I/O Bits: User-Driven, Situated, and Dedicated Self-Tracking

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We present I/O Bits, a prototype personal informatics system that explores the potential for user-driven and situated self-tracking. With simple tactile inputs and small e-paper visualizations, I/O Bits are dedicated physical devices that allow individuals to track and visualize different kinds of personal activities in-situ. This is in contrast to most self-tracking systems, which automate data collection, centralize information displays, or integrate into multi-purpose devices like smartwatches or mobile phones. We report findings from an e-paper visualization workshop and a prototype deployment where participants constructed their own I/O Bits and used them to track a range of personal data. Based on these experiences, we contribute insights and opportunities for situated and user-driven personal informatics.

CCS Concepts: • Human-centered computing \rightarrow Interface design prototyping; Information visualization; Ubiquitous computing.

Additional Key Words and Phrases: Personal Data/Tracking, Visualization, Ambient Devices, Internet of Things

ACM Reference Format:

Kendra Wannamaker, Sandeep Kollannur, Marian Dörk, and Wesley Willett. 2021. I/O Bits: User-Driven, Situated, and Dedicated Self-Tracking. In *Proceedings of DIS '21: ACM Conference on Human Factors in Computing Systems (DIS '21).* ACM, New York, NY, USA, 22 pages. https://doi.org/10.1145/nnnnnnnnnnnn

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Manuscript submitted to ACM

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1 INTRODUCTION

Data surrounds each of us in our daily lives, presenting numerous opportunities for personal data collection and reflection. The majority of existing self-tracking systems automate data collection (FitBit, Strava, Mint)¹ or integrate into multi-purpose devices like smartwatches or mobile phones (Toggl, My Fitness Pal, Track Your Happiness)². Most current systems then display the resulting data via those same kinds of computing devices. Yet, using these strategies for personal informatics system design has several drawbacks related to awareness, control, and flexibility.

While an automated data collection approach is successful in reducing burdens on the user, it also limits the types of data a user collects to phenomena that are easily detected [6]. Automated data collection is often rigid, which can lead to conflict between what the user cares about and what the system is capable of tracking [21, 48]. User-driven (or manual) data collection on the other hand, allows the user to frame the question, decide what counts, and capture subjective and qualitative observations that can be difficult to track automatically. Incorporating self-tracking tools into existing systems, such as mobile phones, can provide an inexpensive approach to collecting a wide range of data. However, this approach forces the self-tracking tool to compete with other applications for attention and introduce a non-trivial amount of interaction overhead for logging while engaged in an activity. A dedicated tracker with a distinct physical presence and location has the potential to remind people to log and facilitate faster interactions. Centralizing data consumption on phones or computers allows people to access the data at will, often providing favorable conditions for complex interactions and deeper self-reflection. In contrast, distributing personal data into the physical spaces where it is most relevant allows that information to be easily considered in moments of decision making.

In response to these trade-offs, we explore a novel approach to personal informatics, which examines how a userdriven, situated, and dedicated tool might support new kinds of self-tracking behavior. Our work includes the design, development, and deployment of a personal informatics system that we call *I/O Bits*. Our prototype system combines a simple, user-driven data-collection process with a set of visualizations in a self-contained and dedicated hardware unit. These small, battery-operated devices can be situated in a wide variety of locations and support many tracking tasks. Each I/O Bit includes a low-power WiFi-enabled microcontroller, a rechargeable battery, and an e-paper display. Users can log data using two input buttons on the face of the device that produce time-stamped logs on a local server. These logs, while structurally simple, can capture a wide range of different activities and self-tracking use cases.

As an initial exploration of the design space of situated tracking tools, we ran four situated ideation workshops. Next, we ran an e-paper visualization workshop that generated 40 designs, from which we derived a set of design clusters and axes for visualizations on small e-paper displays. Using our workshops as inspiration we designed and built several generations of prototypes. Finally, we conducted a study in which we asked six participants to build and use I/O Bits for a period ranging from 4 days to 3 weeks. We then used semi-structured interviews and qualitative analysis to distill participants' experiences. Our work showcases several novel and unconventional approaches to personal informatics. We demonstrate the potential for de-automated, de-centralized, and single-function self-tracking applications and highlight opportunities for future research with that focus. While I/O Bits are relatively straightforward technically, they run contrary to many common self-tracking tropes. Our experiences designing I/O Bits, as well as results from our initial deployment, illustrate a variety of potential benefits of encouraging more immediate, personal, and situated approaches to self-tracking. We contribute: (1) Design clusters and axes characterizing opportunities for self-tracking visualizations on small e-paper displays. (2) A collection of critical observations and design opportunities that highlight

¹www.fitbit.com, www.strava.com, www.mint.com

²www.toggl.com, www.myfitnesspal.com, www.trackyourhappiness.org

the potential for self-tracking tools that subvert the conventions of contemporary personal informatics and emphasize physicality, simplicity, privacy, and personal identity.

2 RELATED WORK

Our work builds on prior research in (1) personal informatics, (2) user-driven data collection, (3) data identity and agency, and (4) situated tracking and visualization.

2.1 Personal Informatics

Research in personal informatics aspires to empower people through tools that help them collect and reflect on personal data. Collecting and analysing personal data can, for example, help people improve their diet [11], examine spending [24], and manage chronic illness [46]. Many researchers have examined expert users (or quantified-selfers) to gain insights, understand challenges, and formulate design requirements for more lay users [8, 31, 40, 44]. Li et al. put forward a stage-based model for personal informatics, whose five stages (preparation, collection, integration, reflection, and action) have cascading burdens. These barriers include the initial decisions of what and how to track, the day-to-day cognitive and time costs of logging, and the combination and organization of data required for analysis and reflection [30]. The stages are either system-driven or user-driven (meaning that either the system or the user is primarily responsible for the stage) [31]. This logical and systematic personal informatics model received pushback from Rooksby et al. who found personal tracking was often a highly emotional experience interwoven with one's life story [38]. They coined the term lived informatics and pushed personal informatics researchers to consider not only goal-driven or directive tracking but also alternative tracking motivations (documentary, diagnostic, rewards-based, and number fetishised). Epstein et al., inspired by Rooksby et al., proposed an alternative model for personal informatics that aims to encompass a more varied and nuanced understanding of how and why people use and abandon self-tracking technology [16]. In the following years many researchers have called for more flexible and customizable self-tracking systems to better support people and their unique tracking processes [4, 15, 26, 27]. Our work marks a continuation of this philosophy, and we designed I/O Bits to be a highly flexible self-tracking system in an attempt to support a variety of tracking motivations, processes, and activities.

