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Research paper

Tangible data visualization of physical activity for children and adolescents: A qualitative study of temporal transition of experiences

Parisa Eslambolchilar [a,*], Katarzyna Stawarz [a], Nervo Verdezoto Dias [a], Melitta A. McNarry [b], Sam G.M. Crossley [b], Zoe Knowles [c], Kelly A. Mackintosh [b]

[a] School of Computer Science and Informatics, Cardiff, CF24 4AG, UK
[b] Applied Sports, Technology, Exercise and Medicine (A-STEM) research centre, Swansea, SA28PP, UK
[c] Liverpool John Moores University, School of Sport and Exercise Sciences, Physical Activity Exchange, Liverpool, UK

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ABSTRACT

Children and adolescents in the UK are increasingly at risk of significant health problems due to physical inactivity. While activity trackers and fitness applications have focused on addressing this problem in youth, poor wear-time compliance and usability and accessibility issues have been frequently reported in the literature as barriers to engagement. Physicalization of data offers an alternative approach to engage with physical activity (PA). In this paper, we present the results of a seven-week qualitative study with 97 primary and secondary school children (8–14 years old). We took a temporal approach to collect children's and adolescents' perspectives in short video interviews as they received 3D-printed models representing their faded-weekly PA levels. Our findings showed that children's and adolescents' emotional engagement with the models remained high throughout the study, while their reflection on the models and their knowledge of what constitutes PA and its different types evolved over time. The findings from this temporal study suggest that tangible data visualization of PA evokes experiences such as embodied reflection, active learning, emotional engagement, and temporality of PA experience. Therefore, we argue that the motivational impact of regular tangible visualizations as a form of feedback should be considered alongside wearable trackers in addressing childhood inactivity.

1. Introduction

Physical activity (PA) is important for physical and mental health from a young age and physical inactivity is the fourth leading cause of death worldwide (Kohl et al., 2012). The UK Government (U.K. Chief Medical Officers, 2019) and World Health Organization (WHO) recommend that children and adolescents aged 5 to 17 years should do at least 60 min of moderate-to-vigorous physical activity (MVPA) per day (WHO, 2010). Despite this recommendation, inactivity is widespread and childhood obesity and related public health issues are rising rapidly in the UK (Jago et al., 2020). A recent study with more than 2000 British children aged 6, 9 and 11 years (Jago et al., 2020) found that MVPA declines and sedentary time increases on average for all children between ages 6 and 11 years. With latest UK figures showing that around 23% of children aged 4 to 5 years are overweight or obese (NHS Digital, 2018), increasing to 34% of children who are age 11 years, this recent study supports the need to promote and maintain PA as children get older (Jago et al., 2020).

Research shows that wearable activity trackers, their companion apps, dashboards, ambient displays and social media have the potential to influence children's and adolescents' PA levels (Drehlich et al., 2020; Mackintosh, Niezen, & Eslambolchilar, 2016). However, the effort required to wear the trackers or use companion technologies are shown to negatively influence overall engagement with the PA and reduce technology acceptance (Drehlich et al., 2020; Ridgers, McNarry, & Mackintosh, 2016; Ridgers et al., 2021, 2018). Research has also frequently reported poor wear-time compliance for activity monitoring (Attig & Franke, 2022; Clawson, Pater, Miller, Mynatt, & Mamykina, 2015; Tang et al., 2018). Moreover, these devices tend to rely on numbers and graphs to present data on a 2D on-screen display. Whilst screen-based feedback has some advantages, such as being able to access precise and detailed information or historical data, screens demand visual attention and detachment from the physical environment (Jansen, Dragicevic, & Fekete, 2013; Moere, 2008; Stusak, Hobe, & Butz, 2016). To address these limitations and to increase engagement with PA, physical representation of PA data has been suggested and studies have shown promising results with adults (e.g., Khot, 2014; Sauvé, Bakker, Marquardt, & Houben, 2020; Stusak, Tabard, Sauka, Khot, & Butz, 2014).

* Corresponding author.
E-mail address: eslambolchilarp@cardiff.ac.uk (P. Eslambolchilar).

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Physical objects have been used for information presentation for thousands of years, from the Mesopotamian clay tokens to note measures of grains to the Inca rope knots (Quipus) used to keep records and communicate information (Dragicevic & Jansen, 2014; Marín Díaz, 2016). Although physical visualizations (physicalizations) are not new, recent innovations in 3D printers and laser cutters have made the fabrication easier and more accessible. Furthermore, since 3D printers are also getting cheaper, more accurate, smaller, faster, and environmentally friendly, frequent use of these devices in everyday life is expected in the near future (Behm, Waite, Hsieh, & Helmus, 2018). These advances have triggered new interests in the Human–Computer Interaction (HCI) community and have created opportunities for personal data physicalizations. This includes bringing data to life from flat 2D displays to interactive objects (Jansen et al., 2015); incorporating data into the physical environment and daily routines to help people become more aware of their data (Bakker, van den Hoven, & Eggen, 2015; Khot & Mueller, 2013); offering a more creative and mindful way to look at and reflect on one's data (Sauvé et al., 2020, 2017); and evoking user curiosity and learning (Hogan et al., 2017). As such, physicalizations have a potential to support behavior change.

It is argued that as PA happens in the physical world, the physical representation of PA can be placed in the everyday environment and the data should be available in a more seamless way (Khot, 2014; Khot & Mueller, 2013; Sauvé et al., 2017). 3D-tangible-artifacts can provide a basic, abstract understanding of data in the periphery of attention, which makes them a great educational tool (Rodić & Granić, 2022). Additionally, 3D tangible artifacts such as LEGO have shown to help with children's spatial visualization and creative learning (Delson, van Den Einde, Tuazon, & Yang, 2020). Given that about 80% of children and adolescents are visual and tactile learners (Dunn & Dunn, 1975; Liang, Li, Weber, & Hußmann, 2021), and that there are limited benefits to using only numbers and figures as a source of knowledge (Liang et al., 2021; Lupton, 2016), a richer way of data representation is required (Hassenzahl, Laschke, & Praest, 2016). Indeed, recent research shows that 3D-personalized-models of PA can be effectively used as a reward and goal-setting strategy for children and adolescents, and may offer a unique opportunity for the promotion of PA levels and associations to the 60-min MVPA guidelines (Crossley, 2019).

It is important to note that behavioral flexibility is developed with time, and that behavioral adaptation in turn builds individual resources, such as reflection, learning, resilience, and physical health (Bentvelzen, Woźniak, Herbes, Stefanidi, & Niess, 2022; Cohn, Fredrickson, Brown, Mikels, & Conway, 2009; Fletcher, Hanson, Page, & Pine, 2011). In addition, time is a central aspect of human daily psychological functioning, with a pronounced impact on human thoughts, feelings, and behaviours (Burzynska & Stolarski, 2020; Daugherty & Brase, 2010). Previous research shows that time can be a crucial factor regarding user experience in consumer products (e.g., mp3 players) (Hassenzahl & Marc, 2004), smartphones (Karapanos, Zimmerman, Forlizzi, & Martens, 2009), social media (Kujala, Roto, Väänänen-Vainio-Mattila, & Sinnelä, 2011), slow technologies (Odom, Banks, Durrant, Kirk, & Pierce, 2012), and automation and robotics (Wurhofer, Meneweger, Fuchsberger, & Tscheligi, 2015). Time is also shown to be significant in developing reflection in children as they have limited experiences to reflect on due to their development stage, environment or education (Saksono & Parker, 2017). Therefore, to foster reflection in technologies that contribute to health and wellbeing, temporality should be considered a key resource in design (Bentvelzen et al., 2022; Fleck & Fitzpatrick, 2010; Hassenzahl, 2010; Karapanos, Jain, & Hassenzahl, 2012). Longitudinal studies of temporality with interactive products and technologies in the field of HCI show that a user's need for stimulation and personal growth is fulfilled over time (Epstein, Eslambolchilar, Kay, Meyer, & Munson, 2021; Harrison, 2020; Hassenzahl, 2010; Kujala et al., 2011). However, temporal studies with children and/or adolescents, especially in the context of learning about PA through tangible models, are limited within the HCI domain. It is therefore important to understand how interaction with 3D-printed models can potentially evolve children's and adolescents' experience towards PA.

Moreover, user experiences are by nature subjective and individual, and need to be understood as such (Forlizzi & Battarbee, 2004; Wright, Wallace, & McCarthy, 2008). Whilst recent HCI studies have examined the role of physicalizations in advancing children's and adolescents' understanding of and motivation to engage in PA (Crossley, McNarry, Eslambolchilar, Knowles and Mackintosh, 2019; Crossley, McNarry, Hudson et al., 2019; Crossley, McNarry, Rosenberg et al., 2019) , the temporality of children's and adolescents' experience with tangible artifacts that represent PA is yet to be explored. Therefore, we present a longitudinal study conducted to explore primary and secondary school children's (8–14 years old) experiences with tangibles visualizations (models) representing their PA including embodied reflections, emotional engagement and temporality of their experiences with the models. We report the results of short interviews conducted as part of a 7-week study during which children and adolescents received four 3D-printed models representing their faded-weekly PA levels compared to the recommended 60 min of MVPA guidelines (U.K. Chief Medical Officers, 2019; WHO, 2010). Our results show that children's and adolescents' reflection and experiences with the models and the PA evolved over time. The reflection expanded and evolved across many layers from revisiting the past to seeing things in new light and from making conversations to making discoveries and that provided motivation to change, learn or experiment with one's behavior. These findings suggest that tangible artifacts evoke a number of experiences such as embodied reflection, active learning, and emotional engagement and temporality of PA experience. Therefore, we argue that regular tangible visualizations as a form of feedback can have motivational impact and could reduce childhood inactivity if used alongside wearable activity trackers.

In the following sections, we present related work on physical data visualizations, physicalizations of PA, and temporality in HCI. Next, we describe our study and the key interview findings, which are next considered through the lens of temporality. We conclude by discussing the role of physicalizations in supporting PA, temporality of experience with physical models, and challenges of using PA physicalizations aimed at children and adolescents.

2. Related work

Over the last couple of decades, technological solutions have been proposed to foster change in sedentary lifestyles, from pedometers for monitoring steps to high specification watches for monitoring a wide-range of biological signals (e.g., heart rate). Such solutions have been motivated by the social challenges our societies are facing such as obesity or cardiovascular diseases (Hruby & Hu, 2015). In this section, we provide some basic definitions of physical visualizations and their role on personal reflection, and summarize relevant research on such representations in the context of PA awareness. We then conclude by discussing the concept of temporality in HCI as users' behaviors and experiences with physical artifacts change over time.

2.1. Physical visualizations for personal reflection

Representing data visually (i.e., a visualization) involves the process of visual mapping, such as the choice of visual variables (i.e., color, position, size) to encode data (Chi, 2000). As our interest is in PA and its temporal aspects, in this paper we focus on information visualizations where the data is non-spatial. Jansen et al. (2013) defined such "physicalizations" as *"visualizations that are made of physical matter, as opposed to presented on a computer screen or projected on a surface as is traditionally the case. This includes matter whose shape or properties change over time"*. Jansen et al. (2013) (p.2954). Jansen et al. (2015) claimed that such presentation has several benefits over on-screen visualizations: it is interactive (e.g., responds to user's action, changes over time), allows active perception, can leverage non-visual senses, the interplay between vision and touch can facilitate cognition, and by integrating with the physical world it makes the data more accessible to the user. However, Jansen et al. (2015) did not provide case studies where thinking, learning, problem solving, or communication could be enriched with data physicalizations.

Moreover, a vast body of research in educational science and developmental psychology suggests that the manipulation of physical objects can promote understanding and learning (Bara, Gentaz, Colé, & Sprenger-Charolles, 2004). Additionally, it has been argued that interaction with physical objects could extend human memory and memorability (Ware, 2012). Furthermore, previous studies have revealed that physical objects are recalled more frequently than pictures (Bevan & Steger, 1971). In a study with 40 participants, Stusak, Schwarz, and Butz (2015) compared a physical bar chart to the same chart displayed on a tablet screen and measured the memory performance immediately after exploration and again after two weeks. The results showed that participants who used the physical visualization forgot less information about maximum or minimum values compared to those who used the digital visualization.

Physical representation of information can depict varying degrees of data abstraction with creativity in mapping data for different human senses (e.g., visual Moere, 2008; Zhao & Moere, 2008, tactile Claes & Vande Moere, 2015; Khot & Mueller, 2013 and gustatory Khot, Aggarwal, Pennings, Hjorth and Mueller, 2017; Khot, Lee, Aggarwal, Hjorth, & Mueller, 2015; Wang, Ma, Luo, & Qu, 2016). Such abstract and sometimes artistic physical representations are called data sculptures and are used for artistic, communicative or educational purposes (Moere, 2008; Stusak et al., 2014; Zhao & Moere, 2008). It has been argued that data sculptures can be a pleasant way to represent and analyze data, and therefore an engaging and educational experience. For example, different shapes, textures, colors and sizes (Khot & Mueller, 2013; Moere, 2008; Sauvé et al., 2017; Stusak et al., 2014; Zhao & Moere, 2008) or different gustatory cues (Khot et al., 2015; Wang et al., 2016) could enhance the quality of data visualization and/or help with communicating complex concepts with lay users. As such, physical visualizations were advocated as an alternative to support non-work information visualization (Moere, 2008). Multimodal representation of data (e.g., edible or drinkable data) have further advantages over visual-only representation such as attractiveness, richness, memorability, affectiveness, and sociability (Khot, Aggarwal et al., 2017; Khot et al., 2015; Wang et al., 2016). Therefore, they may exert a more enduring effect than the other types of data representations, which may potentially benefit from education point of view. However, the research on temporal nature of such tangible artifacts in self-reflection and learning specially in the context of PA and health with children and adolescents is limited in the HCI literature.

2.2. Physical visualizations for physical activity for awareness

Data visualizations can support learning and self-reflection about one's health and PA (Choe, Lee, & Schraefel, 2015; Huang et al., 2015). For example, Choe et al. (2015) designed a visualization system to help non-expert Quantified Selfers gain and communicate personal data insights. Through the lens of their participants, Choe et al. (2015) found that to support personal reflection, visualizations and visual analytics should include comparison features, help individuals create interesting questions and hypotheses about their activities and lifestyle, and capture and use various contextual information. Moreover, contextual and personal inferences and reflections are essential to maintain engagement with PA (Khot, Stusak, Butz and Mueller, 2017), but are not always captured by tracking apps or devices. Kirk and Sellen (2010) argued that material artifacts have personal reflective value and therefore, using material artifacts to represent PA data can provide users with a stimulus for reflection on achievements. Indeed, printed family or friends' photos, souvenirs from trips or small rocks collected from walks are put on display at home or at workplace—this is far less likely to happen with digital objects. Therefore, physical artifacts are often seen as more valuable compared to digital objects because of their higher visibility in the surroundings and low replication possibility (Golsteijn, van den Hoven, Frohlich, & Sellen, 2012; Kirk & Sellen, 2010). This suggests that the unique pattern of PA represented in a physical form could elicit more meaning, emotion and memory to the individual as they have invested time and effort similar to that of a physical photo of a loved one or a souvenir from a holiday trip.

