelines, for instance, an adult should drink eight glasses of water each day, therefore designers should take these patterns of interactions into account to best utilize available opportunities of engagement.

In all three systems, the printing and interaction with the material artifacts occurred in the evening. Participants enjoyed this scheduled pattern of interacting with their data: monitoring during the day, loading their data into the system in the evening, printing the artifacts, and subsequently consuming them. With *EdiPulse*, participants also refrained from eating other sweets during the day and waited for the "deserving" treat of chocolate in the evening. Despite the chocolate being so accessible to them, none of the participants felt tempted to eat the chocolate at other times, instead choosing to interact with the chocolate only when it was offered through the *EdiPulse* system. In *TastyBeats*, we found similar traits of behavior from participants. Even after heavy exercise, participants were happy to wait for the interaction of *TastyBeats* to complete before quenching their thirst with a well-deserved drink. A couple of participants also said that the study nurtured healthy eating habits, where instead of eating something unhealthy as a snack, they were happy to wait until the evening where they got what they considered to be not only a healthy drink, but one that was tailored to the amount of exercise they did that day. Drawing on this, we believe utilizing materials with inbuilt necessity could not only positively reinforce users in achieving their health goals but can also influence their interactions with the materials.

The frequency of our interactions with physical materials highlights the need to think about how frequently we should offer users material representations. The material representation can be printed and received each day, week, or month but there is an associated cost and effort. For instance, in the *SweatAtoms* study, participants printed their representations each day for the purpose of the study. Participants mentioned that printing these artifacts daily was not only time consuming but also diminished the value of the artifacts. Instead they would have chosen to print their representations on days when they achieved their goals as discussed under the *Lifetime* theme. On the other hand, perishable materials like food can be good for scheduling feedback on self-monitored data in fixed intervals, for example, around meal times as identified in the *TastyBeats* and *EdiPulse* study. Structuring interactions in such a way also means that feedback on data is not immediately available but rather is delayed to a certain time of the day, which can be appreciated when supporting slow reflection on data.

7.11 Material: Multisensory

The final card in the *Material* category is *Multisensory*. It describes the way in which multisensory properties of materials could be utilized to enhance an individual's engagement with the representation by making the experience of re-living physical efforts more cherishing and evocative.

Previous research advocates the use of multiple modalities not only to grab a user's attention, but also to reduce the cognitive load associated with using only one modality—typically visual [Obrist et al. 2016]. Additionally, the interplay of different senses can make the experience long lasting [Hekkert 2006], thereby, creating a greater impact on a user's motivation. For instance, the addition of a pleasant fragrance can create pleasurable memories related to physical activity that the user could later cherish. A material representation, in comparison to a digital on-screen representation could thus be more advantageous as it affords the possibility of multi-sensorial engagement with the data.

An essential aspect of the multi-sensory experience however is that all the senses should communicate the same message [Hekkert 2006]. In cases when different senses communicate a different message at the same time, the overall experience is not pleasurable since users will not be able to focus. The cosmetic industry draws on this to provide a prospective buyer with a positive multi-sensory experience through a harmony of color, texture, and smell in its packaging [Ludden et al. 2006]. Within the field of physical visualization, Houben et al. [2016] developed the *Physikit* system that represents environmental data using various modalities such as light, vibration, movement, and air flow. We drew on these works to offer a harmonious experience of engaging with the data through the amalgamation of different senses. Let us first describe the importance of how material artifacts look.

The three studies highlighted that the visual aspect of material representations was crucial to contributing to a positive experience. In *EdiPulse*, we found that participants wanted appealing and perfectly printed activity treats and, in this pursuit, they were happy to perform multiple prints if the initial print was not as good as expected. We also found that irrespective of their activity levels, participants were motivated to print their activity routines daily. Similar results were found in other two studies. In *SweatAtoms*, the cute looking *Frog* was appreciated mainly because it always printed well, without any rough edges or extra lumps. With *TastyBeats*, participants enjoyed the use of visually appealing interactive fountains to create a sports drink and found it integral to the overall experience.