2.2 User-Driven Data Collection

The act of collecting personal data presents numerous challenges, including limited time, effort, motivation, and memory [30]. To overcome these barriers, many industry and research systems rely on system-driven (or *automated*) data collection to alleviate the burden on the user. As a result, many people who use personal informatics tools do so via commercial trackers capable of recording readily sense-able data like step counts, heart rates, blood glucose levels, and geospatial locations.

However, when automated data collection is too limited, it can lead to unexpected behaviour change or abandonment. For example, Yang et al. interviewed people who adopted fitness trackers that focused on steps and could not track other physical activities such as bike rides, weight lifting, and swimming. This limited data collection resulted in participants either walking more over alternative activities or abandoning the practice of self-tracking altogether [48]. When Lazar et al. gave participants \$1,000 to buy self-tracking equipment, they were surprised when participants purchased devices that were not relevant to their pre-stated goals. After two months, 80% of their participants had abandoned tracking, with many citing a lack of interest in the data collected [27]. As Kim et al. note, "Despite the vast number of available tracking apps and devices, it can be challenging to find a tool that perfectly suits one's tracking needs, preferences, and

commitments. Commercial tracking apps are often highly specialized, providing little or no flexibility over what and how to track" [26].

While many tracking tools seek to minimize or eliminate the burdens of data collection on the user, there is growing resistance to the notion that all human intervention is a deficit to self-tracking systems [17]. Simm et al. introduced the concept of *intentive computing*, the intentional requirement for the user to consciously and knowingly trigger a system. They argue that "intentional interactions, not only could provide real-time tactile 'relief' but could also function as cognitive anchors for self-reflection and long-term learning" [41]. Ayobi et al. found that the analog and customizable self-tracking provided by bullet journaling often better supports people's practical and emotional needs in everyday settings compared to their more rigid digital journals. They suggest integrating the mindful design practice of bullet journaling into digital self-tracking tools [4].

Choe et al. examined a range of sleep, mood, and food trackers based on their automation level. They argue that a carefully considered balance of user-driven and system-driven data collection can promote awareness, accountability, and engagement while also lowering capture burdens [6]. Several recent research systems have explored different ways of integrating technology into user-driven data collection [1, 2, 7, 17, 26, 46]. Many of these explorations examined ways of reducing interaction friction for situated tracking on mobile phones by introducing simple gestures [1], widgets [7], and tangible objects (like stand-alone buttons, belt-clips, and key chains) that connect to phones [17]. Others have embraced more analog data entry, like Vega et al. who created structured paper journals that could be automatically digitized [46]. Finally, Kim et al.'s Omnitrack app lets users interweave manual and automatic data collection to build highly customized self-tracking routines [26]. When designing I/O Bits, we carefully considered the balance of user and system-driven data collection using the trade-offs described in previous work. We also wanted to explore manual data collection as a mechanism to provide flexible self-tracking on digital devices.

2.3 Data Identity and Agency

The issues with rigid data collection go beyond the irritation users experience when self-tracking systems clash with their expectations. There is also a risk that rigid data collection can reinforce narrow social norms, limit personal data-agency, and create unhealthy obsessions with fitness, finances, and sexuality.

Commercial tracking tools often make default recommendations to help users make sense of their data. Unfortunately, the easily digestible numbers produced by these tools tend to conflate normal — or rather, the number at the center of the normal distribution curve — with optimal [34]. As Crawford et al. note during their comparison of historical weight scales to modern day fitness trackers, "The history of the weight scale reminds us that tracking devices are agents in shifting the process of knowing and controlling bodies, individually and collectively, as they normalize (and sometimes antagonize) human bodies" [12]. When examining reproduction-related tracking applications, Lupton et al. found that these apps supported and reinforced highly reductive and normative ideas. For example, they found that male-targeted apps focused on performance metrics (thrust count, duration, frequency, and number of partners) while female-oriented applications were more focused on medicalization and risk [32]. Examining self-tracking through the lens of menstruation, Epstein et al. found that the design, language, and functionality of such applications often made assumptions about gender identity, sexual orientation, and family goals, which made those who fell outside of those assumptions feel alienated. Even those who did fit into the assumptions of these systems often found the stereotypical feminine UI elements condescending [15]. Marathe et al. note that just giving users control over cosmetic elements of an interface can invoke a strong psychological connection with the system and allow users to better adapt the system to their personal identity [33]. Inspired by the practice of bullet journaling, Ayobi et al. built a meaningfully customizable



Fig. 2. Existing situated tracking and visualization systems. (a) Claes et al.'s public visualization and polling displays [9]. (b) Coenen et al.'s Citizen Dialog Kits for community engagement in public places [10]. (c) Grosse-Puppendahl et al.'s energy neutral e-paper displays [19]. (d & e) Constructed physicalizations from Thudt et al.'s study of craft-based personal visualization [45].

self-tracking application for Multiple Sclerosis. They allowed users to define tracking parameters and flexibly colour-in and make sense of their pictorial trackers, which lead to users feeling a sense of identity, ownership, self-awareness, mindfulness, and control. [3].