In the HCI literature, there are a few case studies of physicalizations that have been used in the context of PA awareness. For example, Jafarinaimi, Forlizzi, Hurst, and Zimmerman (2005) designed Breakaway for representing sitting posture as an early example of PA data physicalization. The physicalization was a small sculpture placed on the desk and its design was inspired by animation arts and theater, which relied heavily on body language to express emotions. More recently, Khot, Hjorth, and Mueller (2014) and Stusak et al. (2014) designed 3D-printed physical artifacts to represent PA data (see Fig. 1). Stusak et al. (2014) focused on visualizing a large number of running variables (running time, distance, speed, duration, elevation gain). They ran a 3-week field study during which their participants ($N = 14$) received four sculptures (a figure, a necklace, a lamp and a jar) representing their running activity (Fig. 1, top). Similarly, Khot et al. (2014) conducted a 2-week study with six households. They used a mixed-representation of heart rate data that combined aspects of abstract and accurate data together so that only the significant changes in the activity during the PA or exercise were represented (Khot et al., 2014). Their participants experienced five different material representations of their PA in the form of a Graph, Flower, Frog, Die and Ring (Fig. 1, bottom). Overall, both studies revealed that not only user relationship with PA was positively influenced with physical metaphors, but also that tangible artifacts complemented active mechanisms of persuasion with more playful and reflective look at ones' activity. Lastly, Woźniak, Kiss, Zbytniewska, and Niess (2021) compared GraFeet, a shoe-based display, with an on-screen dashboard. Both visualizations presented running metrics albeit GraFeet presented a limited amount of metrics in a form that reminded users of the activity and enabled them to relate the data points to their bodies. The pilot study included 36 advanced amateur runners who ran a distance of 1.75*mi* on a university campus. The study showed that GraFeet empowered users to generate significantly more insights about their foot mechanics than the dashboard. However, the direct comparison between the dashboard and Grafeet was not

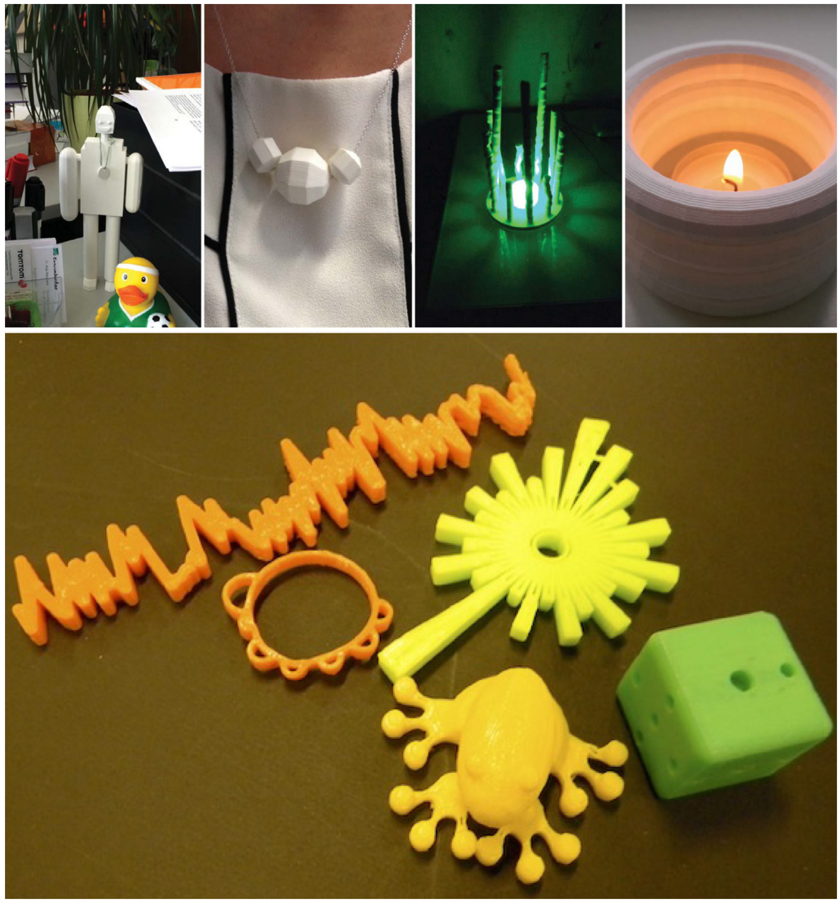

Fig. 1. Top: Four Activity Sculptures of running activity: a figure, a necklace, a lamp and a jar. The sculptures are extensible by additional pieces, and each individual piece represents a specific run; reused with permission copyright ©IEEE (Stusak et al., 2014). Bottom: Five material representations of physical activity, each depicting a different aspect of physical activity e.g., line and floral pattern depicting the heart rate variation, bubbles representing number of active hours, size capturing the amount of PA, and cube zones depicting heart rate zones; reused with permission copyright ©author (Khot, 2014).

possible because the dashboard was designed for expert users not amateur runners. Additionally, Grafeet was not studied as a situated artifact e.g., at home environment.

The tangible forms of PA visualizations and their studies are not limited to 3D-printed artifacts. For example, Lee, Cha, and Nam (2015) created a Patina Engraving System that represented a single PA with a specific line pattern that captured the frequency of a specific activity. Multiple activities over time created different lines and contributed to the unique aesthetic of the personal bracelet. In a field trial with eight participants over five weeks, the study found that visualizing PA in a fashionable manner creates an engaging experience for activity tracker users. Khot et al. (2015) and Khot, Aggarwal et al. (2017) explored edible and drinkable representations of PA data. They translated heart rate data into quantity and flavour of fluids or small 3D-printed chocolate treats. The accompanying studies (a field trial with eight participants for five weeks (Lee et al., 2015), a 2-week study with six participants (Khot et al., 2015) and a 2-week study with 13 participants (Khot, Aggarwal et al., 2017)) highlighted that such visualizations can support individual's self-expression, curiosity, personal history (also known as "memory landscape" Van Den Hoven, 2004) and playfulness, while also increasing awareness of PA, motivation to do more exercise and spontaneous co-located interaction. Khot et al. (2015) and Khot, Aggarwal et al. (2017) also showed that a drinkable material after exercise or printed treat at the end of the day (known as delayed feedback) was appreciated and promoted more activity throughout the day. Since there was no feedback on whether the participant had achieved their activity goal for the day until evening, the delayed feedback added a surprise element to what the activity treats were going to be and fueled their interest in doing opportunistic PA (Consolvo, Klasnja, McDonald, & Landay, 2012).

Some data physicalizations have been built to dynamically represent PA data. For example, Menheere, Van Hartingsveldt, Birkebaek, Vos, and Lallemand (2021) and Sauvé et al. (2017) proposed LOOP and Laina respectively, shape-changing physical artifacts, designed to make personal activity data available as ambient information in the home environment. LOOP visualized the step data collected from Fitbit trackers and contained seven inner rings for representing the days of the week and one outer ring, representing the step goal set by the user. Laina, in the other hand, visualized running data from Strava and RunKeeper apps and comprised of wooden black pins pushed on the hard wood surface to depict the running route in an abstract way. A one-week field study with LOOP with five participants and deploying Laina at three participant's homes for three weeks demonstrated that providing an aesthetic presence for real-time information in one's living environment was welcomed and facilitated deep reflection. However, both studies were limited to a handful of participants and lasted for short period of time. Even though the studies were conducted "in the wild" (Menheere et al., 2021; Sauvé et al., 2020), these highlight limitations on reaching any conclusions about PA awareness.

There are few examples and studies of data physicalization with children and or adolescents in the context of health in the HCI literature. For example, Ananthanarayan, Siek, and Eisenberg

(2016) proposed a personalized Arduino-based tool for visualizing health technology in the form of paper cherry blossom leaves, flowers, or felt and Velcro stick-objects that could be attached to backpacks. Through informal, creative and playful ways of crafting, they explored ways in which children could become more aware of serious health concepts. The study was conducted with nine children (age 11–14) over a period of two months with repeated crafting sessions. Ananthanarayan et al. (2016) argued that children's perspective of health is not necessarily the same as adults. Specifically, from a child's point of view, health included more than just exercise and dietary habits—activities such as coloring and playing musical instruments were regarded as healthy activities. Even though the health crafting study was at a very early stage, Ananthanarayan et al. (2016) argued that crafting could enhance children's awareness about serious health concepts and wellbeing.

Although in recent years the HCI research community have focused on studying physicalizations of PA in children and enhancing PA (Ananthanarayan et al., 2016; Crossley, McNarry, Eslambolchilar et al., 2019; Crossley, McNarry, Hudson et al., 2019; Crossley, McNarry, Rosenberg et al., 2019) , to the best of our knowledge there are no studies that have investigated the temporality of children's or adolescents' experience with tangible artifacts representing PA to understand their general engagement with PA and feelings in relation to such objects.

2.3. Temporal methods for participant engagement in HCI

To understand the effectiveness of technologies that motivate users to adopt health-promoting habits, longitudinal studies are necessary. The adoption of longitudinal qualitative research in HCI to understand the sustainable and prolonged use of digital products has increased in the past decade (Karapanos et al., 2012). Karapanos et al. (2009) identified temporality (i.e., *"how users' experiences develop over time"*; p.729) as an important factor to investigate in adoption of digital products. In addition, Odom et al. (2018) argued that the interaction between a human and a computer (broadly defined as any interactive object, including digital artifacts) is inherently temporal or *"time is the medium through which an interactive dialogue between a human and computer begins, unfolds, and resolves"* (p.384).

In an early study on temporality of user experience (UX), Karapanos et al. (2009) studied participants who purchased a new smartphone over a period of five weeks and found that prolonged use was motivated by different qualities than the ones that provided positive initial experiences; early experiences seemed to relate mostly to hedonic aspects of product use, whereas prolonged experiences became increasingly more relevant to the meaning of the product in individual's life. Their findings showed that UX of a digital product develops over time and goes through three phases of orientation, incorporation, and identification (i.e., final emotional attachment). Although Karapanos et al.'s study provided important insights, their research did not look at individual differences in use, and the phases of use proposed were not clearly related to progression in time.

Since the initial framework for longitudinal studies was proposed by Karapanos et al. (2009), two different types of methods for evaluating longer UX have been adopted in the HCI literature: repeated evaluation and retrospective evaluation (Kujala et al., 2011). Repeated evaluation methods involve longitudinal field studies in which individual experiences are measured on several occasions throughout the study. There are not many such studies in the literature due to amount of effort and commitment required both from researchers and participants (Karapanos et al., 2012). Retrospective evaluations, however, do not require such a substantial effort as they are lightweight in resources, cheap to conduct and fast to analyse (Karapanos, Martens, & Hassenzahl, 2010; Vermeeren et al., 2010). They ask participants within a single contact to recall past experiences concerning the use of a particular product or application (Karapanos et al., 2010). The problem with them, though, is that memory biases may occur and memories may vary substantially from the actual experiences (Kahneman, Krueger, Schkade, Schwarz, & Stone, 2004). It is also argued that reliability (i.e., consistency over multiple recall trials) is more important than consistency between the memory and the experience (Kahneman et al., 2004). Although there are a few case studies of retrospective method in the HCI literature (examples include, but are not limited to Kim, Han, Park, & Park, 2015; Pradhan, Jelen, Siek, Chan, & Lazar, 2020; Sim et al., 2016; Vissers, De Bot, & Zaman, 2013), in this research we focus on repeated evaluations with children and adolescents, which is rarely explored in the literature. It is important to capture a complete picture of how the user's experience changes with respect to timeliness and evolving familiarity with the object of measurement (Bentvelzen et al., 2022; Karapanos et al., 2009). Additionally, a repeated evaluation allows the researchers to identify user preferences and usage contexts, which can guide the general direction of product development (Yang, Liu, Liang, & Tang, 2019), service delivery, and government policies.

Whilst there are not many UX studies that adopt repeated evaluation methods, Wurhofer et al. (2015) explored human–robot interaction in a semiconductor factory and Odom and colleagues (Odom et al., 2012, 2018) focused on deployment of a photobox, a domestic technology that prints four or five randomly selected photos from a user's Flickr collection at random intervals each month. Each study lasted for over a year and interviews with the same participants took place in intervals. Both studies explored expectations and general attitudes, as well as actual feelings and reflections towards objects of the study. They applied a narrative interview technique at each phase to evoke reports on workers' or participants' experience. Overall, the findings from both studies highlight the importance of longitudinal evaluations: to understand the pace of technology in one's life and the need for time for reflection, temporal process and repeated evaluations are crucial.

Following the literature discussed above, our research explores real-world material artifacts that are constructed to provide visual and tangible representation of measured PA data of children and adolescents. Conducting HCI research through material artifacts allows to focus on the whole experience and the construction of potential solutions for addressing childhood inactivity in the future instead of developing an understanding of the present (Zimmerman & Forlizzi, 2008). Additionally, tangible artifacts produce research outcomes that serve as design exemplars that aid in the translation of findings to the practice community (e.g., technologists, public health researchers) (Zimmerman & Forlizzi, 2008). Moreover, the research especially in the HCI community has shown that 3D printing has many advantages in children's and adolescents' education at schools and beyond, from rapid and quality prototyping (Ding, 2017) to flexibility in producing different tangible shapes (Berman, Deuermeyer, Nam, Chu, & Quek, 2018; Ding, 2017), from financial affordability of 3D printers to cost effectiveness of producing artifacts in masses (Berman et al., 2018; Ding, 2017; McNally, Norooz, Shorter, & Golub, 2017) and, from utilitarian needs to promoting social good, encouraging play, and providing rapid interventions (McNally et al., 2017). Furthermore, research through design of artifacts addresses the need within the HCI community to explore how 3D printed artifacts can advance current and future design of activity trackers and implementation of potential services for tackling childhood inactivity (Khot, Stusak et al., 2017; Zimmerman & Forlizzi, 2008). Representing personal data makes the artifacts unique and personalized while recognizing that children's and adolescents' experiences with such artifacts are individual, subjective and relational (Bentvelzen et al., 2022; McCarthy & Wright, 2007). The personalized representation also enhances the customized tracking experience and sense-making of health data (Coşkun & Karahanoğlu, 2022). Therefore, we investigated how faded-weekly tangible visualizations might open a space for connecting, reflecting, interpreting, and learning about PA over time.

3. Case study: Understanding the experience of using tangible forms of physical activity

3.1. Background and research context

This qualitative study represents additional, complementary findings from *Phase 3* of a larger project that aimed to explore the tangibility of personalized 3D-printed feedback on enhancing children's and adolescents' PA awareness, goal-setting, and motivation. The first phase (*Phase 1*), formative study, utilized a co-design approach with children and adolescents and demonstrated that children and adolescents have the ability to conceptualize PA data represented as 3D-printed objects (Crossley, McNarry, Hudson et al., 2019). The *Phase 1* formative study comprised of semi-structured focus groups with 28 primary school children (aged 8.4 [SD = 0.3] years; 15 boys and 13 girls) and 42 secondary school children (aged 14.4 [SD = 0.3] years; 22 boys and 21 girls) who used Play-Doh to create and describe a model that could represent their PA levels. Phase 1 findings revealed that children and adolescents preferred different types of 3D model design, leading to the development of 2 age-specific 3D models of physical activity. For children, a preference for a combination of both abstract (43%, 12/27) and graphical (54%, 15/27) models was demonstrated, most commonly expressed as Play-Doh models of flower- or sun-like shapes. However, to avoid any potential sex bias resulting in boys dissociating with a flower-shaped 3D model, the more neutral sun-shaped 3D model design was chosen for further development. The majority of adolescents (67%, 28/42) however, showed a preference through Play-Doh models for a simple bar chart design. In the second phase (*Phase 2*), validation study, two age-specific 3D-printed model representations of children's and adolescents' PA data were developed from the formative research (Crossley, McNarry, Hudson et al., 2019), which were further validated as a potential tool to increase children's and adolescents' awareness and understanding of PA and the recommended PA guidelines (Crossley, McNarry, Rosenberg et al., 2019). Twelve primary school children (aged 7.8 [SD 0.4] years; 9 boys and 3 girls) and 12 secondary school children (aged 14.1 [SD 0.3] years; 6 boys and 6 girls) participated in individual semi-structured interviews as part of *Phase 2*. Interview questions, in combination with two interactive tasks, focused on children's and adolescents' ability to correctly identify PA intensities and interpret the age-specific 3D models (Figs. 2 and 3).

As part of the third phase (*Phase 3*), intervention study (Crossley, McNarry, Eslambolchilar et al., 2019), we investigated the efficacy of age-specific 3D-printed models. The study reported in this paper focuses on the qualitative part of that *Phase* (Part 2), but for context we provide a brief description of the whole intervention study. It was conducted with 97 children and adolescents: 39 primary school children (aged 7.9 [SD 0.3] years; 22 boys and 17 girls) and 58 secondary school adolescents (aged 13.8 [SD 0.3] years; 37 boys and 21 girls) (Crossley, McNarry, Eslambolchilar et al., 2019). The seven-week intervention study was conducted in Swansea, UK. All primary school and 96% of secondary school children were White British, with the remaining 4% being Asian British (2%; n = 1) and Black British (2%; n = 1). The recruitment took place at the school level, then all consenting schools invited all children and adolescents in each included year group. All children and adolescents who provided the written informed parental/carer consent and child assent were included. No financial incentive was provided to children, adolescents or their parents/carers. Ethical approval was granted by the University Ethics Committee (ref: PG/2014/40) and conducted in accordance with the Declaration of Helsinki.