Besides the visual, other sensory characteristics of the material came into play during the construction process. For instance, in *SweatAtoms*, we utilized plastic material, which caused a slightly striking smell during the printing process that participants found a little unpleasant. The unpleasant smell along with the mechanical sound of the 3D printer did not invite the participants to become engaged in the construction process. However, the results were quite opposite in the *EdiPulse* study, where participants enjoyed both the smell and the printing sound of the printer. The sight and smell of the chocolate being slowly overlaid on the print bed further added to the sensorial experience. The *EdiPulse* study thus highlights the importance of an appealing multi-sensorial material such as food to represent data, because participants found the sight, smell, and the taste of a beautifully printed chocolate difficult to ignore. As such, we found that the interplay of these senses had a significant impact on the overall experience.

Next, we look into the tangible properties of the chosen material. According to Zhao et al. [2008], tangible qualities can be split into the following four dimensions: (1) geometrical dimension: e.g., volume, shape, or texture; (2) physical–chemical dimension: e.g., color, weight, temperature, hardness, or moisture; (3) emotional dimension: e.g., comfort and elegance; and (4) associative dimension: subjective comparison to existing things of the perceiver's experience, e.g., tangible qualities such as feather-like or silky touch. In terms of the tangible qualities, the material artifacts from the *SweatAtoms* study had a rigid and firm feel when touched, whereas in *EdiPulse*, the chocolate treats had a softer texture. In terms of geometric dimension such as volume, both systems followed a simple mapping where the size of an artifact increased based on the amount of activity. In terms of physical–chemical dimension, *SweatAtoms* gave users the option to choose plastic filaments from a set of colors (red, green, blue, yellow, and white). Participants liked the option of changing filaments as it helped them to segregate and categorize artifacts from different days.

Finally, in this work, we not only considered altering the visual forms of material representations, but also features such as flavor, aroma, and texture [Obrist et al. 2016], which could be explored to support pleasurable interactions with material artifacts. The ongoing research in digital fabrication [Bader et al. 2018] might unveil new ways to incorporate tangible properties into

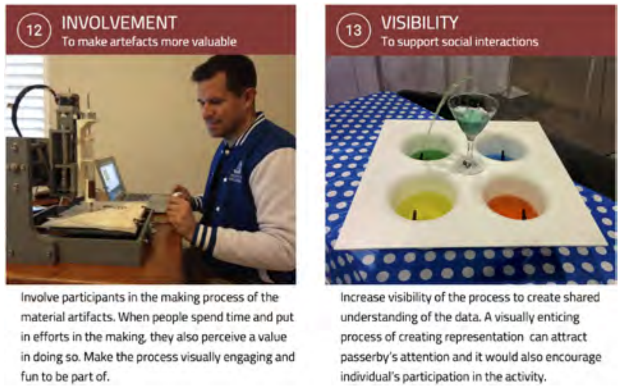

Fig. 16. The two cards from the *Process* category are: (1) *Involvement* and 2) *Visibility*.

the design. Finally, we conclude with the two cards belonging to the *Process* category as shown in Figure 16.

7.12 Process: Involvement

The first card in the *Process* category is *Involvement.* This card is concerned with aspects related to the physical creation of the artifacts, which include time and effort on behalf of the user, making it an important catalyst to the decision-making process. Next, we outline several advantages of involving users in the creation process of artifacts.

As Jansen et al. [2015] have argued, the assembly and manufacturing features of material representations can play an influential part in engaging participants with their data. Involving users in the creation process can support meaning making and reflection [Nissen and Bowers 2015]. Nissen and Bowers [2015] refer to such activities as "participatory data translation." They argue that by involving people in the creation process, the constructed material artifacts appear less "alien" than mass-manufactured artifacts [Lupton 2017]. Earlier research [Ananthanarayan et al. 2016; Thudt et al. 2016] highlights that physical artifacts become mementos by virtue of the time and emotion invested in them by their owner. Creating an artifact can be an enjoyable experience, giving individuals the feeling of wonder, agency, and satisfaction [Gauntlett 2013]. Thus, it is not usually the physical characteristic of the artifacts that make them biographical, but the meaning imbued by users as their significant personal possession.