Notably, researchers who raised concerns about identity and normalization have also expressed concerns about data-autonomy. As Crawford et al. note, the weight scale gave data directly to consumers, but with modern day personal informatics systems data has a much longer and more complex lifespan [12]. Indeed, we see the commercialization of personal data³, careless handling of private information⁴, and an abundance of security breaches⁵. The issue of data autonomy is further complicated when data is collected about a space rather than an individual. For example, when Denefleh et al. examined customizable automatic data in shared living spaces, they found that participants used the system to monitor and control other flatmates' behaviour, which presents complex issues of consent [13]. What constitutes 'the home' can greatly differ from person to person [35], and designing for a homogeneous notion of home may not only be challenging [13], it may also be dangerous. Leitão, who worked with survivors of intimate partner abuse to anticipate the dangers of smart home technology, also highlights the importance of data-autonomy for each individual user of a system, and of making clear to users who has access to their information [29]. We kept these principles and concerns in mind while we designed our self-tracking system, focusing on DIY and open-ended approaches that give users the power to frame their own questions and using opt-in logging and offline storage to support data autonomy.

³https://www.oviahealth.com

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 $^{^{5}} https://www.nytimes.com/2018/04/04/us/politics/cambridge-analytica-scandal-fallout.html and the second seco$

2.4 Situated Tracking and Visualization

Situated visualization is an area of research that explores placing data representations in proximity to their physical data *referents* — the physical objects, spaces, or people to which the data refers [47]. This research aims to decentralize data consumption and help people use data to reflect and make decisions in-situ. Situated and embedded tools promise to surface relevant data in-context, in much the same way that refrigerator calendars allow families to share information, coordinate schedules, and make decisions about what to do next. Situated data representations can take many forms including embedded screens, augmented/mixed reality displays, and physical artifacts.

A number of recent systems have focused on small displays that can be embedded into a variety of environments. Grosse-Puppendahl et al.'s energy-neutral displays (Figure 2c) are capable of continuously visualizing small bits of information they receive wirelessly from nearby computers or smartphones [19]. Similarly, Pablo et al.'s PostBits introduce low-maintenance devices that can be placed in-situ to display news feeds, weather, social media content, or virtual sticky notes [36]. Both Grosse-Puppendahl et al. and Pablo et al.'s systems are contextually rich e-paper displays capable of showing a broad range of data collected by other systems, but neither examined in-situ data collection. Claes et al. [9] used similar e-displays to create dedicated and situated tracking systems to help inform community members about civic issues and solicit public input via button-based in-situ inputs (Figure 2a+b). Denfleh et al.'s Sensorstation, meanwhile, was designed for more open-ended ended personal data-exploration. Sensorstation utilizes a set of simple sensors, custom notifications, and a touch-screen display to help residents explore data in a shared apartment [13]. We integrated components from each of these systems into I/O Bits — including the small in-situ e-paper displays used by Grosse-Puppendahl et al.'s systems, the button-based inputs deployed by Claes et al., and the flexible data exploration explored by Denfleh et al.'s systems, the button-based inputs deployed by Claes et al., and the flexible data exploration explored by Denfleh et al. By building on this prior work and applying similar features to user-driven personal tracking devices, we aim to support personal data exploration in a lightweight, casual, and novel way.

In their recent literature review, Ghajargar et al. examined the entanglement between reflections, behaviours, and artifacts, noting that "the ability of smart artifacts to stimulate human reflective behavior and to evoke thoughts in users is still relatively unexplored" [18]. However, a number of recent projects have begun to examine the use of physical artifacts to connect people with their personal and environmental data. These include Houben et al.'s dynamic and customizable physicalization cubes [22], Stusak et al.'s incrementally-printed activity sculptures [43], and Sauvé's dynamic Loop sculpture [39] — all of which provide glanceable and persistent representations of personally relevant data in everyday spaces. Other visible examples include YouTuber Simone Giertz's Every Day Calendar ⁶, a large dedicated tracker designed specifically for building daily habits. This large wall-mounted display includes 365 buttons, one for each day of the year, which light up when pressed (with the implied goal of lighting up every single button). Thudt et al. [45] have also highlighted expressive low-fidelity opportunities for situated self-tracking, allowing individuals to collect and explore data in their homes using materials such as beads, string, clay, and paint. (Figure 2d+e). Together, these approaches inspired us to imagine lightweight, general-purpose tracking tools that might support a wide range of domestic tracking applications.

3 DESIGN WORKSHOPS

We conducted a set of four situated ideation workshops to help us explore opportunities for situated visualizations and tracking in a variety of spaces. Inspired by a set of use-cases that embedded toggles, counts, and timestamps in the environment, we then decided to examine the unique constraints and opportunities for small low-power e-paper

⁶https://www.kickstarter.com/projects/simonegiertz/the-every-day-calendar



Fig. 3. Sketches generated during our situated ideation workshops. The sketches are on whiteboard tiles and illustrate from left to right: a timestamp showing when the jar of pickles was started, a toggle to show if the office occupant is in and if they are busy, and two counts to track how many coffees were consumed from the reusable versus paper cups.

displays in a subsequent e-paper visualization workshop. While the methodological details of the design workshops were reported in an earlier paper [5], here we consider the insights and results generated during the workshops which directly informed the design of I/O Bits.

3.1 Situated Ideation Workshops

We conducted four situated ideation workshops as part of our formative research. Participants used a variety of sketching materials including whiteboard tiles, photos, and sticky notes to prototype situated visualization systems. Each workshop had between 5 and 15 participants, all of whom had prior experience with interaction and visualization research (as students or scholars in these domains). We specifically recruited visualization experts because their high level of visualization literacy enabled them to quickly ideate a diverse range of visual representations that reflected their own personal experiences. This allowed us to generate a rich set of candidate designs while still capturing personal use cases. To take inspiration from particular places where self-tracking may occur, we conducted workshops in diverse locations, including home environments, office spaces, a fab lab, and a pick-your-own farm. The workshops lasted between one and two hours, with one exception where participants took materials home for a period of one week.