In the intervention study (*Phase 3*), participants were asked to wear a belt with an accelerometer (ActiGraph LLC, Pensacola, FL) on their right iliac crest (hip) to measure PA at 100 Hz; the data collected with the accelerometer was presented on 3D-printed models. Participants were instructed to wear the accelerometer all the time (24 h per day), except for when engaging in water-based activities (swimming, showering, and bathing) and contact sports. Parents/carers did not receive any instructions from the researchers. Each day's moderate PA (MPA) and vigorous PA (VPA) levels were calculated using Evenson child cut-points (Evenson, Catellier, Gill, Ondrak, & McMurray, 2008), which are known for providing the closest estimates of MPA and VPA levels during the free-living measurement (Crouter, Horton, & Bassett, 2013). The National Health Service (NHS) in the UK defines moderate PA for children and adolescents as activities that raise heart rate, increase breathing rate and feel warmer (NHS, 2019). Examples include walking to school, cycling, walking a dog, skateboarding and playground activities. In the other hand, vigorous PA makes one breathe harder and faster up to the point that normal talking becomes difficult (NHS, 2019). Examples include playing football, hockey and rugby, swimming, running, cycling fast or on hill and gymnastics. Participants' MPA and VPA levels and personal ID code (e.g., participant initials and model number) to distinguish participants' personal 3D model were then inserted into the age-specific custom-developed 3D model code and subsequently 3D-printed. The 3D models were printed in a university 3D printing facility and the color of filaments was not a controlled variable, i.e., the color depended on what filament was already available in the 3D-printer's extruder. However, in all cases the filaments had off-white or light blue colors. The models (a sun and a bar graph; see Figs. 2–4) had rays or bars representing the days of the week and a target bar representing the PA guidelines recommended by World Health Organization (i.e., 60 min MVPA per day) (U.K. Chief Medical Officers, 2019; WHO, 2010). The target bar was highlighted with a key ring, which could be used to attach the model to a bag or an item of clothing (no explicit use of the key ring was suggested to participants).

To present the data, we used a faded approach, as shown in Fig. 5. The faded approach has been proposed as a method for maximizing the long-term effectiveness of feedback compared with frequent feedback, which only provides short-term benefits (Goodman & Wood, 2009). In our study, we started with high levels of feedback during Baseline and *Week 1* to allow participants to understand their model and its different components and then we gradually reduced – or faded – the frequency of feedback (Weeks 3 and 6) until children and adolescents had in depth understanding of their model and what it represented (Rock & Thead, 2007). Our research also utilized delayed feedback: Over the course of the study, children and adolescents received a total of four 3D models each, following Baseline (Model 1), *Week 1* (Model 2), *Week 3* (Model 3) and *Week 6* (Model 4). Children and adolescents received their personal 3D-printed model approximately 1–3 days after their data was downloaded from the accelerometer.

As part of the intervention study (*Phase 3*), we conducted short video interviews with children and adolescents immediately after they had received each model. In total, we conducted 369 video interviews (19 video interviews were missed due to participant's

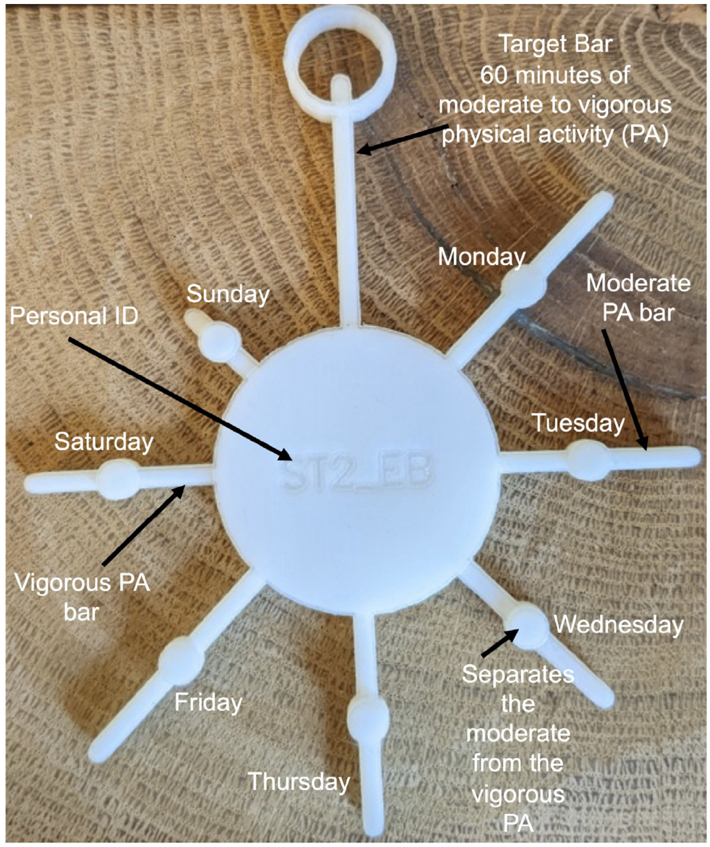

Fig. 2. 'Sun', primary school children's 3D Model of physical activity instruction manual.
Source: Reproduced from Crossley, McNarry, Eslambolchilar et al. (2019).

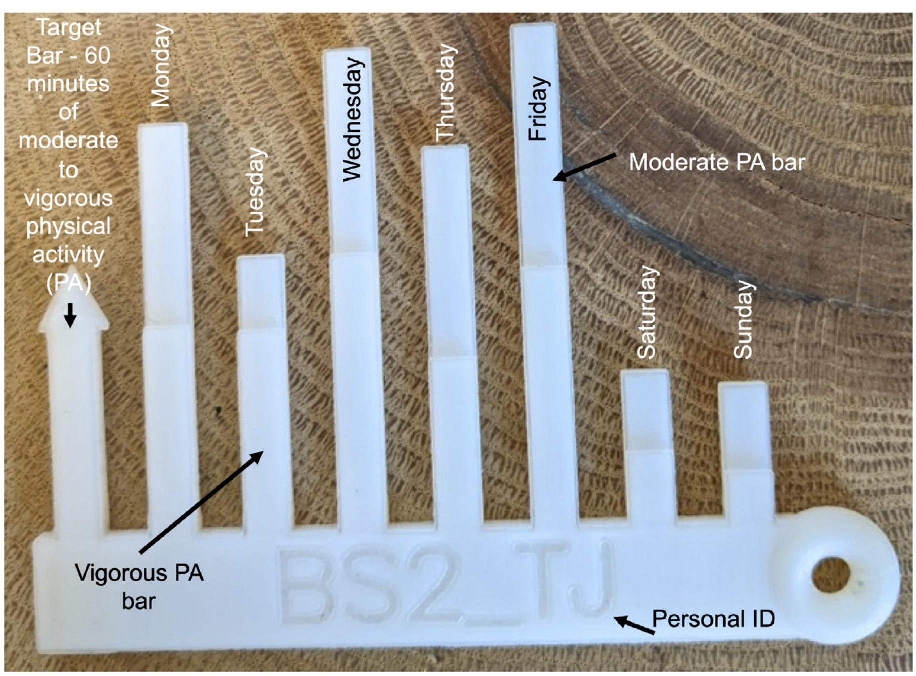

Fig. 3. 'Bar Chart', secondary school children's of physical activity instruction manual.
Source: Reproduced from Crossley, McNarry, Eslambolchilar et al. (2019).

illness or personal circumstances). The interviews were structured and focused on three key topics: the models, PA, and children's and adolescents' attitudes towards both. Participants were asked "What do you think of your 3D model?", "What you think physical activity means?", "How does your 3D-printed model show your physical activity?", "What kind of activities might be vigorous and moderate physical activities?" and "What will you do with your 3D model now?". The same questions

Fig. 4. Left and Middle: Two primary school children with their Models 2 and 1 (Sun) respectively. Right: A secondary school boy with his Model 3 (Bar graph).

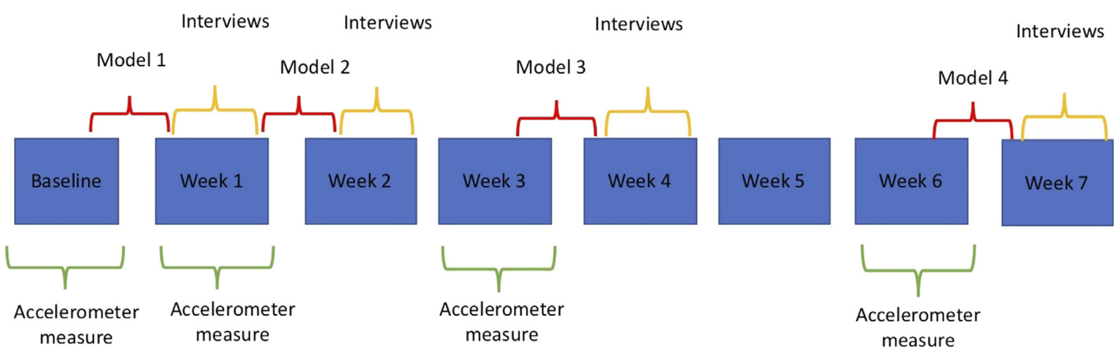

Fig. 5. Timeline of the study and weeks the models were given to participants. In the study, we started with high levels of feedback during Baseline and *Week 1* and then, we gradually reduced – or faded – the frequency of feedback (*Weeks 3* and *6*).

were repeated in each interview to capture how children's and adolescents' understanding of these topics evolved throughout the study. We kept the interviews short (5 min on average) and structured to limit the disruption to participants' curricular activities, they were conducted during physical education lessons or in the school library during breaks. This method also allowed the research team to gauge first impressions and ensured all children's and adolescents' views were captured.

The results revealed that by the end of the study, 72% of participants used the models as a goal-setting tool and 88% were able to accurately interpret the information presented on the models. In addition, 75% were able to relate their results to activities from the previous week. Full quantitative and pen-profile data analyses are published in Crossley, McNarry, Eslambolchilar et al. (2019) and longitudinal short interviews were used as secondary data to provide a rich context to the quantitative results and pen-profiles. The key themes emerged based on the topics of interview questions (Table 3 Crossley, McNarry, Eslambolchilar et al., 2019) were: enthusiasm, level of satisfaction, reflection, uncertainty, definition, moderate intensity, vigorous intensity, accurate interpretation, inaccurate interpretation, comparisons, goal setting, motivational tool, recall and/or relatedness, self-evaluation, display, family and, peers.

3.2. The current study

In this paper, we focus on the in-depth qualitative part (Part 2) of *Phase 3* and investigate children's and adolescents' experience of engagement with 3D models in the seven-week intervention study. We report the results of a thematic analysis of the short video interviews conducted with children and adolescents immediately after they received each model to explore their engagement and experience with the models and how their experience evolved over time.

3.2.1. Qualitative data analysis

All recordings of short video interviews were transcribed verbatim, uploaded to NVivo 12, and analysed inductively using reflexive thematic analysis (Braun & Clarke, 2006; Clarke & Braun, 2021). As our goal was to identify various ways in which children interacted with the models and how the models affected their behavior, the reflexive approach to the analysis was deemed the most suitable (Clarke & Braun, 2021), in contrast to other approaches that prioritize the quantification of patterns and accuracy e.g., coding reliability approaches, qualitative content analysis, etc., aligned to (post) positivist research values (Braun & Clarke, 2021).

All transcripts were read and discussed by two researchers who led the analysis (PE and KS), which is a typical process often used in HCI research (McDonald, Schoenebeck, & Forte, 2019). Each researcher independently read and coded all transcripts in detail. The researchers then discussed the codes and initial themes they identified; we did not calculate an inter-rater reliability agreement as this is a statistical measure of agreement between coders, which is often not suitable for qualitative research methods (McDonald et al., 2019), including the reflexive thematic analysis approach that was followed Clarke and Braun (2021). Subsequently, the codes were grouped into broader, predominately descriptive themes (i.e., they described patterns in the data relevant to personal experience and engagement). Researchers read the data associated with each theme and considered strength of support ensuring that themes worked both within a set of interviews with a single participant as well as across all interviews for all participants. Finally, the results were grouped into four major themes that are described in the next section. Given the method that was used (Braun & Clarke, 2021; Clarke & Braun, 2021), the codes were not quantified, as the goal was to identify a broad range of behaviors and interactions, rather than quantify which ones were the most/lease frequent.

4. Findings: Fostering PA through engagement and reflection

We have identified four key themes. First, our data showed that for many children and adolescents the *tangible models were appropriated as personal mementos, reminders, motivational prompts, and for parental use* to display, look at, act on and be looked after by parents. This personal connection to the models was enhanced by the second major theme, *emotional responses and social experiences of tangible models*. Our data showed that emotional responses and social experiences triggered by the models impacted children's and adolescents' reflections on PA over time. Additionally, the engagement with the tangible models allowed children and adolescents to develop strategies to enhance active learning, and thus the third major theme we identified was *experiences and strategies developed to support active learning through tangible models*. Finally, we observed how the *embodied engagement with tangible artifacts shape PA over time*. For example, we noted children's and adolescents' evolution of knowledge of what constitutes PA and its different types, and the changes in their attitudes and behavior towards PA beyond increasing their awareness. In the following sections we describe each theme in more detail.

The quotes used to illustrate the findings use the following identification scheme: each child is referred to with a pseudonym that includes a school identifier (P for primary school, S for secondary school), gender (B for boy, G for girl) and a participant number, followed by the number of the model/interview. For example, "SB12, M1" means participant number 12, who is a boy from a secondary school, whose quote is from the interview about his first model.

4.1. Theme 1: Appropriation of tangible models as personal mementos, reminders, motivational prompts, and for parental use

Children and adolescents in the study, and their parents alike, value the tangible models and saw them as more than just physical data visualizations and appropriate them in different ways. Participants attribute different meanings to the models such as personal mementos, reminders, or motivational prompts that should be displayed appropriately for such use. Children's and adolescents' attitudes and appropriation of the models were reflected by locations they displays the models. In particular, some children reported keeping the models in more public locations in the house as they saw them as precious items that create a memento. For example, PG32 wanted to hang the models on the wall with all her trophies and medals, while PG09 reported keeping them with her collection of "interesting" items. Others wanted to attach the models to their belt or a school bag.

> *I will find a key ring or something to hang on it and then I will hang it on my belt or something* – PB34,M2

While this trend was more prominent in primary school children, secondary school children were more interested in keeping the models in their own rooms because of their perceived value and tracked their progress privately. They reported keeping them with their "important" items such as wallets, books or phones. In one way or another, participants saw the tangible models as significant to them.

> [I will] *keep it somewhere very very very very very very special but no one can touch it.* – PG06, M4

In addition, many participants also reported that they wanted to use the models as visual reminders that would motivate them to not *"fall back into that dark hole called anti exercise where you just procrastinate about everything"* (SG35, M4). As a result, they often reported keeping the models in a visible place to support their ability to remember:

> *I will put it on my fridge to remind myself not to stray from doing activities because otherwise you're just going to be stuck inside all the time. And that's not good at all.* – SG32, M4

> *When I go home I'll probably look at it, think like 'oh, I can do five times better than this', especially how much time I wear it, because as it shows I don't wear it on Sunday a lot, so I'll try and do that more and then next time if I get one I'll look at that and do exactly the same, compare it to my other one and then try and get better than that.* – SB25, M1

Some adolescents expressed a desire to use their model as a reminder to be active on days they were not usually active (e.g., weekends).

> *Probably keep it as a reminder of how much I'm doing and maybe improve certain days and do more on certain days than others so you can see that I've done more in the middle of the week than at the beginning of the week, so I should maintain it toward the end of the week as well, rather than just doing it all at the beginning of the week.* – SG35, M4

In a few cases, children and adolescents reported that their parents were the keepers of the models because they were either interested in monitoring their child's PA, wanted to show off their child's model, or they were more careful than participants in storing the models. For example, a participant expressed "[I'll] give it to parents because they like to monitor how I do" (SG11, M2), and another one stated that she gives her models to her dad because "Dad is keeping and showing it to everyone". When a child was not able to look after the models, especially the younger children, they transferred the responsibility of looking after models to their parents. As a result, a small number of participants reported that they did not know where the models were kept.

> *I don't know, I don't really know* [where the models are. I put] *them in the kitchen, but now I have lost them, but I think my mum knows where they are so should be in the kitchen* – PB13, M3

4.2. Theme 2: Emotional responses and social experiences triggered by the tangible models

Throughout the study, the tangible models evoked different emotional responses and social experiences in children and adolescents and such experiences remained high despite their evolving models, positively influencing the user engagement with the models.

On the one hand, participants wanted to keep the models out of sight to avoid upsetting others which in turn evoked emotional responses—although such admissions often sounded more like bragging:

> [I will] *hide it somewhere so nobody can see it* [...] *Well, I wouldn't want to make anybody feel awkward for having such a smaller one than mine cos* [sic] *mine is absolutely huge.* – SB50, M3

This linked to the wider trend of pride and desire to share the models with others. For example, aligned to their desire to show their progress, some children and adolescents also wanted to explain the models (their looks, how they work) to their social network including friends and family members.