In all three studies, participants utilized the printing duration as a time to reflect on their exercise achievements for that day. In the *TastyBeats* study, participants found the interactive process of creating a sports drink as rewarding as consuming the drink itself. In *EdiPulse*, all the participants liked the sound of the printer. We believe that the perceived value of the material representation among the participants also increased with the time they waited for the printing to end. The slow reflection on data in terms of the printing process was considered a valuable part of the overall experience. In particular, with *EdiPulse*, we found that participants cherished the printing process almost as much as the consumption afterwards. Participants felt that the benefits like the excitement of seeing their data in an edible form were bigger than the duties they had to perform. To this end, involving users in the creation process of material representations was found advantageous as this gave users more time to anticipate and reflect on their data, thereby possibly increasing the potential value of these representations.

With all three of our systems, participants also enjoyed creating the artifacts in their own homes as it gave them agency and could be achieved at times convenient to them. For example, in *SweatAtoms* and *EdiPulse* study, representations were created in front of their eyes, which gave them some sense of ownership over their data and the final material product. We do acknowledge here that purchasing and using 3D printers to print material artifacts at home might not be possible for everyone because of the associated costs as well as efforts, but this is only one of the possible uses of the presented systems. Participants can also make use of increasingly growing makerspace culture [Hudson et al. 2016], to find a 3D printing hub in the neighborhood or library to construct these artifacts.

It is important to make the process fun and engaging, for instance, in the *TastyBeats* study, participants liked how a drink became a celebration of their physical activity, giving them an opportunity to express themselves in front of other members of the households. As a result, participants were tempted to try out new forms of physical activity and be imaginative and creative with their exercise patterns. This is in line with Goffman's theory, which says that any material representation, if put on display, becomes the public representation of the self and craftsmanship [Goffman 1959].

Involving users in the creation process requires that the user has access to necessary hardware and materials at home, as well as the time and skills to create material representations. Efforts are also needed on the behalf of the designer to ensure that the process is user-friendly and less prone to error. However, the process need not have to be 100% error free and it could allow some ambiguity, for example, in *TastyBeats*, improper handling of the system caused accidental spilling and a mess on nearby surfaces. On the one hand, participants welcomed this mess as a dramatic outcome of the playful interaction; while on another hand, it also challenged their notion of playing with consumable materials as for some of them food is mostly a forbidden object to play with. Designers should consider the cultural beliefs of participants when designing certain playful interactions around the use of consumable materials or to offer multiple methods of interactions with the artifacts.

We draw designers' attention to four factors that can make the process of creating material representation engaging. These are the: (1) sound of the machine; (2) choice of the representation; (3) surprise element due to the non-linear printing of representations; and (4) pleasant smell of the material. The interplay of different senses, together with slow reveal of data facilitated by non-linear printing lends itself to "savoring" [Bryant and Veroff 2007]. Savoring aims to prolong and intensify the enjoyment of a consumption experience by drawing attention to sensory aspects of the experience that might otherwise be missed (ibid). Learning from these insights, we encourage designers to accommodate both printer and food characteristics to engage users in the printing process.

7.13 Process: Visibility

The final card in the *Process* category is *Visibility*. This card highlights the consequences of improving the visibility of the data and making it more accessible to bystanders, families, and co-located individuals. In the previous theme "involvement" we saw the merits of involving users in the creation process of the artifact. This theme takes involvement a step further and encourages involvement of bystanders, families, and co-located individuals to elicit further engagement with the data, drawing on the literature on social norms [Cialdini 1998].