These situated ideation workshops inspired our simple, user-driven, and generic data collection. An interesting cluster of ideas required simple timestamps, counts, or binary toggles (See Figure 3 for ideation sketches). For example, participants used timestamps to support tracking home pickling, labeling each jar with the date and time when they were made. In the same workshop, a participant used counts to track how many cups of coffee were bought versus made. Another participant used binary toggles to indicate if someone was in their office and could be interrupted. The data required by these examples could be collected using a plethora of sensors or simple button presses. Inspired by these use-cases, we decided to develop a user-driven tracker that could capture timestamps, counts, or binary toggles in an effort to support a range of personal data.

3.2 Self-tracker Design Goals

Based on these observations, we chose to explore the potential impact of simple, dedicated personal tracking tools that can support user-driven tracking in a variety of settings. Using the ideas and insights from the ideation workshops and a survey of related work, we articulated four design goals and used them to guide the development of our prototypes.

G1. *Prompt data-driven reflection and insights:* Support tracking in a simple, yet meaningful way by prompting moments of reflection and/or generating actionable insights.

- **G2.** *Integrate into everyday tasks and settings:* Ensure the system integrates into a person's home, supports tracking while engaged in other tasks, and provides information when and where it is relevant.
- **G3.** *Minimize start up and operational burdens:* Keep the monetary cost, infrastructure setup, and required maintenance low and ensure that the effort to use the system does not render it unwieldy.
- **G4.** *Cover a broad range of tracking practices:* Enable self-tracking for various facets of everyday life while supporting individuals' unique tracking rituals and preferences.

These design goals formed the basis for our subsequent prototype development and an additional workshop.

3.3 E-Paper Visualization Workshop

To more deeply explore how visualizations on small e-paper devices might support these goals, we held a workshop with ten participants — five male and five female (who we refer to with alphanumeric codes EP1-EP10). We recruited researchers and students with a background in visualization design and who would be comfortable with quick and creative visualization ideation. To help the participants understand the context of the problem, we began the workshop by showing them a low-fidelity, non-functional prototype self-tracking system and a few key hardware components we wanted to utilize. Participants then randomly choose several prompts from a set of potential use-cases we generated that covered different scales of measurements [42] and various motivations for personal tracking. After a group discussion, the second half of the workshop was more open-ended and participants were invited to imagine their own use-cases.

On average, each participant generated four sketches over the course of the workshop for a total of 40 designs⁷. During the second half of the workshop participants generated 13 more use-cases. After the workshop, we analyzed the designs that participants had generated, clustering them based on recurring design elements and organizing them to reflect emergent design dimensions.

3.4 Design Clusters

While examining the visualizations, we noticed several repeated designs. After grouping the visualizations based on their prompt, we found that each group's individual designs were unique, with the reoccurring designs appearing across groups. This was encouraging, as it meant there were overlapping designs that could be used to track multiple things. This was done unprompted by the participants and supported the possibility that a small set of visualizations could cover a relatively large range of topics. From the 40 designs, we isolated five distinct clusters of visual encodings.



Text: These visualizations focused on displaying a single component of the data in plain text. Often this involved displaying counts, averages, or a single timestamp. These designs tended to have contextual clues in the form of text or icons that would statically be displayed throughout tracking.

Tokens: These visualizations added a new token for each button press. In our samples these tokens were typically circles or squares, but might also include stars, tallies, or emojis. These tokens were generally grouped into categories, placed along a timeline, or clustered into roughly temporal groupings.

⁷We gave participants the option to be credited for their designs in the final publication. Sketches marked with stars were authored by Yaron Zimmermann (*) and Tobias Kauer (**) respectively

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Grids: These visualizations had an initial structure that was filled in based on the inputs. The initial structures were often grids, but some designs used a series of lines or an outline of an image. These designs were usually used to show many data points over an interval of time ranging from three days to a full month. The initial structures were filled in by icons, dots, colours, and lines. This resembles the approach used in Ayobi et al.'s Trackly app, where users colour in pictorial grids to track aspects of their multiple sclerosis [3].

Resizable Shapes: These visualizations used button presses to scale a variety of shapes. This included more traditional graph shapes like the bars of a bar chart as well as less traditional forms such as circles within a traffic light and speech bubbles. Mapping quantitative personal data to the size of sketched glyphs like these has been recently explored in Kim et al.'s DataSelfie system [25].

Visual Ratios: These visualizations were described using words that emphasized tension between two distinct parts. The pushing halves either used the whole display to show a single aggregated ratio or used curves and jagged edges to visualize ratios that might change over time.

3.5 Design Axes

After examining the similarities in the visualization sketches, we looked at how they differed. We identified design axes, primarily focused on scoping and representation of the information. These design axes highlight potential visualization strategies to overcome the challenges the e-paper display presents. We identified five design axes (Figure 4).

Data Window: To accommodate for the small display size, some participants narrowed the amount of information shown to a small amount of data, or even a single data point. In contrast, other participants chose to present all of the data in a highly aggregate form.

Time Frame: Some participants focused on a specific period of time to limit the amount of information displayed. A majority of the visualizations that implemented this approach look like small calendars. The calendars exclusively had the granularity of days and a time frame ranging from three days to a full month. Again, this is in juxtaposition to the visualizations that displayed all the information as an aggregation.

Input Complexity: While we had primed our participants to consider a small number of buttons, we had also presented a low-fidelity prototype to encourage discussion around its final form. Most of the designs used one to three buttons as defined by the brief, but some visualizations needed up to 6 buttons, dials, or sensors. In addition to the sketches that utilized more complex inputs, participants discussed other input mechanisms such as voice control.

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Fig. 4. Snapshots of the five design axes we derived from designs participants produced during the e-paper visualization workshop.