I will probably see if my dad could put a screw through one of my walls and then I could hang it up or I could put it on my school bag to see, so then I can see how much activity I have been doing. I could put them all on my bag and then when I get home I could show my mum how much activity I've been doing. – PG16, M1

In addition, the comparisons across models often evoked emotional responses. When the change in PA was positive, children and adolescents were delighted and their pleasure and satisfaction were evident:

Ooh look at this one! I really like it cos [sic] *I think it's the biggest I've ever done and then I think this* [model] *is the smallest I've done!* – PB21, M2

However, when the results were worse than in previous weeks, children and adolescents were often disappointed and reluctant to compare the models. For example, PB21 felt uneasy about keeping his smallest model together with others as all the others were progressively getting bigger; the final model broke that trend and did not look as good:

I think I'm going to put it in a separate place so I know it's the worst one I've done and then I'll put them like, oh no, I put them in a row hanging up and then it will get bigger, bigger and bigger until the biggest one. – PB21, M4

The perceived preciousness of the models also indicated that some children and adolescents reported worrying about models getting broken or lost. For example, PG29 worried about the model and wanted to keep it safe *"from my dog because he eats anything"*, while PB21 wanted to keep it away from his brother.

Lastly, while a participant commented how she might worry *"if you're not active you'll end up having a very, well kind of not nice figure [body shape]"* (SG14, M2), none of the participants we interviewed felt that the tangible models would trigger negative feelings towards their body image as they enhanced their personal reflection as *"you'll be more confident because like people won't judge you"* (SG34, M1), highlighting the positive experiences of the models.

4.3. Theme 3: Experiences and strategies developed to support active learning through tangible models

Throughout the study, each participant received four models. When discussing new models, primary school children often focused on their size, shape or color, and what a 3D printer can do (*"I've never heard of movement being 3D printed!"* – PG09, M2), while secondary school children were more interested in their PA levels. Receiving a new model always prompted learning through comparisons with the earlier ones, and this was the case for both age groups. Upon seeing a new model, children and adolescents automatically described how much it differed (or not) from the previous one and speculated on the reasons, especially when they were surprised by the results:

I didn't really know Saturday was going to be that big, because I normally go and watch the football with my mum's [work colleagues] *and have lots of sweets. I thought that Thursday would probably be bigger than Saturday because I go to football training on there.* [...] *So Monday, Wednesdays and Fridays they've all normally been the same because I don't really do activities on there... on Saturdays probably be, not that big, but Sundays would probably be big, because I normally go to football and Sunday it was called off.* – PB35, M2

It's better than last week which I'm pretty glad about cos [sic] *I'm quite shocked... I think I've done pretty much the same thing as last week. So I don't really... I'm quite surprised that it's better.* – SG06, M2

Those who had regular active hobbies during which they could wear the accelerometer (e.g., running, dancing, walking the dog) were aware of their impact on PA levels and were often positively anticipating good changes in the models over time. However, those engaging with less energetic activities often did not expect that they would be picked up by the tracker:

I am quite surprised that it's [the model] *so high on a Wednesday since it* [the monitoring device] *must have recorded me doing horse riding. I didn't think it would generally do that. I didn't think it would pick up as much.* – SG42, M1

Participant's emotional responses (e.g., feelings of surprise) together with anticipating specific results meant that children and adolescents often compared models with earlier versions and they employed different strategies to compare, for example by stacking them one on top of another or by keeping them next to each other. Such comparisons and attempts to explain the reasons for change or levels of activity helped children and adolescents develop new mental models: even though later models looked different, they quickly learned how to interpret the data. This also helped them better understand their PA levels and provided motivation to be more active.

Now I see why I need to get outside a bit more, so then I get more exercise to get me big and strong, yeah, it would allow me to see how much more I've been doing – PB27, M2

Children and adolescents also appreciated that models enhance their learning and made it easier for them to make sense of the information. While the physical format was new to them, some found it easier to contextualise the data compared to traditional way of presenting PA data on screens because the artifacts allowed them to touch, inspect and think outside the box regardless of the number steps taken per day:

You can see on a screen that you've walked six kilometres but you can't really imagine it. But with this, it's kind of really useful. – SB59, M3

In addition, where there were gaps in data, such comparisons often led to reflection on forgetting and reasons for not wearing the accelerometer. This was mentioned more often by the secondary school children. Our participants also reported that they often had to remove the accelerometer before contact sports such as a rugby or football match or when swimming, and often forgot to put the accelerometer back on afterwards. As a result, they were often disappointed when receiving the models, which sometimes motivated them to be more active.

It's tiny, err... Oh yeah, because I forgot to put it [accelerometer] *on. I think it shows like that I normally do a bit more exercise, so I've been doing a bit less exercise and that I've improved this one more than this one* – PB27 - M3

4.4. Theme 4: Embodied engagement with tangible models shape knowledge, attitudes and behavior over time in relation to PA

The results highlighted unexpected disparities in children's and adolescents interpretations and understanding of PA. For example, in early interviews, participants did not always understand what PA actually means. For some primary school children it was an abstract term, *"sporty science stuff"* (PG17), while others interpreted the phrase literally, assuming that if there was no physical contact it was not PA:

Err... [PA is] *Erm when it's like a contact sport, it's like football when you go inside and tackle, rugby, when you're going in to tackle and like sort of involves physical contact with somebody else* – SB25, M3

Sometimes, they conflated PA with effort or any type of movement, which resulted in embodied practices like playing computer games, doing maths homework or even sleeping being listed as examples of PA:

The medium [level of PA] *is like moving sometimes, like umm... kind of like in your bed sleeping, cause you don't really move that much but sometimes you move there so that's part of the medium and it's when you're not using your energy like that that much* – PG9, M3

Similarly, some participants, especially the primary school children, thought that PA meant being healthy in general, and often mentioned healthy eating in their definitions of PA. In addition, sometimes even in later interviews they misunderstood what "vigorous" and "moderate" PA was. They often asked for clarification and the researcher would explain that "vigorous" meant also "hard". However, primary school children often interpreted it as "difficult", which was reflected in their responses grounded in bodily and social experiences:

[Vigorous, hard activity is] *Erm... Homework – that's hard... erm... The work at school is quite hard and sometime the Maths is... and ermm... they're hard because there's sheets with how many... and one of them was how many sets of six in 30* – PB18, M1

[So difficult activity is] *climbing a tree with no branches* – PB19, M3

In many cases, children and adolescents interpreted vigorous, or 'hard', exercise as difficult *for them*, and so they often perceived embodied activities they engaged in as examples of vigorous physical activities, while others were seen as easy. For example, children and adolescents playing rugby thought it was difficult, while gymnastics or football were examples of moderate PA—the opposite was reported by children and adolescents who did gymnastics or played football. Nevertheless, their knowledge about PA shaped over time, even though the researcher never corrected their answers. For example, PG28 described PA as simply "*doing something*" in the first interview ("*when you're doing something like err... when you're doing something*", PG28, M1), but when asked the same question after receiving the final model, described it as "*sports and exercises*", "*running*" and "*going to the shop*". Similarly, PB34's understanding also changed with time: in the first interview he said he did not know what PA was, but in the final one described it as fun activities that require physical effort. While secondary school children understood what PA means from the first interview, their knowledge also evolved over time, although the nature of that change was different. For example, the models helped them see what did and did not contribute to their activity levels:

You have to do more than just walk around to stay physically active, which I didn't think you had to do before I started wearing the belt, but you have to do more actual sport than just walking around daily to hit the target that you're supposed to be. – BS39, M3

Overall, participants' knowledge of their own levels of PA changed over time. Quite often, when they received the first model, they were surprised how high or low the activity bars were. With subsequent models due to their engagement with the tangible models, they developed a better understanding of how their behaviour affected the shape of the models and what they needed to do to reach their targets.

Yeah, I think it's changed a lot because usually I thought "ah let's go on a run", which would usually be very short, but now, since I've been getting these, then I think "wow I really want to go on a really, really, really long run" so then now like I can see how much that does by these models – PB25, M3

The understanding of the tangible models prompted a few children and adolescents to actually change their behaviour (e.g., some started going to the gym or added new activities to their schedule) because they were not able to record their regular activities.

I couldn't wear it [the monitoring device] *for rugby and that's a lot of what I do, but I've started going cycling a lot more so it's* [the 3D model] *sort of prompted me to go and do more stuff to try and boost my levels.* – SB59, M1

While in some cases seeing an individual model was enough to motivate children and adolescents to try to be more active, sometimes that change in attitude took time. This was dependent on their current activity levels and also their overall attitudes towards PA. For example, SG43's embodied engagement evolved throughout the study:

At the very start before this I kind of, you know, when you were talking during the assembly [about this study] *I kind of thought this would be a thing to push me to do more exercise and* [...] *then seeing my graph I kind of saw like "oh, I need to do more" or "that's good" and just... kind of pushing to do more exercise then to see what it's like.* – SG43, M2

My dad has always said I need to do more exercise and I never really listened, by then this graph has kind of put it into perspective that he's right, I should do a bit more. – SG43, M4

In addition, some participants also reflected on reasons for inactivity or the general lack of change, as their activity levels were dependent on factors beyond their control. As such, even though their attitudes or feelings towards PA changed with time, it was not always possible to sustain or improve activity levels, even if they wanted to. For example, spending time with different parents resulted in different routines, and therefore different opportunities to be (in)active:

In general, on a school day I do quite a lot of walking but like even on weekends you go out for walks around places. You walk the dog and things like that. Yeah, I think it really depends so at my mom's I have a dog and I walk him out every weekend. At my dad's it's not always certain that we'll walk out, so I may not be reaching the amount of exercise I need to achieve for those days. – SG42, M2

The models and participation in the study increased children's and adolescents' awareness and helped them understand the importance of PA, even though we did not explicitly explain it, and even supported participants to change their physical activities. In addition, to make sense of their new embodied experiences participants compare them with similar situations (e.g., previous bodily and social experiences such as reading) as in case of PG31, a book she once read:

I read a book before, it showed this little girl, she hadn't done any exercise in her life and she kept on watching TV. She got stuck to the sofa. If you don't do any physical activity then you get stuck in the sofa like the little girl in the book. – PG31, M3

5. Discussion

Our research explored how faded-weekly tangible visualizations can be used to provide delayed feedback (Consolvo et al., 2012; Khot, Aggarwal et al., 2017; Khot et al., 2015) and might help to explore how – over time – tangible visualizations influence children's and adolescent's experience and engagement with the PA. Our findings show that the models were viewed as personal reminders, mementos, and motivational tools whilst emotional and social meanings were attached to them (Dix, 2007). Tangible models also had a positive impact on children's and adolescents' embodied engagement, active learning and experiences with PA. Even though educating them about PA was not our goal, simply interacting with the tangible models and participating in the interviews were enough for children and adolescents to learn more about PA and their own behavior and lifestyle. When receiving a new model, participants often commented on it and compared it with earlier versions. The differences in shape and size prompted reflections on one's PA levels, helping children and adolescents learn which activities were counted as PA and were tracked, and which ones were not. The models also provided motivation to be more active—especially when children and adolescents discovered that their usual activities were not tracked, when they forgot to wear a tracker and had incomplete data (i.e., smaller or missing bars on the model), or when they could see days when they were simply not active. In contrast with the emotional and social experiences of tangible models that stayed largely the same throughout the study, learning and embodied engagement with PA changed over time. Participants developed more knowledge about themselves and their lifestyle and were able to see how their everyday activities translate into the data.

In the following sections, we discuss the experiences the tangible representations of PA triggered in children and adolescents, and the potential roles of such artifacts in promoting longer-term changes in healthy behavior in these age groups.

5.1. Designing physicalizations to support sense-making of physical activity

5.1.1. Supporting embodied reflection of PA

The intervention study illustrated how tangible artifacts can be used to support reflection in practice, contributing to developing knowledge and encouraging a whole range of behaviors at different levels simultaneously. This supports Fleck's and Fitzpatrick's (Fleck & Fitzpatrick, 2010) proposed systematic structure for reflection from R0 (the most basic reflection) to R4 (the most advanced reflection), where each level builds on the previous one and corresponds to a deeper understanding. Below, we discuss the embodied reflection of PA amongst our participants following this structure.

R0: Technology for revisiting. - 3D models provided a record of events for our participants to return to and spectate at any point in time. By revisiting the tangible data, participants had the possibility to create a new perspective about the past week, which supports the existing HCI research that claims that tangible artifacts are a promising medium for that, especially in the context of PA (Bentvelzen et al., 2022; Choe, Lee, Zhu, Riche, & Baur, 2017; Saksono & Parker, 2017; Sauvé et al., 2020; Stusak et al., 2014). Although, the short, repeated interview questions allowed our participants to revisit the past week and recall what had triggered peaks and troughs in their daily data, memories reflected participants' perspective on the past. Bentvelzen et al. (2022) argue that revisiting the past tries to offer an objective portrait of the past, whereas artifacts that use memories choose a more subjective approach. We agree with this argument, and we observed that during the interviews: our participants reconstructed and revisited life events from memory combined with a further analysis (explanation and evaluation) of these memories. Using time as a means to offer users a new point of view, which, in turn, can lead to reflection, has been defined as 'temporal perspective' (Bentvelzen et al., 2022). 'Past' and 'memories' are two out of four resources contributing to the temporal perspective (Bentvelzen et al., 2022).

R1: Technology to prompt explanation. Revisiting the 3D models at any time formed the basis for discussion with the researcher in the short interview sessions, with a family member or with a friend, and provided an opportunity to explain and justify the observed events. Our findings showed that the artifacts encouraged our participants to engage in conversation with family members or friends and reflect on their activity levels in light of others' comments (e.g., parents commenting on child's (in)active days or hobbies). This finding supports social dimension of reflection through conversations, a design resource for reflection identified by Bentvelzen et al. (2022) and Kocielnik, Xiao, Avrahami, and Hsieh (2018).

R2: Technology to see more. The models were reported to support a few aspects of 'seeing from another perspective'. Physicalizations helped children and adolescents understand concepts related to the data and activities they tracked, and to clear any misconceptions. In this regard, our results echo the research conducted by Ananthanarayan et al. (2016) whose participants' definition of health involved non-health-related activities such as coloring or playing music, and thus varied from the scientific definition (although arguably these activities can have positive effect on one's mental health (Lefevre, 2004; Moss, 1993)). In our study, this misunderstanding was evident when participants described difficult and tiring activities, such as playing computer games or doing homework, as PA. We agree with Ananthanarayan et al. (2016) who argued that such erroneous understanding may be a great starting point for children and adolescents to facilitate thinking about the topic in a correct way in the future, which was also the case here. Rather than forcing a particular agenda or definition on children and adolescents, having them think about their own health, in a manner they are comfortable with, is a necessary stepping stone towards evolving understanding of the types of health activities adults consider necessary (e.g., running, eating more vegetables) (Ananthanarayan et al., 2016). Our results support this and show that physicalizations can address the misconceptions and help children and adolescents understand their behavior and its consequences. This may also relate to 'discovery', the fourth design resource for reflection (Bentvelzen et al., 2022), where participants saw PA in a new light ('reframing'). Reframing is often implemented through the use of data physicalization as a design pattern (Bentvelzen et al., 2022); however, its examples in the HCI literature related to children and adolescents and their PA levels are limited.

R3,4: Transformation. In our intervention study, 3D models led to higher levels of reflection, including challenging of original assumptions and acquiring knowledge about the PA and its intensity levels in the context of participants' lives. For example, children and adolescents were anticipating the shape and size of their future models, adjusting their activities or hobbies to meet the goal, or keeping the artifacts visible. Especially the latter (e.g., wearing the models on a key ring) enabled further opportunities to engage in reflection-in-action, leading to signing up to a gym or picking up cycling. Reflection-in-action is related to thinking ahead of the action, critically experiencing and adjusting to the activity as it unfolds (Schon & DeSanctis, 1986). This highlight further benefits of wearable physicalizations, as opposed to static models that people keep at home. Previous research (Stusak et al., 2014) showed that out of four different models (see Fig. 1), a necklace was the only physicalization that could be worn or shown to others, thus fulfilling participants' expectation on visiting the past (R0), and self-expression and comparisons (to other models belonging to the same participant, or other participants' models). While a significant amount of research on tangible visualizations for PA is focused on ubiquitous nature of such visualization (Khot, 2014; Sauvé et al., 2020, 2017; Stusak et al., 2014), our work suggests that we can further facilitate reflection by designing the 3D models in a way that encourages publicly displaying them or keeping them at hand.