According to social norms theory, our behaviors are shaped by the behaviors of our family, friends, and people we work with [Cialdini 1998]. By involving others, we can therefore potentially increase the chances of building a sense of commitment which can likely lead to a change in behavior. Drawing on this, many tracking devices already allow and encourage social sharing and comparison of the tracked data, by employing gamification strategies. However, the sharing of data is distributed over the internet, with little data shared among co-located individuals. Material representations given their tangible nature, afford the possibility of encouraging and supporting interactions among co-located individuals as identified in the three studies. Improving the visibility of data and its accompanying processes can also enable glanceable mode of feedback [Gouveia et al. 2015], where users can have frequent yet brief interactions with the data.

In all three studies, the systems were deployed in people's home and participants kept these systems visible to everyone. For example, the *TastyBeats* and *EdiPulse* system were kept on the table or a bench in the kitchen space whereas *SweatAtoms* occupied a space in a living room. The creation of artifacts occurred in the evening when most members of the family were at home. For instance, in *EdiPulse*, most participants printed chocolate shortly after their supper whereas in *TastyBeats*, the drinks were prepared earlier in the evening.

The visibility of the systems and the processes made it possible for others to notice the data: it served as a conversation piece between participants and the observers. Participants found watching the preparation of the drink in *TastyBeats* to be one of the best parts of using the system and were keen to watch the creation of their partners' drink in order to compare their relative amounts of physical activity that day. Often the drink was made with both participants present and, through watching the making process, each participant became more aware of each other's physiological state, which in turn triggered discussions and playful social interactions. Interestingly, even the non-study family members were intrigued by the idea of seeing the data in a visceral form and their involvement in the process further supported participants. These findings correlate with the work on family-based reflection [Grimes et al. 2008] where healthy competition in a family setting led to enjoyment and motivation towards physical activity. In EdiPulse, the ad-hoc printing of the treats glued participants to the printing site and they treated this activity as a game. Although the preparation in terms of getting the chocolate ready for printing was felt to be laborious, participants' interests in printing sustained throughout the study. In the *SweatAtoms* study, we witnessed a prevalent behavior of "showing off" with the material artifacts of their exertion. The artifacts were intentionally placed where they could be noticed by others, for example, on the computer screen in an office space. These artifacts generated a sense of curiosity and sparked conversations among the visitors who did not know what the design actually meant. Participants were enthusiastic about explaining the meaning of the artifacts to inquisitive visitors. To this end, the material artifacts become "Social objects" [Latour 2005] that got people talking, communicating and connecting.

Besides showing off, gifting of material artifacts was also commonly observed in *SweatAtoms*. Sharing of one's physiological data is now possible with current physical activity trackers, and this opportunity illustrates how material representations of one's physical activity can extend their value beyond the self. This is also possible with sharing virtual badges; however, here they have more meaning as they cannot just be copied, but by gifting, one person always loses something: maybe add that point, creating important mementos for not only the individual, but also their loved ones. In much the same way that loving parents collect their child's handprints, or record their child's movements, material artifacts create a snapshot of an individual's bodily activities in a memorable souvenir. We imagine that, in a near future, someone could view this artifact as a memento of one's bodily aspirations and exertion. Drawing on these findings, we encourage designers to make the process of creating material representations visible. As we identified in the three studies, the visceral process of creating material artifacts can play a crucial role of social catalyst, inviting conversations around the data and its creation process. The public display of physical activity data however could lead to issues around data privacy, which can potentially be dealt with abstract forms of visualizations as explained in *Personalization* and *Readability* themes.

8 USING THE *SHELFIE* FRAMEWORK

The *Shelfie* cards can be used individually or in a group to ideate on new concepts for material representations as well as to analyze existing design choices. There is no predefined order to use these cards nor is it necessary to use all the cards in a design project. The cards can be deployed and used in a design project in a flexible manner. Below we describe one possible way of using these cards as used during the ideation of the design of sports souvenirs [Khot et al. 2016]. The design team were tasked with the idea of coming up with material representations of individual's tweets during a sports match. The research question was to understand how and why individuals leverage social media data to support and discuss an ongoing sports event and how the introduction of personalized souvenir would alter their existing relationships with social media and the corresponding sports event.

The design team consisted of five people with varied academic backgrounds, comprising of academics as well as professionals. Their age varied from 21–40 years and they shared their experience of interacting with the framework through verbal conversations.