Fig. 5. Exterior and interior views of an I/O Bit prototype with components labeled: (1) 4*cm* e-paper display, (2) tactile push buttons, (3) LED lights, (4) WiFi-enabled ESP-32 micro-controller, (5) 5000mAh rechargeable Li-Po battery.

Specificity: Some visualizations from the study were carefully tailored representations for a particular task. In contrast, other visualizations purposefully obfuscated their underlying meaning in an effort to maintain privacy. In between, many participants added icons or labels to their data to hint at the data's meaning without stating it explicitly.

Graphicality: Finally, the set of visualizations generated by the participants had a wide range of graphicality – the continuum between text and images. While some participants opted to convey all the information in plain text, others used text as an image that would grow based on input, and finally others opted to only use images without any labels.

These ideas for small-scale visualizations of personal data open up a broad spectrum of visual encodings to be used by situated, self-tracking devices.

4 I/O BITS

Based on the outcomes from the ideation workshops — the design goals for self-trackers and a design space for situated e-paper visualizations — we then proceeded to prototyping a self-tracking device. For most people, even the seemingly innocuous act of pulling out a mobile phone, navigating to a particular app, and entering in data can be an inconvenience, which might be an unwelcome interruption while engaged in a task. As such, we wanted to explore the potential for a dedicated tracker as a way of reducing interaction friction and supporting self-tracking mid-task. Due to the cost and battery life we ruled out using existing devices such as tablets, e-readers, mobile phones, and smart watches as dedicated components of our system. Using any of these as a situated single purpose device would be expensive and require a high-level of maintenance as most of them require daily charging. Alternatively, we could require the device always be plugged in, but that would restrict where the self-tracker could be placed. These limitations and drawbacks conflicted with many of our goals, and as such we decided to build our own system that could be deployed in a wide range of home and office locations for extended periods without charging. Below we detail the various components of our prototype I/O Bits system. The source code and instructions to re-create I/O Bits can be found on Github⁸.

4.1 Hardware

Each I/O Bit is a stand-alone wireless device with dimensions of $11cm \times 7cm \times 3cm$. Each device contains a 4cm black-and-white e-paper display, a set of physical buttons, a WiFi-enabled ESP-32 micro-controller, and a 5000mAh rechargeable Li-Po battery (see Figure 5). Two input buttons on the front of the device allow a user to log new data, while three buttons on the top act as system controls (undo, new file, switch visualization). Additionally, we included a small status light to provide instant feedback to the user, as even black-and-white e-paper displays can take several seconds to fully update. We covered the exterior of the unit with adhesive whiteboard material, allowing users rapidly annotate and customize their I/O Bits to reflect their current use. The combination of a large battery with a low-power display and micro-controller results in a battery life of at least three weeks under typical use.

To reduce cost and improve battery life, individual I/O Bits do not store data locally or maintain an internal clock. Instead, they wirelessly connect to a server running on a Raspberry Pi, computer, or cloud service. This allows the devices to spend most of their time in a low-power deep sleep mode, waking only in response to a physical button press. On a press, the I/O Bit wakes, connects to the server, and transmits an update. The server then records the value and responds with the data necessary to update the visualization. Multiple I/O Bits can share a single centrally-positioned server.For this iteration, we connected the I/O Bits directly to a nearby Raspberry Pi, allowing all data to remain offline.

We created two different case designs which can be fabricated using a laser cutter or 3D printer. However, we also developed a low-fidelity approach which re-used the cardboard boxes originally used to ship the e-paper displays. In practice, we found that re-using these cardboard boxes worked well, considerably reducing construction time and giving the devices an approachable do-it-yourself aesthetic.

4.2 Visualizations

We wanted to create a set of visualizations that covered a wide range of use-cases, so that users could switch between them as needed. When designing the data visualizations for the I/O Bits, we tried to balance the clusters and cover the design axes across the visualization ideas generated during the e-paper visualization workshop. We briefly describe the five final visualization designs (Figure 6) and illustrate their purpose by describing everyday examples.

⁸https://github.com/kawannam/IO-BITS

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Fig. 6. The inspiration, iterations, and final design for our final set of five e-paper visualizations. **Button A** refers to the upper button on the face of the I/O Bit, while **button B** refers to the lower button.

- The **Instance** visualization adds tokens to a timeline. These tokens are different shapes depending on which button was pressed (x,+). The time frame of this visualization is a week, with a data granularity of one hour. The current time is indicated with a small tally. This visualization might be used for personal tracking medication intake, cookie consumption throughout the day, or bathroom trips.
- The **Interval** visualization fills in space on a grid, corresponding to the time between two button presses. Like the prior design, it shows a week of data at a one-hour granularity, along with a mark indicating the current time. This type of visualization could be used to track sleep, time spent on a hobby, or one's progress in completing their morning run.
- The **Counts** visualization is the simplest, displaying the total number of presses for each button using plain text along with the time of the last button press. An individual might use this design to track the last time they called home, or compare many times they biked to work vs. took the bus.
- The **Ratio** visualization highlights what fraction of the recorded button presses correspond to each of the two buttons. This ratio is shown both by the background colour and in two small numeric labels in the bottom corners. This visualization could support competitive tracking of household tasks by two roommates, keeping track of the percentage of the meals an individual eats out, or the portion of good vs. bad workout days.
- The **Streak** visualization provides a graphical indication of the number of consecutive days a button has been pressed. Each day the visualization adds a new lines of dots (if the first button is pressed), a line of dashes (if the second button is pressed), or a solid line (if both buttons are pressed). If the user misses a day, the visualization goes blank, and for each subsequent missed day, the visualization adds more randomly scattered dots across the



Fig. 7. Photos taken by participants of their I/O Bits in the location of the deployment. (a) IP2's I/O Bit on her desk at work (b) A close-up of IP3's I/O Bit showing button annotations and his active win ratio. (c) IP4's I/O Bit on his personal desk where you can see his player choices are currently even. (d) IP4's desk with his I/O Bit. (e) IP5's I/O Bit on his 'nightstand' right next to the Raspberry Pi Server. (f) IP1's initial setup of her I/O Bit on the nightstand with descriptive button labels. (g) IP1's I/O Bit on nightstand.

display to indicate a growing negative streak. The length of the current streak is also shown in the lower right corner. This visualization was the only one not inspired directly by the designs generated in the workshop, and instead originated in EP8's discussion of streaks in their own habit tracking practice.