Additionally, the transformation can happen via reflection-on-action (i.e., the appraisal of the action after it has occurred) (Schon & DeSanctis, 1986). This was observed as our participants compared their pieces throughout the study, which Bentvelzen et al. (2022) consider as another resource for reflection. The flat design enabled stacking the models on top of one another, which allowed children to make size-based comparisons and visually assess the overall progress over time. It also helped to separate models they were more (or less) proud of to either use as a motivator or to hide (e.g., because it was too good and thus too valuable, or too small and thus too embarrassing). Moreover, our participants compared their daily activity levels with the target bar (ideal status or 'absolute reference' (Bentvelzen et al., 2022)) and made comments on how far or how close they are to its full-length. The position and the shape of the target bar (and its additional function as a key ring) made comparison easy and quick. With the above in mind, we argue that designers should consider building tangible artifacts that are easy to compare, to be inspected, and to be seen. This will help to leave room for active perception, even when the embodied information about the actual PA can be as little as "I did some physical activity" in any given time scale. This may open numerous opportunities for accessory design to enhance wearable visualizations for children and adolescents (Bae et al., 2022).

The experience of reflection. During the interviews, we did not respond to or comment on participants' answers, but merely asked the same questions to see if the models changed participants' knowledge about the meaning of PA and the intensity of PA levels. Similar to health crafting (Ananthanarayan et al., 2016), through experimentation and repeated short interview questions as prompts, children and adolescents in our study reflected on and developed an understanding of how their physical activities and the context they operated in influenced the artifact's shape and size, and, as a result, gained knowledge about their PA. For example, participants were able to see that spending time with a physically active parent, going for long runs outside the house instead of short runs in the garden, or playing long hours at the computer all had impact on the shape and size of the models.

Our findings highlight that there is no clear distinction between technology encouraging revisitation and technology for seeing more or transformation, for example. We agree with Fleck's and Fitzpatrick's (Fleck & Fitzpatrick, 2010) view on the circularity of reflection: "*there is a certain circularity to it all with higher levels of reflection following from lower levels by making use of the same techniques*" (p.221).

5.1.2. Supporting emotional engagement, memorability and aesthetic versatility

One of the key elements of our study design was delayed feedback (Khot & Mueller, 2013). We decided to use it as receiving feedback on activity after it has been completed can add a surprise element and may encourage curiosity and interest in doing opportunistic PA (Consolvo et al., 2012; Khot, Aggarwal et al., 2017; Khot et al., 2015). Our results show that this indeed was the case. Interacting with physical objects involves human perception (Gibson, 1986) and can evoke emotions (Jansen et al., 2015), and our results showed that handing each model after a break built pleasant surprise element, encouraged curiosity, or caused disappointment.

Additionally, this delayed feedback did not appear to reduce participants' ability to recall events from the week before. Similar to the findings reported by Stusak et al. (2015), children and adolescents were able to recall why and how their activities changed throughout the past week and which week/model was the worst or the best—even if they did not have all the models at hand during the interviews. The delayed feedback therefore appears to have enhanced memorizing the best and worst experiences, which can be exploited in future interventions.

Children and adolescents had different attitudes to presenting their physicalizations i.e., children were more likely to display their models publicly while adolescents were likely to keep the models in their own private space. Regardless of the arrangement of models in public or private spaces at home, the models acted as a memory landscape, memory trigger and motivational prompt (Bentvelzen et al., 2022; Van Den Hoven, 2004). This allowed participants to recall their previous weeks' activities, remember to wear the accelerometer or adhere to PA. Khot and Mueller (2013) argue that the arrangement of tangible objects is driven by the aesthetics rather than the embodied information in the tangible artifact. Our results support this, as our primary school participants were more likely to share their models publicly, while secondary school children kept them in their private space. Although both models in our study conveyed similar information about one's activity levels, the sun model had more abstract representation compared to the bar graph. The abstraction might have made the sun model looks cooler, but conveying information might have been difficult for family members and friends. Therefore, this abstract nature might have contributed to younger children's preference to keep the model visible, which suggests that perhaps designers and researchers should also consider aesthetics of tangible artifacts aimed at children and adolescents.

5.2. Tangible artifacts and temporality of experiences

Time is an important factor in studying UX of digital technologies and the experience changes and evolves as time goes by Karapanos et al. (2009) and Odom et al. (2018). Indeed, our results show that the understanding of PA itself, of the tangible artifacts and how they relate to PA, developed over time.

In their study, Karapanos et al. (2009) show that early experiences of digital products seemed to relate mostly to hedonic aspects of that product's use, whereas prolonged experiences became increasingly more relevant to the meaning of the product in individual's life. They also identified three phases for the adoption of digital products: orientation (i.e., making sense of the product and its purpose), incorporation (i.e., understanding how it fits into one's life (functional role)), and identification (i.e., final emotional attachment). However, these phases were not clearly present in our study and seemed to overlap. For example, the first tangible model (baseline data, *Week 1*) played a crucial role in orienting participants to understand what models look like (shape and size), but it took a while for some of them to understand the meaning of PA. Children and adolescents looked at their activities through the lens of the models and therefore the understanding of what PA is and how different factors influence it developed with a slower pace and generally continued throughout the study. Additionally, throughout the whole study, participants incorporated the models in their lives as personal objects in either private or public/shared spaces; there was no clear stage where this incorporation took place. Children's and adolescents' attitudes to the models were reflected by locations where the models were kept, and their attitudes towards the models and emotional attachments stayed largely the same throughout the study. Although our findings seemingly contradict those of Karapanos et al. (2009), it should be noted that their research did not look at individual differences in use and the proposed phases of use were not clearly related to progression in time neither for the individual participant nor across participants. Additionally, there are not many temporal studies of user experiences with children and adolescents in the literature and thus opportunities to discuss our findings in this context are limited.

To capture a full picture of one's experiences with tangible artifacts and how they change, it is important to measure individual's familiarity with the artifacts over time. Additionally, repeated evaluations with participants and across two age groups allowed us to capture differences amongst children's and adolescents' engagement and interaction with the models as personal objects, understanding of the models and the impact on personal circumstances, and understanding of PA. Therefore our study suggests that temporal process and regular interviews are crucial to understand the role of regular physicalization on children's and adolescents' engagement with PA and the importance of time to reflect, actively perceive and interact with the models.

5.3. Challenges and opportunities of physical activity physicalizations aimed at children and adolescents

Using 3D-printed artifacts as physicalizations of PA aimed at children and adolescents opens up many opportunities, but also challenges for the research and user communities. For example, scalability is an interesting problem as 3D-printing models regularly cost time and resources, and longer-term approach to this type of an intervention is necessary. After all, the understanding of PA and its benefits does not develop overnight, and getting used to the models, what they represent (or not), and how and what data could be linked to the models evolves over many weeks.

Additionally, the tangible artifacts should stand on their own and be meaningful over a period of time. Our models were scaled for one week and participants were able to identify the days of the week, reflect on the daily PA levels and compare the days and weekly models. Although the fading method lasted seven weeks, for longer-term studies (e.g., focused on behavior change and habit formation) more models may be required. In such studies, at a certain point the number of models would become less manageable or comparable. Moreover, as the awareness and understanding increase over time, children and adolescents are likely to lose interest in the models or engaging with PA (Epstein, Ping, Fogarty, & Munson, 2015). A solution could be choosing varying personal goals and once a goal is met, a harder goal is set and printed. This idea follows on gamification principles (Johnson et al., 2016), unlocking a new game (meeting the activity goal in our case) after achieving certain points in the game. Another idea is to build planned obsolescence into the intervention design: models could serve as initial motivators and visual cues to help simulate new behaviour (Stawarz, Cox, & Blandford, 2015). Contextual cues are effective as visual reminders and prompts to action (Einstein, 1993; Manning & Edwards, 1995), but their effectiveness decreases with time (Tobias, 2009). However, as the automaticity of behavior (that is associated with habit strength, see Gardner, 2012) increases with time, the need for motivation and conscious deliberation decreases, which means that cues are the most effective while the behavior is still new. Physicalizations could serve as such cues.

Another challenge is sustainability and the environmental impact of producing *de facto* disposable models. For our study, we used 3D printers that produced plastic-based artifacts. Such materials raise serious issues for sustainability and environmental pollution. However, with advances in 3D printing recyclable materials and edible/liquid-based artifacts (Khot, Aggarwal et al., 2017; Khot et al., 2015; Wang et al., 2016), there are more sustainable and environmentally-friendly ways to produce artifacts for PA awareness in larger scales and over longer periods. For example, Behm et al. (2018) argue that less expensive and more sustainable material (blend of 70% recycled plastic and 30% recycled wood fiber) are just as durable as the more expensive material (100% virgin plastic). A possibility is the usage of biodegradable or plant-based PLA filament (Behm et al., 2018). Another solution would be offering summary artifacts that represent the data of an entire month after children and adolescents have become expert in understanding PA and their models. The parents or schools can also take an active role in recycling plastic-based objects, although it should be noted that many children and adolescents in the study valued and treasured their models and wanted to keep them.

It is important to note that 3D visualization naturally has a higher level of visibility compared to screen-based feedback (Golsteijn et al., 2012). This increased visibility offers many opportunities as well as challenges for children, adolescents and the research community. For example, visibility of the models in public or private spaces evoked experiences of embodied reflection, active learning and emotional engagement for children and adolescents in our study however, wearing health tracking devices such as Fitbit and using its companion health screen-based app have shown to have limited engagement with the device and the data, increased resistance to learning about self and modest increase or no increase in the PA levels (Goodyear, Kerner, & Quennerstedt, 2017; Ridgers et al., 2021). Therefore, tangible visualizations may be a more supportive approach for changing youths behavior in learning about self in longer term and potentially tackling childhood inactivity. In the other hand, 3D-printed PA data is more publicly visible to friends, teachers and family members. The interviews highlighted that friends and family members did indeed come into regular contact with the 3D models given the range of ways that children and adolescents displayed their models in the bedroom, on their school bag or attached to the house keys. In this regard, it is important to consider how the visibility of the 3D models may have stimulated more social-interactions with friends and family and thus, influenced children's and adolescents' levels of self-perception and reflection of their PA levels, rather than the 3D model itself. Indeed, the involvement of friends (Maturo & Cunningham, 2013; Pearce, Page, Griffin, & Cooper, 2014; Salvy et al., 2009) and family (Davison et al., 2013; Haerens, De Bourdeaudhuij, Maes, Cardon, & Deforche, 2007; Haerens, Deforche, Maes, Cardon, Stevens, & De Bourdeaudhuij, 2006; Pearce et al., 2014; Sleddens, Gerards, Thijs, De Vries, & Kremers, 2011) can play a significant role in motivating children and adolescents to be more engaged in PA. On the contrary, sharing and comparing 3D models with friends or peers may increase competition, which can lead to negative feelings of the self and peer pressure to engage in an activity (Goodyear et al., 2017). Of concern are adolescent girls as they are particularly vulnerable at this age to body dissatisfaction, as this is a time when self-awareness, self-consciousness and preoccupation with self-image all dramatically increase (Harter, 1993). Indeed, a number of adolescent girls in the present study reflected on how their parents expect them to be more active or how they are being perceived as physically active according to the 3D model. As a consequence, children and adolescent who display such feelings of pressure and guilt for not achieving enough PA may hesitate or remove themselves from sharing their PA levels with others (Crossley, 2019; Goodyear et al., 2017;

Kerner & Goodyear, 2017) and abandon the 3D model, although we did not find this in our study. These issues do question how public displays of PA data could potentially compromise individual's privacy (Khot, 2014). In this light, future research should consider observing more closely how children and adolescents, and in particular adolescent girls, personally reflect and evaluate their PA levels with respect to body image and the influence of interactions and support from parents, friends and peers on PA levels.

Finally, studying children and adolescents at schools poses its own unique challenge. In our study, we manually collected the accelerometers at the end of each week, downloaded the data, and handed over the artifacts at specific intervals. We conducted short interviews with participants in schools after handing over the artifacts and this enabled us to gather feedback from participants in the field and to better understand their initial/real-time feelings and relationship to the models. However, this process required time commitment and coordination with the schools and teachers. For example, we tried to minimize disruption to children's and adolescents' study time by conducting interviews during physical education lessons or in the school library during breaks. It is also important to highlight the role parents played in the study: their consent, direct (e.g., actively engaging in activities with their children) and indirect (e.g., looking after the models) support and time were as important as schools' role in such studies. Additionally, and perhaps more importantly, parents saw the health benefit for their children's participation in our study and some were in fact concerned about their child's inactivity (e.g., playing computer games for too long). It is noteworthy that longer-term studies are associated with increased time and resources and careful planning around children's and adolescents' education time. One solution to address this could be blending the study with the teaching curriculum and having printers based in the school; longer-term studies could start with regular contact time with the research team for a few weeks, then hand over to the schools with bi-monthly interviews with the research team.

6. Limitations and future work

Our study comprised of 97 children and adolescents over the duration of seven weeks. While our number of participants is larger compared to similar studies in the literature (e.g., Khot, Aggarwal et al., 2017; Khot et al., 2014, 2015; Odom & William, 2015; Saksono & Parker, 2017; Sauvé et al., 2020; Stusak et al., 2014), our interviews were relatively short. However, due to exploratory nature of this study, they were sufficient to capture and investigate all children's and adolescents' attitudes and engagement with PA. Nevertheless, we believe longer studies with more participants are needed to draw strong conclusions on the effectiveness of tangible artifacts and the motivational impact of such objects on PA education and potentially reducing childhood inactivity.

In some PA studies (e.g., Stusak et al., 2014) it has been argued that the data collection process might influence the participants' experience (i.e., participants might have felt obliged to comply and be 'good participants') (Barabasz & Barabasz, 1992), and thus the collected data or study results were not representative of real-world behaviors. However, those studies were conducted with adults and not with children and adolescents who may find the activities fun. Moreover, we did not observe such obligations from our participants. Because of the delayed feedback, it was difficult to know whether one's behavior 'pleases' the researcher, children and adolescents also frequently expressed their surprise at the results. In addition, our data also shows that participants were motivated to be active to influence the shape of their models (Bae et al., 2022). Some children and adolescents also freely admitted forgetting to wear the activity tracker, while others were unable to change their circumstances (e.g., living with an inactive parent), which would have prevented them from trying to be more active for our sake. Additionally, we minimized interpersonal contact between the interviewer and the participant by not correcting or answering participants' questions regarding models during the interviews, which might have reduced experimenter expectancy effect (Barabasz & Barabasz, 1992).

Further work should explore the role of involving children and adolescents in 3D-printing their own models and exploring different formats, as well as involving parents in data collection and sense-making, and exploring their role in this process. Embedding tools such as 3D printers in schools and enabling children and adolescents to create their own data physicalizations can open up further opportunities for teaching programming, data science or supporting science education, as they are an engaging way for presenting collected data. As our study included two age-specific models, future research could compare our results against more diverse age-specific models, ideally driven by personalization and individual participants' preferences, where different mappings of activity data could be explored. Additionally, future designs could include engravings and different colors to detail the different components (i.e. moderate- and vigorous-intensity bars, guideline bar) to heighten especially children's understanding of terms.

Physicalization has far-reaching applications, beyond reducing childhood inactivity. As the findings of this study show, physicalization supports learning, reflection, and emotional engagements, and that physicalization could address childhood gambling, unhealthy eating, mental health, carbon footprint of household activities and wider environmental issues and, evoking compassion and humanitarian causes (Dragicevic, 2022; Morais, Andrade, & Sousa, 2022; Willett et al., 2021), for example. To apply physicalization to such domains, it is important to understand children's perceptions and understanding about those topics through crafting (e.g., Play-Doh modeling, drawing, storytelling) in the first instance. Then, iterative process and user-centred design is essential to refine the artifacts. Future research to apply physicalization to domains beyond PA should note that behavior change requires reflection and active learning and, those are temporal processes and children's and adolescents' experience with the artifacts and their learning evolves over time. Therefore, repeated evaluations with children and adolescents are important to capture differences amongst participants regarding their interactions with models as personal objects, understanding of the models and the impact on personal circumstances, and understanding of the subject of study.

7. Conclusions

We explored children's and adolescents' general experience of PA through tangible artifacts and their feelings and reflections on the use of physicalizations to represent their activity data. Our findings suggest that the physical representation of PA evoked a number of experiences in children and adolescents: (a) they were able to use the models for reflection, from revisitation of the past to active learning and transformation; (b) they actively perceived their models (i.e., they inspected, compared and displayed them publicly or privately); (c) the one-week delayed feedback not only enhanced children's and adolescents' memorability of events but also triggered elements of surprise and curiosity throughout the study; and (d) models supported temporal perspective, comparison, conversation, and discovery. Our study therefore suggests that regular (albeit not necessarily frequent) contact with physicalizations offers a positive experience and a gateway for children's and adolescents' reflection on their PA and transforming their awareness about PA over time. We believe that enforcing the PA guidelines through tangible visualizations could encourage children and adolescents to engage in embodied reflection and active learning, which may be a more supportive approach for changing their behavior in longer term and potentially tackling childhood inactivity.