Before we began the ideation process, we kept the cards on a Lego board (38cm × 38cm) in a spread-out manner with each card "face up." The intention behind this was to ensure that the cards are visible and quickly accessible at all times during a design ideation. Such an arrangement of cards is partially inspired by the popular board game *Guess Who*[8] and it allows the designer to easily view all cards at once. We also provided designers with paper and pens to sketch out their ideas for the design.

After briefing, participants started working on the cards. We observed that the participants did not follow one particular order but rather picked cards in an ad-hoc manner. Once any card was picked, it was discussed among the team, particularly how it would help in the design. We observed that all the cards were picked and discussed at least once. Some cards were picked again and contributed more discussion in comparison to others.

Understanding the cards was easy. However, participants felt some constraints with the design choices, which lead to discarding some of the design ideas. For example, some participant wanted to incorporate commercial aspects (production and delivery cost), but the current framework did not support that. Participants however enjoyed working with the cards. One participant said "the tangible aspect of the framework is great. Using cards and the Legos, you can construct things and give shapes to your ideas." Various ideas emerged for the possible souvenirs as shown in Figure 17. Each individual sketch was influenced by existing understanding of the game and knowledge of known sports souvenirs. Many of them were quite detailed, featuring innovative ideas around the physicality of the artifact and the key aspects of the game. The final outcome was *Fantibles* [Khot et al. 2016] that highlighted an individual's commentary about sports on Twitter along with the uniqueness of each sports match. Table 3 shows how the *Shelfie* cards helped in shaping the design of *Fantibles*.

Next, we describe how Shelfie cards could be used to reflect on the existing project on data materialization such as "Love Project."[9] In "Love Project," heart rate, electroencephalogram (EEG) waves, and voice data are used to construct physical manifestations of people's love stories.

In this project, designers invited participants to an exhibition, where participants were asked to narrate their love stories while equipped with the different sensors. The captured stories were 3D-printed in real time to produce unique souvenirs that participants took home. We could use *Shelfie* cards to analyze the design and how some of the themes might be relevant here.

[8]Guess Who board game: https://www.boardgamegeek.com/boardgame/4143.
[9]https://gutorequena.com/love-project.

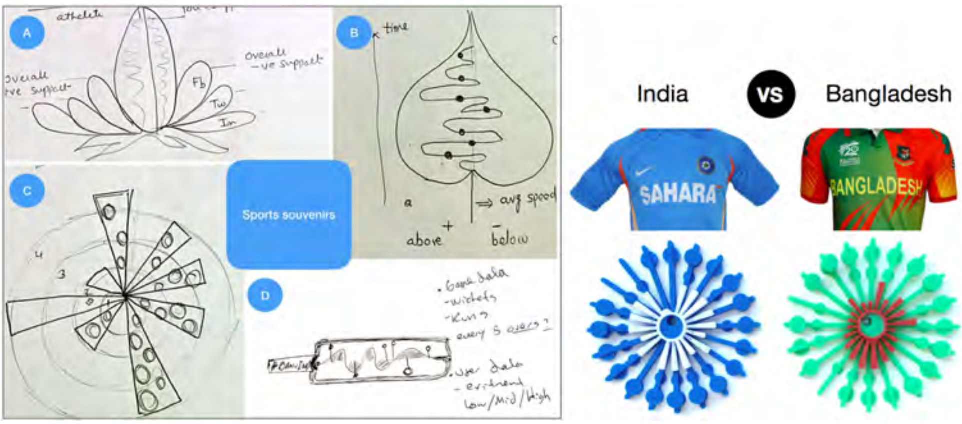

Fig. 17. (1) Ideas for the sports souvenirs based on individual's tweet data: (A) Lotus, (B) Leaf, (C) Flower, and (D) Bat; (2) Final design of *Fantibles.*