5 DEPLOYING I/O BITS

To explore the potential of these tools, we conducted a small scale deployment with six participants (who we refer to with alphanumeric codes IP1-IP6), in which we used our I/O Bit prototypes as a design probe to elicit feedback. Inspired by the collaborative, open-source, and DIY ethos of the Citizen Data and Quantified Self communities, we decided to have participants construct their own I/O Bits. We hypothesised that the process of building their own tracking devices might endear participants to their I/O Bits and encourage more personalization and engagement. This led us to recruit an initial set of participants with soldering and fabrication experience as a way of exploring the impact of building one's own tracker. We recruited six participants (two female, four male) via a research lab mailing list. Our participants ranged in age from 19 to 33 and were all comfortable with technology. During the study, the participants filled in a personal tracking questionnaire, built and used their own I/O Bit, and completed an interview about their experience.

5.1 Results

In this section, we summarize each participant's experience based on their interviews. These summaries capture what the participants tracked, their likes and dislikes about the system, and what an ideal future version of the system might look like. See Table 1 for an overview of each participant's use-case, placement, and visualization.

5.1.1 Participant 1: Bedtime Routine. IP1 used I/O Bits to track both the ideal and non-ideal completion of her bedtime routine. She placed her I/O Bit on her nightstand and used the *Instance* visualization. Though she only used the tracking for a short period of time, she found the device helped her reflect on which end-of-day activities made it difficult to build a bedtime routine. IP1 found the persistent, "hard to dismiss" physical presence of the dedicated tracker a nice

#	Tracked	Duration	Placement	Visualization
IP1	Bedtime Routine	4 days	Night Stand	Instance
IP2	Work Life Balance	4 days	Desk (Work)	Counts, Ratio
IP3	Video Game Wins and Losses	2 weeks	Desk (Home)	Ratio
IP4	Video Game Character Selection	2 weeks	Desk (Home)	Counts
IP5	Sleep Schedule	3 weeks	Night Stand	Counts
IP6	Roll Playing Dice Rolls	3 weeks	Table/Book Shelf	Ratio

Table 1. An overview of the tracked phenomena, duration, placement, and visualizations by participant.

alternative to the "irritating and noisy" notifications of mobile tracking apps. Overall, she liked the physicality of the system and its low barrier to entry, but wished the raw data was easier to access and examine with other tools.

5.1.2 Participant 2: Work-Life Balance. IP2 used I/O Bits to achieve a better work-life balance while finishing her thesis. She kept her I/O Bit on her desk at work, and while she began with the *Ratio* visualization, she moved to the *Counts* visualization part way through tracking. IP2 found that the act of tracking helped her take more deliberate and meaningful breaks. While she enjoyed several aspects of this form of tracking, including its playful aesthetic, physicality, and simple input mechanism, she seemed to particularly value the system as a generic and flexible tracking tool. She spoke at length about the potential for other personal tracking devices to be judgemental and influence personal goals in a negative way. IP2 envisioned a future version of I/O Bits that might be wearable, musing that it wouldn't even need a screen — suggesting that the mindfulness of tracking would provide insights in-situ and accessing the visualization could happen more consciously later.

5.1.3 Participant 3: Video Game Wins vs. Losses. IP3 used I/O Bits to track his win/loss ratio in a strategy video game. He placed his I/O Bit on his home desk and used the *Ratio* visualization for the duration of the study. IP3 found that the I/O Bit both prompted him to start playing the game and stop if he was on a losing streak. IP3 liked that this was a standalone tracking device became part of his desk's ecosystem. IP3 did struggle with the I/O Bit's simplicity — noting that his win ratio was above average but that it wasn't able to capture the nuance of the data — either in terms of game mechanics and his improvement over time. IP3 described his ideal I/O Bit as a much more complex and customizable personal tracker.

5.1.4 Participant 4: Video Game Character Selection. IP4 decided to track character selection in a fighting video game with his I/O Bit. He placed his I/O Bit on his home desk and exclusively used the *Counts* visualization. While he initially described his motivation for tracking as a way to determine which character he enjoyed playing more, he later described switching characters if the counts were becoming too uneven. IP4 appreciated the physical device and tactile input, comparing it to a mechanical keyboard. He liked that the I/O Bit's physical and dedicated nature helped his tracking 'stick out' in contrast to having everything on a phone. IP4's ideal I/O Bit would maintain the simplistic and tactile input but pair it with a larger high-resolution display and more customization options.

5.1.5 Participant 5: Sleep Schedule. IP5 decided to track when he went to sleep and woke up each day with his I/O Bit. He placed it on his night stand and used the *Counts* visualization. While the I/O Bit did not help IP5 achieve a more regular sleep schedule during the study, he did notice that using the I/O Bit in the morning helped him remember to complete his other personal tracking activities. IP5 liked the manual control over the logging, comparing it to his smart

watch which would incorrectly estimate his sleep schedule. IP5's ideal I/O Bit would be a slim, easily mountable device, capable of drawing attention to itself (possibly via an alarm) and automatically adding data to a dashboard.

5.1.6 Participant 6: Role-playing Dice Rolls. IP6 used I/O Bits to track dice rolls during a weekly table-top role-playing game he facilitated. The game was played in various locations from week to week, and he stored his I/O Bit on a shelf between games and set it up during each game session. IP6 used the *Ratio* visualization to compare high and low dice rolls. After 86 dice rolls, the visualization was completely balanced between high and low rolls. IP6 initially struggled to decide what to track, finding the two button input mechanism too limiting. Like IP4, he wished there was a visualization that showed the ratio over time. Notably, IP6 had already tracked dice rolls with a pen and paper, and preferred that experience to using the I/O Bit.