Selection and participation of children

We investigated the efficacy of age-specific 3D-printed models with 97 children and adolescents: 39 primary school children (aged 7.9 [SD 0.3] years; 22 boys and 17 girls) and 58 secondary school adolescents (aged 13.8 [SD 0.3] years; 37 boys and 21 girls).

The seven-week intervention study was conducted in [Anonymized], UK. All primary school and 96% of secondary school children were White British, with the remaining 4% being Asian British (2%; $n = 1$) and Black British (2%; $n = 1$).

The recruitment took place at the school level, then all consenting schools invited all children and adolescents in each included year group. All children and adolescents who provided the written informed parental/carer consent and child assent were included.

Ethical approval was granted by the University Ethics Committee (ref: PG/2014/40) and conducted in accordance with the Declaration of Helsinki.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Ananthanarayan, Swamy, Siek, Katie, & Eisenberg, Michael (2016). A craft approach to health awareness in children. In *Proceedings of the 2016 ACM conference on designing interactive systems* (pp. 724–735). New York, NY, USA: ACM, ISBN: 978-1-4503-4031-1, http://dx.doi.org/10.1145/2901790.2901888, URL http://doi.acm.org/10.1145/2901790.2901888.

Attig, Christiane, & Franke, Thomas (2022). Why do people abandon activity trackers? The role of user diversity in discontinued use. *International Journal of Human-Computer Interaction*, [ISSN: 15327590] http://dx.doi.org/10.1080/10447318.2022.2067935.

Bae, S. Sandra, Zheng, Clement, West, Mary Etta, Do, Ellen Yi Luen, Huron, Samuel, & Szafir, Danielle Albers (2022). Making data tangible: A cross-disciplinary design space for data physicalization. In *Conference on human factors in computing systems - proceedings*. Association for Computing Machinery, ISBN: 9781450391573, http://dx.doi.org/10.48550/arxiv.2202.10520, URL https://arxiv.org/abs/2202.10520v1.

Bakker, Saskia, van den Hoven, Elise, & Eggen, Berry (2015). Peripheral interaction: characteristics and considerations. *Personal and Ubiquitous Computing*, [ISSN: 1617-4917] *19*(1), 239–254. http://dx.doi.org/10.1007/s00779-014-0775-2.

Bara, Florence, Gentaz, Edouard, Colé, Pascale, & Sprenger-Charolles, Liliane (2004). The visuo-haptic and haptic exploration of letters increases the kindergarten-children's understanding of the alphabetic principle. *Cognitive Development*, [ISSN: 08852014] *19*(3), 433–449. http://dx.doi.org/10.1016/j.cogdev.2004.05.003, URL https://hal.archives-ouvertes.fr/hal-00733557/document.

Barabasz, Arreed F., & Barabasz, Marianne (1992). Research designs and considerations. In *Contemporary hypnosis research* (pp. 173–200). New York, NY, US: Guilford Press, ISBN 0-89862-893-8 (Hardcover).

Behm, Jocelyn E., Waite, Brenna R., Hsieh, S. Tonia, & Helmus, Matthew R. (2018). Benefits and limitations of three-dimensional printing technology for ecological research. *BMC Ecology*, [ISSN: 14726785] *18*(1), 32. http://dx.doi.org/10.1186/s12898-018-0190-z, URL pmc/articles/PMC6131837/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC6131837/.

Bentvelzen, Marit, Woźniak, Paweł W, Herbes, Pia S F, Stefanidi, Evropi, & Niess, Jasmin (2022). Revisiting reflection in HCI. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, *6*(1), 1–27. http://dx.doi.org/10.1145/3517233, URL https://dl.acm.org/doi/abs/10.1145/3517233.

Berman, Alexander, Deuermeyer, Elizabeth, Nam, Beth, Chu, Sharon Lynn, & Quek, Francis (2018). Exploring the 3D printing process for Young children in curriculum-aligned making in the classroom. In *IDC 2018 - Proceedings of the 2018 ACM conference on interaction design and children* (pp. 681–686). Association for Computing Machinery, Inc, ISBN: 9781450351522, http://dx.doi.org/10.1145/3202185.3210799.

Bevan, W., & Steger, J. A. (1971). Free recall and abstractness of stimuli. *Science*, *172*(3983), 597–599. http://dx.doi.org/10.1126/science.172.3983.597, ISSN 0036-8075 (Print).

Braun, Virginia, & Clarke, Victoria (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101, URL http://eprints.uwe.ac.uk/11735/2/thematic_analysis_revised....

Braun, Virginia, & Clarke, Victoria (2021). Can I use TA? Should I use TA? Should I not use TA? Comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches. *Counselling and Psychotherapy Research*, [ISSN: 1746-1405] *21*(1), 37–47. http://dx.doi.org/10.1002/CAPR.12360, URL https://onlinelibrary.wiley.com/doi/10.1002/capr.12360.

Burzynska, Bozena, & Stolarski, Maciej (2020). Rethinking the relationships between time perspectives and well-being: Four hypothetical models conceptualizing the dynamic interplay between temporal framing and mechanisms boosting mental well-being. *Frontiers in Psychology*, [ISSN: 16641078] *11*, 1033. http://dx.doi.org/10.3389/FPSYG.2020.01033/BIBTEX.

Chi, Ed H. (2000). A taxonomy of visualization techniques using the data state reference model. In *Proceedings of the IEEE symposium on information vizualization 2000* (p. 69). Washington, DC, USA: IEEE Computer Society, ISBN: 0-7695-0804-9, URL http://dl.acm.org/citation.cfm?id=857190.857691.

Choe, Eun Kyoung, Lee, Bongshin, & Schraefel, M. C. (2015). Characterizing visualization insights from quantified selfers' personal data presentations. *IEEE Computer Graphics and Applications*, [ISSN: 02721716] *35*(4), 28–37. http://dx.doi.org/10.1109/MCG.2015.51.

Choe, Eun Kyoung, Lee, Bongshin, Zhu, Haining, Riche, Nathalie Henry, & Baur, Dominikus (2017). Understanding self-reflection. In *Proceedings of the 11th EAI international conference on pervasive computing technologies for healthcare - PervasiveHealth '17* (pp. 173–182). New York, New York, USA: ACM Press, ISBN: 9781450363631, http://dx.doi.org/10.1145/3154862.3154881, URL http://dl.acm.org/citation.cfm?doid=3154862.3154881.

Claes, Sandy, & Vande Moere, Andrew (2015). The role of tangible interaction in exploring information on public visualization displays. In *PerDis 2015 - Proceedings: 4th ACM international symposium on pervasive displays* (pp. 201–207). Saarbruecken, Germany: ACM, ISBN: 9781450336086, http://dx.doi.org/10.1145/2757710.2757733.

Clarke, Victoria, & Braun, Virginia (2021). In Virginia Braun Braun, & Victoria Clarke (Eds.), *Thematic Analysis: A Practical Guide*. SAGE Publications Ltd, ISBN: 9781473953246, URL https://uk.sagepub.com/en-gb/eur/thematic-analysis/book248481#description.

Clawson, James, Pater, Jessica A., Miller, Andrew D., Mynatt, Elizabeth D., & Mamykina, Lena (2015). No longer wearing: Investigating the abandonment of personal health-tracking technologies on craigslist. In *UbiComp 2015 - Proceedings of the 2015 ACM international joint conference on pervasive and ubiquitous computing* (pp. 647–658). Association for Computing Machinery, Inc, ISBN: 9781450335744, http://dx.doi.org/10.1145/2750858.2807554.

Cohn, Michael A., Fredrickson, Barbara L., Brown, Stephanie L., Mikels, Joseph A., & Conway, Anne M. (2009). Happiness unpacked: positive emotions increase life satisfaction by building resilience. *Emotion (Washington, D.C.)*, [ISSN: 1528-3542] *9*(3), 361–368. http://dx.doi.org/10.1037/A0015952, URL https://pubmed.ncbi.nlm.nih.gov/19485613/.

Consolvo, Sunny, Klasnja, Predrag, McDonald, David W., & Landay, James A. (2012). Designing for healthy lifestyles: Design considerations for mobile technologies to encourage consumer health and wellness. *Foundations and Trends in Human-Computer Interaction*, [ISSN: 15513963] *6*(3–4), 167–315. http://dx.doi.org/10.1561/1100000040, URL http://www.nowpublishers.com/articles/foundations-and-trends-in-humancomputer-interaction/HCI-040.

Coşkun, Aykut, & Karahanoğlu, Armağan (2022). Data sensemaking in self-tracking: Towards a new generation of self-tracking tools. [ISSN: 15327590] http://dx.doi.org/10.1080/10447318.2022.2075637, URL https://www.tandfonline.com/doi/abs/10.1080/10447318.2022.2075637.

Crossley, Sam G. M. (2019). *Novel methods of measuring and visualising youths' physical activity* (Ph.D. thesis), Swansea: Swansea University, URL https://cronfa.swan.ac.uk/Record/cronfa50756.

Crossley, Sam Graeme Morgan, McNarry, Melitta Anne, Eslambolchilar, Parisa, Knowles, Zoe, & Mackintosh, Kelly Alexandra (2019). The tangibility of personalized 3D-printed feedback may enhance youths' physical activity awareness, goal setting, and motivation: Intervention study. [ISSN: 14388871] URL https://www.jmir.org/2019/6/e12067/.

Crossley, Sam Graeme Morgan, McNarry, Melitta Anne, Hudson, Joanne, Eslambolchilar, Parisa, Knowles, Zoe, & Mackintosh, Kelly Alexandra (2019). Perceptions of visualizing physical activity as a 3D-printed object: Formative study. *Journal of Medical Internet Research*, [ISSN: 14388871] *21*(1), Article e12064. http://dx.doi.org/10.2196/12064, URL https://www.jmir.org/2019/1/e12064/.

Crossley, Sam Graeme Morgan, McNarry, Melitta Anne, Rosenberg, Michael, Knowles, Zoe R., Eslambolchilar, Parisa, & Mackintosh, Kelly Alexandra (2019). Understanding youths' ability to interpret 3D-printed physical activity data and identify associated intensity levels: Mixed-methods study. *Journal of Medical Internet Research*, [ISSN: 14388871] *21*(2), Article e11253. http://dx.doi.org/10.2196/11253, URL https://www.jmir.org/2019/2/e11253/.

Crouter, Scott E., Horton, Magdalene, & Bassett, David R. (2013). Validity of ActiGraph child-specific equations during various physical activities. *Medicine and Science in Sports and Exercise*, [ISSN: 01959131] *45*(7), 1403–1409. http://dx.doi.org/10.1249/MSS.0b013e318285f03b, URL /pmc/articles/PMC3686914//pmc/articles/PMC3686914/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC3686914/.

Daugherty, James R., & Brase, Gary L. (2010). Taking time to be healthy: Predicting health behaviors with delay discounting and time perspective. *Personality and Individual Differences*, [ISSN: 0191-8869] *48*(2), 202–207. http://dx.doi.org/10.1016/J.PAID.2009.10.007.

Davison, Kirsten K., Mâsse, Louise C., Timperio, Anna, Frenn, Marilyn D., Saunders, Julie, Mendoza, Jason A., et al. (2013). Physical activity parenting measurement and research: challenges, explanations, and solutions. *Childhood Obesity (Print)*, [ISSN: 2153-2176] *9 Suppl*(Suppl 1), http://dx.doi.org/10.1089/CHI.2013.0037, URL https://pubmed.ncbi.nlm.nih.gov/23944918/.

Delson, Nathan, van Den Einde, Lelli, Tuazon, Jessica, & Yang, Daniel (2020). Development of a spatial visualization assessment tool for Younger students using a lego™ assembly task. In *ASEE annual conference and exposition, conference proceedings, Vol. 2020-June*. American Society for Engineering Education, http://dx.doi.org/10.18260/1-2--34452, ISSN 21535965.

Ding, Zhaochen (2017). Alternative 3D education for children: Course design of 3D printing interactivity for Beijing's primary schools. In *ACM International Conference Proceeding Series, Vol. Part F128362* (pp. 30–35). Association for Computing Machinery, ISBN: 9781450353083, http://dx.doi.org/10.1145/3080631.3080637.

Dix, Alan (2007). Designing for appropriation. In *People and computers XXI HCI.But not as we know it - proceedings of HCI 2007: The 21st British HCI group annual conference, Vol. 2*. BCS Learning & Development, ISBN: 9781902505954, http://dx.doi.org/10.14236/EWIC/HCI2007.53, URL https://www.scienceopen.com/hosted-document?doi=10.14236/ewic/HCI2007.53.

Dragicevic, Pierre (2022). Towards immersive humanitarian visualizations.

Dragicevic, Pierre, & Jansen, Yvonne (2014). List of active physical visualizations. URL http://dataphys.org/list/http://www.aviz.fr/wiki/pmwiki.php/Research/ActivePhysicalVisualizations.

Drehlich, Mark, Naraine, Michael, Rowe, Katie, Lai, Samuel K., Salmon, Jo, Brown, Helen, et al. (2020). Using the technology acceptance model to explore adolescents' perspectives on combining technologies for physical activity promotion within an intervention: Usability study. *Journal of Medical Internet Research*, [ISSN: 14388871] *22*(3), Article e15552. http://dx.doi.org/10.2196/15552, URL https://pubmed.ncbi.nlm.nih.gov/32141834/.

Dunn, Rita, & Dunn, Kenneth (1975). Learning styles, teaching styles. *NASSP Bulletin*, [ISSN: 0192-6365] *59*(393), 37–49. http://dx.doi.org/10.1177/019263657505939308, URL http://journals.sagepub.com/doi/10.1177/019263657505939308.

Einstein, Gilles O. (1993). The importance of cue familiarity and cue distinctiveness in prospective memory. *Memory*, [ISSN: 14640686] *1*(1), 23–41. http://dx.doi.org/10.1080/09658219308258223, URL https://pubmed.ncbi.nlm.nih.gov/7584257/.

Epstein, Daniel A., Eslambolchilar, Parisa, Kay, Judy, Meyer, Jochen, & Munson, Sean A. (2021). Opportunities and challenges for long-term tracking. *In: Karapanos E., Gerken J., Kjeldskov J., Skov M.B. (Eds) Advances in Longitudinal HCI Research. Human–Computer Interaction Series*, 177–206. http://dx.doi.org/10.1007/978-3-030-67322-2{_}9, URL https://link.springer.com/chapter/10.1007/978-3-030-67322-2_9,

Epstein, Daniel A., Ping, An, Fogarty, James, & Munson, Sean A. (2015). A lived informatics model of personal informatics. In *UbiComp 2015 - Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 731–742). New York, New York, USA: Association for Computing Machinery, Inc, ISBN: 9781450335744, http://dx.doi.org/10.1145/2750858.2804250, URL http://dl.acm.org/citation.cfm?doid=2750858.2804250.

Evenson, Kelly R., Catellier, Diane J., Gill, Karminder, Ondrak, Kristin S., & McMurray, Robert G. (2008). Calibration of two objective measures of physical activity for children. *Journal of Sports Sciences*, [ISSN: 0264-0414] *26*(14), 1557–1565. http://dx.doi.org/10.1080/02640410802334196, URL http://www.ncbi.nlm.nih.gov/pubmed/18949660http://www.tandfonline.com/doi/abs/10.1080/02640410802334196.

Fleck, Rowanne, & Fitzpatrick, Geraldine (2010). Reflecting on reflection: Framing a design landscape. In *ACM international conference proceeding series* (pp. 216–223). http://dx.doi.org/10.1145/1952222.1952269.

Fletcher, Ben C., Hanson, Jill, Page, Nadine, & Pine, Karen (2011). FIT - do something different: A new behavioral programfor sustainedweight loss. *Swiss Journal of Psychology*, [ISSN: 14210185] *70*(1), 25–34. http://dx.doi.org/10.1024/1421-0185/A000035.

Forlizzi, Jodi, & Battarbee, Katja (2004). Understanding experience in interactive systems. In *Proceedings of the 2004 conference on designing interactive systems processes, practices, methods, and techniques - DIS '04* (p. 261). New York, New York, USA: ACM Press, ISBN: 1581137877, http://dx.doi.org/10.1145/1013115.1013152, URL http://portal.acm.org/citation.cfm?doid=1013115.1013152.

Gardner, Benjamin (2012). Habit as automaticity, not frequency. *European Health Psychologist*, *14*(2), 32–36.

Gibson, James J. (1986). *The ecological approach to visual perception* (New Ed ed.). (p. 348). New York: Routledge, ISBN: 0898599598, URL http://www.amazon.co.uk/The-Ecological-Approach-Visual-Perception/dp/0898599598.