Table 3. Using the *Shelfie* Framework to Create Sports Souvenirs

Design card	**Description**
Purpose	To make home sports viewing pleasurable through tangible souvenirs.
Framing	Inclusion of both positive and negative memories of the match but in an abstract manner.
Personalization	Use of team jersey's colour to match the printed souvenir, focus on individuals' tweets along with sports data.
Timing	Printing of the souvenirs after the match is over.
Newness	Use of generative design based on the individual's tweets and sports data, which changes with every match.
Readability	Distribution of information across multiple artifacts that interlock with each other.
Utility	To be used as sports memorabilia.
Pairing	With magnets, so that *Fantibles* can be placed on the fridge door.
Lifetime	Focus on durability hence use of plastic.
Frequency	User defined and one per match.
Multisensory	Focus on tangibility.
Involvement	Printing at home after the match.
Visibility	Placements on fridge doors for visibility.

Next, we describe how the *Shelfie* cards could be used to inspire a new design around data materialization of physical activity. We call this envisioned design "*Jogging Physicalization.*" In "*Jogging Physicalization,*" we represent a jogger's pace using an edible material trail of different height, which is then overlaid on a map that shows the path of the jogger's route. The design also features edible monuments 3D-printed in Marzipan (Figure 18) that show important milestones on the journey with an aim to congratulate users with a small edible treat for completing that milestone. This design provides joggers with an alternative representation of their physical activity data that can be seen in a physical space and also be eaten in comparison to the prevalent information display as known from jogging support apps on mobile phones.

Table 4. Using the *Shelfie* Framework to Analyze "Love Project"

Design card	**Description**
Purpose	To create unique physical souvenirs from one's love stories (more precisely, from one's narration of their love stories).
Framing	Focus on positive memories (however, it might be contextual depending on one's narration.
Personalization	Personalization is achieved by looking into the unique characteristics of one's biofeedback (EEG, heart, and voice), similar to the Flower model in *EdiPulse* and *SweatAtoms* project described earlier.
Timing	Printing happens after one completes the narration of a love story.
Newness	Use of generative design based on the individual's EEG, heart rate, and voice data, which may change with individuals as well as the narration.
Readability	Mapping EEG, heart rate and voice data to particle waves, where acceleration is used to denote sound amplitude and beats per minute while an upward force, attraction, and repulsion of particles is used to denote low gamma and beta values and level of attention and disattention among participants during narration of their love stories.
Utility	To be used as a souvenir or a jewelry piece.
Pairing	Even though the design pattern is fixed, given the focus is on jewelry and wearability, the individual's preferences could influence the choice of colors, size, and material.
Lifetime	Focus on durability hence use of plastic or other durable materials such as different metals.
Frequency	User defined and one per narration.
Multisensory	Focus on tangibility and haptics; no other senses are accommodated.
Involvement	Involvement is minimal in actual printing, but similar to *SweatAtoms*, participants could do printing at home to construct souvenirs of their love stories.
Visibility	Given the focus on making a data-driven personalized jewelry piece, the emphasis is on public visibility and using the artifact for self-expression.

Fig. 18. Jogging Physicalization features edible monuments, 3D-printed in Marzipan that showcase achievement of important milestone on jogger's path.

Table 5. Using the *Shelfie* Framework to Inspire "Jogging Physicalization"

Design card	**Description**
Purpose	To create physical representations of one's jogging route and associated pace at any point on the map.
Framing	Focus on reflection of past athletic performance and plan future performance as well as to highlight achievement of important milestones.
Personalization	Personalization is achieved by sensing map and pace data.
Timing	Printing happens after the jog is completed.
Newness	Use of generative design based on the individual's map and pace data and positioning of the milestone monuments.
Readability	Mapping location to a miniature map, extruded with pace data, which then sits on top of the map data. Special monument design that denote achievement of a milestone.
Utility	To be used as a planning tool for future jogs and souvenir of past jogs.
Pairing	N/A
Lifetime	Probably only "remarkable" jogs will be printed, such as personal bests.
Frequency	One Physicalization per jog.
Multisensory	Focus on haptics as well as gustation.
Involvement	Involvement is minimal in actual printing, this could be even shipped to the person's address, so printing could be outsourced.
Visibility	The relative small size will make the Physicalization mostly visible to the jogger and his/her immediate personal contacts, for example, when visiting his/her home.