6 INSIGHTS AND OBSERVATIONS

Both our initial design workshops and prototype deployment helped us build a clearer appreciation of the unique benefits and drawbacks of user-driven, situated, and dedicated personal informatics tools. To extract themes from our study observations, we collected records from both the e-paper visualization workshop and our I/O Bits deployment, including audio recordings, transcripts, questionnaires, sketches, photos, and our own reflections on the process. We then conducted an affinity analysis, iteratively grouping and regrouping artifacts to find emergent patterns and interesting anomalies. Finally, we distilled these findings into four key takeaways (section 6) and four interesting areas for future exploration (section 7).

6.1 Trackers as Physical Objects

Throughout our explorations, we routinely observed how the presence of physical trackers can serve as reminders, reduce interaction friction, and help bring focus to personal tracking goals. In particular, participants from the epaper visualization workshop and the deployment appreciated how the dedicated trackers eliminated several layers of interaction when compared against mobile phones and other multi-purpose devices. Participant EP8 noted this specifically, saying, *"One thing I find very interesting about [each I/O Bit] is [that] it keeps track of one specific idea or one specific task [...] because I don't do it on my phone. If I have to open it, it is just [not worth it]." During our study 5 out of 6 participants altered their behaviour to some extent as a result of tracking with their I/O Bit. In particular, participants often credited the physical presence of the device alone with triggering certain actions and prompting reflections. For example, IP1 found that she would notice the device and remember to complete her routine, IP2 found that she took fewer and more purposeful breaks, and IP3 would see the device and be prompted to play his video game. In all cases, the physical device acted as a non-intrusive reminder to track, reflect, or act and often eliminated the need for more explicit notifications. As IP1 put it, <i>"Phone notifications are [...] both easy to dismiss and really irritating where [I/O Bits are] not as easy to dismiss and not really irratating"*. This suggests that the physical presence of a dedicated tracker can help drive reflections, insights, and behaviour change.

6.2 Small Displays for Small Questions

Our experiences also emphasize how small situated displays are well-suited for displaying simple and actionable representations of information, augmenting short-term memory, and facilitating situated decision making rather than more complex analyses. A majority of the participants (5/6) who used I/O Bits at home relied on just two of the visualizations, *Counts* and *Ratios*. These two visualizations were the simplest ones we provided and aggressively aggregated the data to provide high-level totals rather than lower-level details. This simplification resulted in visualizations which rendered those values larger and more visible than in the other visualizations, making them considerably more glanceable. The increased visibility of these elements also made it much easier for participants to detect and verify changes each time one of the buttons was pressed.

This emphasis on simplicity was also evident in the way that participants used the visualizations. Interestingly, only 2/6 participants reported altering their behaviour based on the visualizations specifically. IP3 would stop playing his video game when he was on a losing streak that was impacting his win ratio or mood. Similarly, IP4 would notice that he was favouring the character that gave them more instant satisfaction, and would switch to practice with the other character. Instead, most of the participants used the trackers as a form of external memory that they used to drive very immediate decision-making or simply as visual feedback to verify their tracking. For example, IP2 and IP6 reported primarily consulting the *Counts* visualization to determine when they forgot to log an instance.

The visualizations may not even be necessary for some use cases. One participant from our evaluation and two participants from our e-paper visualization workshop even talked about not needing a display. This aligns with Ferrario et al.'s observation that the conscious and mindful act of tracking (in their case, via an anxiety tracker) provided benefits in and of itself, independent of the data being collected [17]. Not having a display may also help people track without being as influenced by existing data. For instance, two of our participants (IP3, IP4) said their tracking goal was to answer a question, yet in both cases they discussed altering their behaviour after looking at the visualization. These and related observations stress that situated self-tracking may not only benefit from simple input mechanisms, but also small-scale and simple visualizations that do not induce in-depth engagements or distract from everyday activities.

6.3 Generic Logging and Context Un-aware Data

Our experiences suggest that simple, generic tracker designs can support extremely diverse tracking tasks while also providing a sense of privacy and control. Every one of our participants, across both the e-paper visualization workshop and prototype deployment, proposed unique ideas for how to use their I/O Bits. The wide range of proposed uses suggests that these kinds of general-purpose trackers with task-agnostic interfaces could indeed enable a diverse set of untapped uses for personal informatics tools. Moreover, during the e-paper visualization workshop, participants highlighted two additional benefits of generic tracking interfaces, noting that they can provide a sense of privacy and also make it easier to purposefully abandon or re-purpose devices:

"I think [the fact that] the system does not need to know what you are tracking is super attractive. If you consider how many people are tracking very sensitive things [...] having that basically not being made explicit to the system. [...] I think it is actually really useful." – EP2

"For it me it takes the pressure off the data. [...] You have the [data] set, but then at some point, the data is outdated [...] and if you don't remember then maybe it's not necessary anymore." – EP4

More broadly, we expect that generic tracking interfaces with decentralized data collection can provide individuals with a sense of control over their data and mitigate concerns that their data might be observed or interpreted by others, either locally or remotely. These kinds of generic trackers may also support more natural abandonment and reuse. In their studies, Epstein et al. found that individuals abandoned self trackers because they felt discomfort and judgement when reflecting on their data [14]. Simpler trackers that allow users to easily wipe the data or let it expire gradually may address some of these concerns, giving users permission to collect data more freely and honestly. These kinds of

trackers may also support a more natural cycle of exploration in which users feel comfortable experimenting with new kinds of tracking, knowing that they can easily abandon, adapt, or reuse a tracker if their practices change.