Golsteijn, Connie, van den Hoven, Elise, Frohlich, David, & Sellen, Abigail (2012). Towards a more cherishable digital object. In *Proceedings of the designing interactive systems conference on - DIS '12* (p. 655). New York, New York, USA: ACM Press, ISBN: 9781450312103, http://dx.doi.org/10.1145/2317956.2318054, URL http://dl.acm.org/citation.cfm?doid=2317956.2318054.

Goodman, Jodi S., & Wood, Robert E. (2009). Faded versus increasing feedback, task variability trajectories, and transfer of training. *Human Performance*, [ISSN: 08959285] *22*(1), 64–85. http://dx.doi.org/10.1080/08959280802541013, URL https://www.tandfonline.com/doi/abs/10.1080/08959280802541013.

Goodyear, Victoria A., Kerner, Charlotte, & Quennerstedt, Mikael (2017). Young people's uses of wearable healthy lifestyle technologies; surveillance, self-surveillance and resistance, 24 (3), 212–225. http://dx.doi.org/10.1080/13573322.2017.1375907 ISSN 14701243 URL https://www.tandfonline.com/doi/abs/10.1080/13573322.2017.1375907.

Haerens, Leen, De Bourdeaudhuij, Ilse, Maes, Lea, Cardon, Greet, & Deforche, Benedicte (2007). School-based randomized controlled trial of a physical activity intervention among adolescents. *The Journal of Adolescent Health : Official Publication of the Society for Adolescent Medicine*, [ISSN: 1879-1972] *40*(3), 258–265. http://dx.doi.org/10.1016/J.JADOHEALTH.2006.09.028, URL https://pubmed.ncbi.nlm.nih.gov/17321427/.

Haerens, Leen, Deforche, Benedicte, Maes, Lea, Cardon, Greet, Stevens, Veerle, & De Bourdeaudhuij, Ilse (2006). Evaluation of a 2-year physical activity and healthy eating intervention in middle school children. *Health Education Research*, [ISSN: 0268-1153] *21*(6), 911–921. http://dx.doi.org/10.1093/HER/CYL115, URL https://pubmed.ncbi.nlm.nih.gov/17032704/.

Harrison, Daniel Bryan Peter (2020). *The Self-Tracker's Journey: situated engagement and non-engagement with personal informatics systems over time* (Ph.D. thesis), London: UCL (University College of London).

Harter, Susan (1993). Causes and consequences of low self-esteem in children and adolescents. In *Plenum series in social/clinical psychology*, *Self-Esteem: The puzzle of low self-regard* (pp. 87–116). New York, NY, US: Plenum Press, http://dx.doi.org/10.1007/978-1-4684-8956-9{_}5, ISBN 0-306-44373-2 (Hardcover).

Hassenzahl, Marc (2010). Experience design: Technology for all the right reasons. *Synthesis Lectures on Human-Centered Informatics*, [ISSN: 1946-7680] *3*(1), 1–95. http://dx.doi.org/10.2200/s00261ed1v01y201003hci008.

Hassenzahl, Marc, Laschke, Matthias, & Praest, Julian (2016). On the stories activity trackers tell. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing Adjunct - UbiComp '16* (pp. 582–587). New York, New York, USA: ACM Press, ISBN: 9781450344623, http://dx.doi.org/10.1145/2968219.2968325, URL http://dl.acm.org/citation.cfm?doid=2968219.2968325.

Hassenzahl, Marc, & Marc (2004). The interplay of beauty, goodness, and usability in interactive products. *Human-Computer Interaction*, [ISSN: 0737-0024] *19*(4), 319–349. http://dx.doi.org/10.1207/s15327051hci1904{_}2, URL http://www.tandfonline.com/doi/abs/10.1207/s15327051hci1904_2.

Hogan, Trevor, Hinrichs, Uta, Jansen, Yvonne, Huron, Samuel, Gourlet, Pauline, Hornecker, Eva, et al. (2017). Pedagogy & physicalization: Designing learning activities around physical data representations. In *DIS '17 Companion*, *Proceedings of the 2017 ACM conference companion publication on designing interactive systems* (pp. 345–347). New York, NY, USA: ACM, ISBN: 978-1-4503-4991-8, http://dx.doi.org/10.1145/3064857.3064859, URL http://doi.acm.org/10.1145/3064857.3064859.

Hruby, Adela, & Hu, Frank B. (2015). The Epidemiology of Obesity: A Big Picture, 33 (7), 673–689. http://dx.doi.org/10.1007/s40273-014-0243-x ISSN 11792027. URL /pmc/articles/PMC4859313/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC4859313/.

Huang, Dandan, Tory, Melanie, Adriel Aseniero, Bon, Bartram, Lyn, Bateman, Scott, Carpendale, Sheelagh, et al. (2015). Personal visualization and personal visual analytics. *IEEE Transactions on Visualization and Computer Graphics*, [ISSN: 10772626] *21*(3), 420–433. http://dx.doi.org/10.1109/TVCG.2014.2359887, URL https://pubmed.ncbi.nlm.nih.gov/26357073/.

Jafarinaimi, Nassim, Forlizzi, Jodi, Hurst, Amy, & Zimmerman, John (2005). Breakaway. In *CHI '05 extended abstracts on human factors in computing systems - CHI '05* (p. 1945). New York, New York, USA: ACM Press, ISBN: 1595930027, http://dx.doi.org/10.1145/1056808.1057063, URL http://portal.acm.org/citation.cfm?doid=1056808.1057063.

Jago, Russell, Salway, Ruth, Emm-Collison, Lydia, Sebire, Simon J, Thompson, Janice L, & Lawlor, Deborah A (2020). Association of BMI category with change in children's physical activity between ages 6 and 11 years: a longitudinal study. *International Journal of Obesity*, [ISSN: 1476-5497] *44*(1), 104–113. http://dx.doi.org/10.1038/s41366-019-0459-0.

Jansen, Yvonne, Dragicevic, Pierre, & Fekete, Jean Daniel (2013). Evaluating the efficiency of physical visualizations. In *Conference on human factors in computing systems - proceedings* (pp. 2593–2602). New York, NY, US: ACM, ISBN: 9781450318990, http://dx.doi.org/10.1145/2470654.2481359.

Jansen, Yvonne, Dragicevic, Pierre, Isenberg, Petra, Alexander, Jason, Karnik, Abhijit, Kildal, Johan, et al. (2015). Opportunities and challenges for data physicalization. In *Proceedings of the 33rd annual ACM conference on human factors in computing systems - CHI '15* (pp. 3227–3236). New York, New York, USA: ACM Press, ISBN: 9781450331456, http://dx.doi.org/10.1145/2702123.2702180, URL http://dl.acm.org/citation.cfm?doid=2702123.2702180.

Johnson, Daniel, Deterding, Sebastian, Kuhn, Kerri Ann, Staneva, Aleksandra, Stoyanov, Stoyan, & Hides, Leanne (2016). Gamification for health and wellbeing: A systematic review of the literature, 6, 89–106, http://dx.doi.org/10.1016/j.invent.2016.10.002 ISSN 22147829, URL /pmc/articles/PMC6096297/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC6096297/.

Kahneman, Daniel, Krueger, Alan B., Schkade, David A., Schwarz, Norbert, & Stone, Arthur A. (2004). A survey method for characterizing daily life experience: The day reconstruction method. *Science*, [ISSN: 00368075] *306*(5702), 1776–1780. http://dx.doi.org/10.1126/science.1103572, URL https://pubmed.ncbi.nlm.nih.gov/15576620/.

Karapanos, Evangelos, Jain, Jhilmil, & Hassenzahl, Marc (2012). Theories, methods and case studies of longitudinal HCI research. In *Proceedings of the 2012 ACM annual conference extended abstracts on human factors in computing systems extended abstracts - CHI EA '12* (p. 2727). New York, New York, USA: ACM Press, ISBN: 9781450310161, http://dx.doi.org/10.1145/2212776.2212706, URL http://dl.acm.org/citation.cfm?doid=2212776.2212706.

Karapanos, Evangelos, Martens, Jean Bernard, & Hassenzahl, Marc (2010). On the retrospective assessment of users' experiences over time: Memory or actuality? In *Conference on human factors in computing systems - proceedings* (pp. 4075–4080). New York, New York, USA: ACM Press, ISBN: 9781605589312, http://dx.doi.org/10.1145/1753846.1754105, URL http://portal.acm.org/citation.cfm?doid=1753846.1754105.

Karapanos, Evangelos, Zimmerman, John, Forlizzi, Jodi, & Martens, Jean-Bernard (2009). User experience over time. In *Proceedings of the 27th International Conference on Human Factors in Computing Systems - CHI 09* (p. 729). New York, New York, USA: ACM Press, ISBN: 9781605582467, http://dx.doi.org/10.1145/1518701.1518814, URL http://dl.acm.org/citation.cfm?doid=1518701.1518814.

Kerner, Charlotte, & Goodyear, Victoria A. (2017). The motivational impact of wearable healthy lifestyle technologies: A self-determination perspective on fitbits with adolescents. *American Journal of Health Education*, [ISSN: 21683751] *48*(5), http://dx.doi.org/10.1080/19325037.2017.1343161.

Khot, Rohit Ashok (2014). Exploring material representations of physical activity. In *Proceedings of the 2014 companion publication on designing interactive systems - DIS Companion '14* (pp. 177–180). New York, New York, USA: ACM Press, ISBN: 9781450329033, http://dx.doi.org/10.1145/2598784.2598792, URL http://dl.acm.org/citation.cfm?doid=2598784.2598792.

Khot, Rohit Ashok, Aggarwal, Deepti, Pennings, Ryan, Hjorth, Larissa, & Mueller, Florian (2017). EdiPulse: Investigating a playful approach to self-monitoring through 3D printed chocolate treats. In *Conference on human factors in computing systems - proceedings, Vol. 2017-May* (pp. 6593–6607). New York, NY, US: ACM, ISBN: 9781450346559, http://dx.doi.org/10.1145/3025453.3025980.

Khot, Rohit Ashok, Hjorth, Larissa, & Mueller, Florian 'Floyd' (2014). Understanding physical activity through 3D printed material artifacts. In *Proceedings of the 32nd annual ACM conference on human factors in computing systems - CHI '14* (pp. 3835–3844). New York, NY, US: ACM, ISBN: 9781450324731, http://dx.doi.org/10.1145/2556288.2557144.

Khot, Rohit Ashok, Lee, Jeewon, Aggarwal, Deepti, Hjorth, Larissa, & Mueller, Florian Floyd (2015). Tasty beats: Designing palatable representations of physical activity. In *Conference on human factors in computing systems - proceedings, Vol. 2015-April* (pp. 2933–2942). New York, New York, USA: Association for Computing Machinery, ISBN: 9781450331456, http://dx.doi.org/10.1145/2702123.2702197, URL http://dl.acm.org/citation.cfm?doid=2702123.2702197.

Khot, Rohit Ashok, & Mueller, Florian "Floyd" (2013). Sweat-atoms. In *CHI '13 extended abstracts on human factors in computing systems on - CHI EA '13* (p. 3075). New York, New York, USA: ACM Press, ISBN: 9781450319522, http://dx.doi.org/10.1145/2468356.2479614, URL http://dl.acm.org/citation.cfm?doid=2468356.2479614.

Khot, Rohit Ashok, Stusak, Simon, Butz, Andreas, & Mueller, Florian 'Floyd' (2017). 10 Design themes for creating 3D printed physical representations of physical activity data. In *LNCS*: *Vol. 10516*, *Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics)* (pp. 85–105). Springer Verlag, http://dx.doi.org/10.1007/978-3-319-68059-0{_}5/FIGURES/6, URL https://link.springer.com/chapter/10.1007/978-3-319-68059-0_5, ISSN 16113349.

Kim, Hyun K., Han, Sung H., Park, Jaehyun, & Park, Wonkyu (2015). How user experience changes over time: A case study of social network services. *Human Factors and Ergonomics in Manufacturing & Service Industries*, [ISSN: 10908471] *25*(6), 659–673. http://dx.doi.org/10.1002/hfm.20583, URL http://doi.wiley.com/10.1002/hfm.20583.

Kirk, David S., & Sellen, Abigail (2010). On human remains: Values and practice in the home archiving of cherished objects. *ACM Transactions on Computer-Human Interaction*, [ISSN: 10730516] *17*(3), 1–43. http://dx.doi.org/10.1145/1806923.1806924, URL https://www.microsoft.com/en-us/research/publication/on-human-remains-value-and-practice-in-the-home-archiving-of-cherished-objects/.

Kocielnik, Rafal, Xiao, Lillian, Avrahami, Daniel, & Hsieh, Gary (2018). Reflection companion. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, *2*(2), 1–26. http://dx.doi.org/10.1145/3214273.

Kohl, Harold W, Craig, Cora Lynn, Lambert, Estelle Victoria, Inoue, Shigeru, Alkandari, Jasem Ramadan, Leetongin, Grit, et al. (2012). The pandemic of physical inactivity: global action for public health. *Lancet (London, England)*, [ISSN: 1474-547X] *380*(9838), 294–305. http://dx.doi.org/10.1016/S0140-6736(12)60898-8, URL https://pubmed.ncbi.nlm.nih.gov/22818941/.

Kujala, Sari, Roto, Virpi, Väänänen-Vainio-Mattila, Kaisa, & Sinnelä, Arto (2011). Identifying hedonic factors in long-term user experience. In *Proceedings of the 2011 conference on designing pleasurable products and interfaces - DPPI '11* (p. 1). New York, New York, USA: ACM Press, ISBN: 9781450312806, http://dx.doi.org/10.1145/2347504.2347523, URL http://dl.acm.org/citation.cfm?doid=2347504.2347523.

Lee, Moon Hwan, Cha, Seijin, & Nam, Tek Jin (2015). Patina engraver: Visualizing activity logs as patina in fashionable trackers. In *Conference on human factors in computing systems - proceedings, Vol. 2015-April* (pp. 1173–1182). New York, New York, USA: ACM Press, ISBN: 9781450331456, http://dx.doi.org/10.1145/2702123.2702213, URL http://dl.acm.org/citation.cfm?doid=2702123.2702213.

Lefevre, Michelle (2004). Playing with sound: The therapeutic use of music in direct work with children. *Child <Html_Ent Glyph="@Amp;" Ascii="&Amp;"/> Family Social Work*, [ISSN: 1356-7500] *9*(4), 333–345. http://dx.doi.org/10.1111/j.1365-2206.2004.00338.x, URL http://doi.wiley.com/10.1111/j.1365-2206.2004.00338.x.

Liang, Meng, Li, Yanhong, Weber, Thomas, & Hußmann, Heinrich (2021). Tangible interaction for children's creative learning: A review. *Creativity and Cognition*, http://dx.doi.org/10.1145/3450741, URL https://doi.org/10.1145/3450741.3465262,

Lupton, Deborah (2016). The diverse domains of quantified selves: self-tracking modes and dataveillance. *Economy and Society*, [ISSN: 14695766] *45*(1), 101–122. http://dx.doi.org/10.1080/03085147.2016.1143726.

Mackintosh, Kelly, Niezen, Gerrit, & Eslambolchilar, Parisa (2016). Mission possible: Using ubiquitous social goal sharing technology to promote physical activity in children. *Movement, Health & Exercise*, [ISSN: 2231-9409] *5*(2), 1–15. http://dx.doi.org/10.15282/mohe.v5i2.115, URL http://mohejournal.com/index.php/mohe/article/view/115.

Manning, Carol A., & Edwards, Mark B. (1995). Functions of external cues in prospective memory. *Memory*, [ISSN: 14640686] *3*(2), 201–219. http://dx.doi.org/10.1080/09658219508258966, URL https://pubmed.ncbi.nlm.nih.gov/7796305/.

Marín Díaz, Juan Pablo (2016). How we did data visualizations before computers. URL https://www.datasketch.co/en/p/how-we-did-data-visualizations-before-computers.

Maturo, Claire C., & Cunningham, Solveig A. (2013). Influence of friends on children's physical activity: a review. *American Journal of Public Health*, [ISSN: 1541-0048] *103*(7), http://dx.doi.org/10.2105/AJPH.2013.301366, URL https://pubmed.ncbi.nlm.nih.gov/23678914/.

McCarthy, John, & Wright, Peter (2007). *Technology as experience* (p. 224). Cambridge, MA, USA: MIT Press, ISBN: 9780262134477, http://dx.doi.org/10.7551/mitpress/6687.003.0011.

McDonald, Nora, Schoenebeck, Sarita, & Forte, Andrea (2019). Reliability and inter-rater reliability in qualitative research: Norms and guidelines for CSCW and HCI practice. [ISSN: 25730142].