9 CONCLUSION

In this work, we presented *Shelfie*, a design framework that contributes to the emerging research field of material representations by unfolding a rich design space as outlined across 13 design cards. This framework provides a foundation for investigating not only critical design elements but also the meaning and relational effects of material representations and the representations' context of use. It provides an analytic lens with which designers can consider digital fabrication as a design resource for materializing personal data. This understanding was accumulated through theoretical grounding from related fields together with designing, studying, and analyzing three different systems that explore different types of material representations.

The proposed design cards could inspire designers to consider different ways of creating representations to offer greater reflection on data. We anticipate that designers can utilize these cards not only in the context of physical activity and self-monitoring, but also in other areas where personal data are of interest e.g., recommendation systems and food and nutrition. The presented design cards can be utilized during the ideation phase in order to come up with new design possibilities, as well as in the iteration phase where the cards could help designers in refining initial designs. Researchers could also make use of these cards to sensitize concepts and insights from the gathered data on studies of material representations. We make a note that these cards were created from the design and study of three systems, two of which focused around digital fabrication process. We invite future research towards extending these themes to other contexts and by discussing other methods (e.g., CNC milling and laser cutting) of creating material representations.

Self-monitoring is a persuasive and powerful tool for reflection and increasing awareness of the self. However, state-of-the-art technology still requires a lot of effort, engagement, and knowledge to interpret the collected data. As a result, despite the technological improvements and popularity, ensuring long-term user engagement with these devices is still a significant challenge. For example, Velayanikal [2014] reports a dropout rate of nearly 85% for such devices. Creating new tools and investigating representation strategies could assist in getting past these hurdles and in that way could also provide active support for self-improvement. The use of different physical materials to represent self-tracking data can create new possibilities and challenges for HCI researchers to push the field forward. Through these cards, we initiated a discussion on how material representations can influence the self-tracking practice and, in turn, how the self-tracking practice can contribute to the field of material representations.

The framework is derived from the design and study of three systems. Each of the presented systems was studied with a small sample for two weeks. Longer trials of the systems could have raised other important issues in terms of sustainability and long-term engagement with one's artifacts and may have contributed more themes or insights into the framework. For instance, could the novelty of individually mixed sports drinks or chocolate treats pale over that kind of time? Would it give rise to rebellion and rejection as commonly observed in the use of wearable tracking devices? These are all valid questions and need to be answered through long-term deployments.

Besides, the three systems discussed in this research are designed with predefined algorithms that measure heart rate and translate this data into some material form. This designer-oriented view may limit or may not fully support autonomy in creating material representations. Therefore, in future work, we are planning to structure these systems as a creative framework that will allow the users to take up the designer's role and express their creativity with their own designs. We are also planning to evaluate this framework by organizing workshops targeted at design researchers in order to demonstrate the utility of the framework in practice. One research direction we are considering is the Sensory Evaluation Instrument tool [Isbister et al. 2007] in order to reflect on how material representations could support the non-arbitrary manner of expression. We will invite participants to an ideation workshop where they will use this framework to come up with design ideas for a given design task centered around new ways of visualizing physical activity data in material form.

To conclude, we invite designers and researchers—both in academia and industry alike—to think beyond screens when it comes to representing physical activity data. As technology evolves, it is important that we, as designers, harness and explore the exciting opportunities that emerging new technologies like 3D printing and food printing can offer. We encourage design researchers to use these technologies, not just to continue to making representations of data we are used to, but to bring to light invisible and internal bodily data (such as heart rate) and explore the novel opportunities that exist in displaying such information in material forms. We hope this work will provoke thinking in this direction and encourages advancement in the area of displaying physical activity with material representations. To this end, we would argue that the proposed themes not only embark the first conceptualized approach to the design, but also paves the way for future explorations in this context. We look forward to exploring and witnessing new ways of connecting the biographies of the material world with the immaterial world.

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