McNally, Brenna, Norooz, Leyla, Shorter, Alazandra, & Golub, Evan (2017). Toward understanding children's perspectives on using 3D printing technologies in their everyday lives. In *IDC 2017 - Proceedings of the 2017 ACM* *conference on interaction design and children* (pp. 298–303). Association for Computing Machinery, Inc, ISBN: 9781450349215, http://dx.doi.org/10.1145/3078072.3079735.

Menheere, Daphne, Van Hartingsveldt, Evianne, Birkebaek, Mads, Vos, Steven, & Lallemand, Carine (2021). Laina: Dynamic data physicalization for slow exercising feedback;. *Designing Interactive Systems Conference 2021*, *16*(21), http://dx.doi.org/10.1145/3461778.

Moere, Andrew Vande (2008). Beyond the tyranny of the pixel: Exploring the physicality of information visualization. In *Proceedings of the 2008 12th international conference information visualisation* (pp. 469–474). Washington, DC, USA: IEEE Computer Society, ISBN: 978-0-7695-3268-4, http://dx.doi.org/10.1109/IV.2008.84.

Morais, L., Andrade, N., & Sousa, D. (2022). Exploring how visualization design and situatedness evoke compassion in the wild. *Computer Graphics Forum*, [ISSN: 1467-8659] *41*(3), 441–452. http://dx.doi.org/10.1111/CGF.14553, URL https://onlinelibrary.wiley.com/doi/full/10.1111/cgf.14553.

Moss, Deborah L. (1993). *Art therapy for young children: a review of the research and literature* (pp. 1–43). Washington, D.C., USA: Distributed by ERIC Clearinghouse, URL https://eric.ed.gov/?id=ED367437.

NHS (2019). Physical activity guidelines for children and young people - NHS. URL https://www.nhs.uk/live-well/exercise/physical-activity-guidelines-children-and-young-people/.

NHS Digital (2018). Statistics on obesity, physical activity and diet - England, 2017 - NHS digital. URL http://webarchive.nationalarchives.gov.uk/20180328133908/http://digital.nhs.uk/catalogue/PUB23742.

Odom, William, Banks, Richard, Durrant, Abigail, Kirk, David, & Pierce, James (2012). Slow technology. In *Proceedings of the designing interactive systems conference on - DIS '12* (p. 816). New York, New York, USA: ACM Press, ISBN: 9781450312103, http://dx.doi.org/10.1145/2317956.2318088, URL http://dl.acm.org/citation.cfm?doid=2317956.2318088.

Odom, William, Lindley, Siân, Pschetz, Larissa, Tsaknaki, Vasiliki, Vallgårda, Anna, Wiberg, Mikael, et al. (2018). Time, temporality, and slowness. In *Proceedings of the 19th international ACM SIGACCESS conference on computers and accessibility - DIS '18* (pp. 383–386). New York, New York, USA: ACM Press, ISBN: 9781450356312, http://dx.doi.org/10.1145/3197391.3197392, URL http://dl.acm.org/citation.cfm?doid=3197391.3197392.

Odom, William, & William (2015). Understanding long-term interactions with a slow technology. In *Proceedings of the 33rd annual ACM conference on human factors in computing systems - CHI '15* (pp. 575–584). New York, New York, USA: ACM Press, ISBN: 9781450331456, http://dx.doi.org/10.1145/2702123.2702221, URL http://dl.acm.org/citation.cfm?doid=2702123.2702221.

Pearce, Matthew, Page, Angie S., Griffin, Tom P., & Cooper, Ashley R. (2014). Who children spend time with after school: associations with objectively recorded indoor and outdoor physical activity. *The International Journal of Behavioral Nutrition and Physical Activity*, [ISSN: 1479-5868] *11*(1), http://dx.doi.org/10.1186/1479-5868-11-45, URL https://pubmed.ncbi.nlm.nih.gov/24679149/.

Pradhan, Alisha, Jelen, Ben, Siek, Katie A., Chan, Joel, & Lazar, Amanda (2020). Understanding older adults' participation in design workshops. In *Conference on human factors in computing systems - proceedings* (pp. 1–15). New York, NY, US: Association for Computing Machinery (ACM), ISBN: 9781450367080, http://dx.doi.org/10.1145/3313831.3376299.

Ridgers, Nicola D., McNarry, Melitta A., & Mackintosh, Kelly A. (2016). Feasibility and effectiveness of using wearable activity trackers in youth: A systematic review. *JMIR MHealth and UHealth*, [ISSN: 2291-5222] *4*(4), Article e129. http://dx.doi.org/10.2196/mhealth.6540, URL http://mhealth.jmir.org/2016/4/e129/http://www.ncbi.nlm.nih.gov/pubmed/27881359http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5143467.

Ridgers, Nicola D., Timperio, Anna, Ball, Kylie, Lai, Samuel K., Brown, Helen, Macfarlane, Susie, et al. (2021). Effect of commercial wearables and digital behaviour change resources on the physical activity of adolescents attending schools in socio-economically disadvantaged areas: the RAW-PA cluster-randomised controlled trial. *The International Journal of Behavioral Nutrition and Physical Activity*, [ISSN: 1479-5868] *18*(1), http://dx.doi.org/10.1186/S12966-021-01110-1, URL https://pubmed.ncbi.nlm.nih.gov/33845853/.

Ridgers, Nicola D, Timperio, Anna, Brown, Helen, Ball, Kylie, Macfarlane, Susie, Lai, Samuel K, et al. (2018). Wearable activity tracker use among Australian adolescents: Usability and acceptability study. *JMIR MHealth and UHealth*, *6*(4), Article e86. http://dx.doi.org/10.2196/mhealth.9199, URL http://mhealth.jmir.org/2018/4/e86/http://mhealth.jmir.org/2018/4/e86/http://mhealth.jmir.org/2018/4/e86/.

Rock, Marcia L., & Thead, Beth K. (2007). The effects of fading a strategic self-monitoring intervention on students' academic engagement, accuracy, and productivity. *Journal of Behavioral Education*, [ISSN: 10530819] *16*(4), 389–412. http://dx.doi.org/10.1007/s10864-007-9049-7, URL https://www.jstor.org/stable/41824418.

Rodić, Lea Dujić, & Granić, Andrina (2022). Tangible interfaces in early years' education: a systematic review. *Personal and Ubiquitous Computing*, [ISSN: 16174917] *26*(1), 39–77. http://dx.doi.org/10.1007/S00779-021-01556-X/TABLES/3, URL https://link.springer.com/article/10.1007/s00779-021-01556-x.

Saksono, Herman, & Parker, Andrea G. (2017). Reflective informatics through family storytelling: Self-discovering physical activity predictors. In *Conference on human factors in computing systems - proceedings, Vol. 2017-May* (pp. 5232–5244). Association for Computing Machinery, ISBN: 9781450346559, http://dx.doi.org/10.1145/3025453.3025651.

Salvy, Sarah Jeanne, Roemmich, James N., Bowker, Julie C., Romero, Natalie D., Stadler, Phillip J., & Epstein, Leonard H. (2009). Effect of peers and friends on youth physical activity and motivation to be physically active. *Journal of Pediatric Psychology*, [ISSN: 01468693] *34*(2), 217. http://dx.doi.org/10.1093/JPEPSY/JSN071, URL /pmc/articles/PMC3202936//pmc/articles/PMC3202936/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC3202936/.

Sauvé, Kim, Bakker, Saskia, Marquardt, Nicolai, & Houben, Steven (2020). LOOP: Exploring physicalization of activity tracking data. In *Proceedings of the 11th nordic conference on human-computer interaction: shaping experiences, shaping society* (pp. 1–12). New York, NY, USA: ACM, ISBN: 9781450375795, http://dx.doi.org/10.1145/3419249.3420109, URL https://dl.acm.org/doi/10.1145/3419249.3420109.

Sauvé, Kim, Houben, Steven, Marquardt, Nicolai, Bakker, Saskia, Hengeveld, Bart, Gallacher, Sarah, et al. (2017). LOOP: A physical artifact to facilitate seamless interaction with personal data in everyday life. In *Proceedings of the 2016 ACM conference companion publication on designing interactive systems - DIS '17 companion* (pp. 285–288). New York, New York, USA: ACM Press, ISBN: 9781450349918, http://dx.doi.org/10.1145/3064857.3079175, URL http://dl.acm.org/citation.cfm?doid=3064857.3079175.

Schon, Donald A., & DeSanctis, Vincent (1986). The reflective practitioner: How professionals think in action. *The Journal of Continuing Higher Education*, [ISSN: 0737-7363] *34*(3), 29–30. http://dx.doi.org/10.1080/07377366.1986.10401080.

Sim, Gavin, Nouwen, Marije, Vissers, Jorick, Horton, Matthew, Slegers, Karin, & Zaman, Bieke (2016). Using the MemoLine to capture changes in user experience over time with children. *International Journal of Child-Computer Interaction*, [ISSN: 2212-8689] *8*, 1–14. http://dx.doi.org/10.1016/J.IJCCI.2016.07.001.

Sleddens, Ester F. C., Gerards, Sanne M. P. L., Thijs, Carel, De Vries, Nanne K., & Kremers, Stef P. J. (2011). General parenting, childhood overweight and obesity-inducing behaviors: a review. *International Journal of Pediatric Obesity : IJPO : An Official Journal of the International Association for the Study of Obesity*, [ISSN: 1747-7174] *6*(2–2), http://dx.doi.org/10.3109/17477166.2011.566339, URL https://pubmed.ncbi.nlm.nih.gov/21657834/.

Stawarz, Katarzyna, Cox, Anna L., & Blandford, Ann (2015). Beyond self-tracking and reminders: Designing smartphone apps that support habit formation. *2015-April*, In *Conference on human factors in computing systems - proceedings* (pp. 2653–2662). New York, New York, USA: Association for Computing Machinery, ISBN: 9781450331456, http://dx.doi.org/10.1145/2702123.2702230, URL http://dl.acm.org/citation.cfm?doid=2702123.2702230.

Stusak, Simon, Hobe, Moritz, & Butz, Andreas (2016). If your mind can grasp it, your hands will help. In *Proceedings of the TEI '16: Tenth international conference on tangible, embedded, and embodied interaction - TEI '16* (pp. 92–99). New York, New York, USA: ACM Press, ISBN: 9781450335829, http://dx.doi.org/10.1145/2839462.2839476, URL http://dl.acm.org/citation.cfm?doid=2839462.2839476.

Stusak, Simon, Schwarz, Jeannette, & Butz, Andreas (2015). Evaluating the memorability of physical visualizations. In *Conference on human factors in computing systems - proceedings, Vol. 2015-April* (pp. 3247–3250). New York, New York, USA: Association for Computing Machinery, ISBN: 9781450331456, http://dx.doi.org/10.1145/2702123.2702248, URL http://dl.acm.org/citation.cfm?doid=2702123.2702248.

Stusak, Simon, Tabard, Aurelien, Sauka, Franziska, Khot, Rohit Ashok, & Butz, Andreas (2014). Activity sculptures: Exploring the impact of physical visualizations on running activity. *IEEE Transactions on Visualization and Computer Graphics*, [ISSN: 1077-2626] *20*(12), 2201–2210. http://dx.doi.org/10.1109/TVCG.2014.2352953, URL http://ieeexplore.ieee.org/document/6888482/.

Tang, Lie Ming, Meyer, Jochen, Epstein, Daniel A., Bragg, Kevin, Engelen, Lina, Bauman, Adrian, et al. (2018). Defining adherence. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, [ISSN: 2474-9567] *2*(1), 1–22. http://dx.doi.org/10.1145/3191769, URL https://dl.acm.org/doi/10.1145/3191769.

Tobias, Robert (2009). Changing behavior by memory aids: A social psychological model of prospective memory and habit development tested with dynamic field data. *Psychological Review*, [ISSN: 0033295X] *116*(2), 408–438. http://dx.doi.org/10.1037/a0015512, URL https://pubmed.ncbi.nlm.nih.gov/19348548/.

U. K. Chief Medical Officers (2019). *UK Chief Medical Officers' physical activity guidelines*: *Technical report*, UK Government, URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/832868/uk-chief-medical-officers-physical-activity-guidelines.pdf.

Van Den Hoven, E. A. W. H. (2004). *Graspable cues for everyday recollecting* (Ph.D. thesis), Technische Universiteit Eindhoven, The Netherlands, http://dx.doi.org/10.6100/IR576837, URL https://pure.tue.nl/ws/files/2359495/200411176.pdf.

Vermeeren, Arnold P. O. S., Law, Effie Lai Chong, Roto, Virpi, Obrist, Marianna, Hoonhout, Jettie, & Väänänen-Vainio-Mattila, Kaisa (2010). User experience evaluation methods: Current state and development needs. In *NordiCHI 2010: Extending Boundaries - Proceedings of the 6th Nordic Conference on Human-Computer Interaction* (pp. 521–530). New York, New York, USA: ACM Press, ISBN: 9781605589343, http://dx.doi.org/10.1145/1868914.1868973, URL http://portal.acm.org/citation.cfm?doid=1868914.1868973.

Vissers, Jorick, De Bot, Lode, & Zaman, Bieke (2013). MemoLine: Evaluating long-term UX with children. In *ACM international conference proceeding series* (pp. 285–288). New York, NY, US: ACM, ISBN: 9781450319188, http://dx.doi.org/10.1145/2485760.2485836.

Wang, Yun, Ma, Xiaojuan, Luo, Qiong, & Qu, Huamin (2016). Data edibilization: Representing data with food. In *Conference on human factors in computing systems - proceedings, Vol. 07-12-May* (pp. 409–422). New York, NY, US: Association for Computing Machinery, ISBN: 9781450340823, http://dx.doi.org/10.1145/2851581.2892570.

Ware, Colin (2012). *Information Visualization: Perception for Design* (3rd). (p. 544). Burlington, Massachusetts, USA: Morgan Kaufmann, ISBN: 0123814642.

WHO (2010). *Global recommendations on physical activity for health who library cataloguing-in-publication data global recommendations on physical activity for health* (p. 58). Geneva, Switzerlan: WHO, ISBN: 9789241599979, URL http://apps.who.int/iris/bitstream/handle/10665/44399/9789241599979_eng.pdf;jsessionid=092AECF1032DFA121303E30D236D0EBF?sequence=1.

Willett, Wesley, Aseniero, Bon Adriel, Carpendale, Sheelagh, Dragicevic, Pierre, Jansen, Yvonne, Oehlberg, Lora, et al. (2021). Perception! mmersion! empowerment! superpowers as inspiration for visualization. *IEEE Transactions on Visualization and Computer Graphics*, *28*(1), 22–32. http://dx.doi.org/10.1109/TVCG.2021.3114844, URL http://arxiv.org/abs/2108.03524.

Woźniak, Paweł W, Kiss, Francisco, Zbytniewska, Monika, & Niess, Jasmin (2021). Making sense of complex running metrics using a modified running shoe; making sense of complex running metrics using a modified running shoe. *Proceedings of the 2021 CHI conference on human factors in computing systems*, http://dx.doi.org/10.1145/3411764,

Wright, Peter, Wallace, Jayne, & McCarthy, John (2008). Aesthetics and experience-centered design. *ACM Transactions on Computer-Human Interaction*, [ISSN: 10730516] *15*(4), 1–21. http://dx.doi.org/10.1145/1460355.1460360, URL http://portal.acm.org/citation.cfm?doid=1460355.1460360.

Wurhofer, Daniela, Meneweger, Thomas, Fuchsberger, Verena, & Tscheligi, Manfred (2015). Deploying robots in a production environment: A study on temporal transitions of workers' experiences. In *Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics), Vol. 9298* (pp. 203–220). Berlin, Heidelberg, Germany: Springer Verlag, ISBN: 9783319226972, http://dx.doi.org/10.1007/978-3-319-22698-9{_}14, URL http://link.springer.com/10.1007/978-3-319-22698-9_14.

Yang, Bai, Liu, Ying, Liang, Yan, & Tang, Min (2019). Exploiting user experience from online customer reviews for product design. *International Journal of Information Management*, [ISSN: 02684012] *46*, 173–186. http://dx.doi.org/10.1016/j.ijinfomgt.2018.12.006.

Zhao, Jack, & Moere, Andrew Vande (2008). Embodiment in data sculpture. In *Proceedings of the 3rd international conference on digital interactive media in entertainment and arts - DIMEA '08* (p. 343). New York, New York, USA: ACM Press, ISBN: 9781605582481, http://dx.doi.org/10.1145/1413634.1413696, URL http://dl.acm.org/citation.cfm?doid=1413634.1413696.

Zimmerman, John, & Forlizzi, Jodi (2008). The role of design artifacts in design theory construction. *Artifact*, [ISSN: 1749-3463] *2*(1), 41–45. http://dx.doi.org/10.1080/17493460802276893.