6.4 Personal Identity and Self-tracking

Similarly, we observed that flexible personal informatics tools can make it easier for users to pose new questions and explore more diverse and personal tracking topics. The tracking topics participants proposed during our workshops were not only unique, but also tended to reflect their particular goals, interests, and personalities. Some participants, like IP4 (who used his tracker to monitor his character choices in a favorite game) noted this personal connection explicitly – *"In this game your choice of character reflects a lot on who you are as a player"*. For others, including a EP4 who designed a chart for breakfast tracking during the e-paper visualization workshop, these topics reflected personal aspirations: *"I think of myself of a person who eats breakfasts, it is a really nice breakfast, but I rarely eat breakfast. It is really sad, cause I never have time for it, or I don't make time for it."*. Meanwhile, some participants emphasized ways in which personalized trackers could help them align with their own identity and ambitions, rather than externally-imposed ones. For example, IP2 suggested that her next use of her I/O Bit might focus on a more intimate interest like reading:

"Reading is part of my personality, I was known for it in my undergrad and it is something I have picked up again. [...] I find a lot of tracking very judgemental, for example all the FitBit trackers, I absolutely hate. [...] I think it would be really stressful to be like "I haven't hit 10,000 steps today" and I am like "who cares?" but this app might make me think really I do care." – IP2

This highlights a tension between personal informatics tools that target specific use cases and more open-ended tracking platforms. When developers build systems to track a specific topic, they tend to limit the questions people can ask with them. Many personal informatics research projects and consumer products center on a few popular tracking topics — including fitness, diet, and finance — with a focus on personal optimization. Yet our preliminary results suggest the presence of a much more diverse set of highly individualized personal informatics use cases that are not readily served by current tools. As IP2 observed at the end of her session, *"I actually started looking up apps online to see if there was a simple 2-input [system] and everything with apps is way more complicated."* As such, we see clear opportunities for minimal, multi-purpose tracking tools to facilitate more personal, casual, and idiosyncratic tracking topics.

7 OPPORTUNITIES FOR SITUATED TRACKING DESIGN AND RESEARCH

The findings from our design workshops, prototyping process, and small deployment underscore a variety of open questions about the design and use of situated personal informatics tools and suggest opportunities for future exploration.

7.1 Balancing Simplicity and Nuance

Reconciling the desire for simplicity with expressive power remains a persistent challenge in interface design, and is particularly salient for tracking tools which are intended to integrate into everyday life. In our I/O Bits deployment, participants' feelings about the simplicity of the tracker fell into three categories. IP1 and IP2 enjoyed the simplicity of the device, noting that its constraints prompted them to more carefully consider their priorities and narrow their tracking to one or two straightforward activities that they could reliably track. IP4 and IP5 were more ambivalent about the device's simplicity, but were still able to capture something they had previously been interested in tracking. On the other hand, IP3 and IP6 found the device limiting and wished it was capable of capturing more nuanced aspects of their lives. These two each struggled to think of something to track and ultimately chose topics that they felt I/O Bits were

unable to fully capture. IP6 commented specifically that, "The biggest problem I had was that this lent itself to tracking binary data like pass-fail type tracking — or one thing or the other thing. Which meant there wasn't [sic] a lot of things that I was doing that I wanted to track."

Nearly all of the participants in our deployment (5/6) chose to use their I/O Bits to track a binary phenomenon (win/loss, work/break, character1/character2, awake/asleep, high/low roll). The only exception was IP1 who used the second button as a way of indicating that she had completed her goal but in a non-ideal manner. In these cases, the devices' simple two-button input mechanism clearly shaped participants' tracking choices. While participants' descriptions of their process made clear that they thought carefully about how to map their specific tasks onto the I/O Bits' generic interface, they chose to capture those mappings in different ways. After deciding what to track IP1 and IP3 annotated the buttons by writing on the device's whiteboard case, while P2 wrote her encoding on a separate piece of paper to maintain privacy. Although IP4, IP5, and IP6 opted to memorize the encodings, only IP6 experienced issues keeping track of the buttons — likely because his logging occurred in the moments just before and after sleep.

Support for more complex, quantitative, or text-based inputs, like those supported by many mobile personal informatics tools, would undoubtedly have encouraged participants to track different kinds of activity. Yet doing so would almost certainly come at the cost of some of the simplicity and physicality of the current trackers. Future dedicated tracking tools will need to carefully consider these trade-offs, finding ways to support a wider range of behaviors without complicating data input. The recent appearance of low-power touch-enabled e-paper displays presents interesting opportunities for these kinds of trackers, and could make it possible to create lightweight dedicated trackers that leverage the full spectrum of inputs seen on mobile phones. Interchangeable and user-configurable tangible inputs, like those on Gyory et al.'s HOT SWAP controllers [20] could also provide a richer space of inputs while retaining the benefits of physical controls.

7.2 Privacy and Visibility

Trackers with always-on glanceable displays accentuate issues of privacy and visibility that emerge frequently in the personal visualization literature [23]. In our deployment, participants regularly speculated about how visitors in their spaces might interact with I/O Bits. For example, IP2 liked that the generic designs obfuscated data from visitors, but thought that the curious object might spark a conversation. During our design workshop, participants also discussed several potential strategies to further maintain privacy from visitors. These included physical obfuscation strategies such as placing trackers in drawers as well as lightweight triggers for toggling visibility on or off. Opportunities also abound for tracker designs (like those explored by Rodgers and Bartram [37] and Kim et al. [25]) which use more artistic, abstract, and personalized representations to encode data in ways that are difficult for others to decode.

7.3 Form Factors

While our initial prototypes allowed participants to integrate trackers into new domestic spaces, they also highlighted the need for trackers with more specialized form factors. Several participants (IP2, IP5, and IP6) experienced limitations due to the bulky size of both the tracker and the base station (a Raspberry Pi), which prevented them from using the trackers in the locations they had originally hoped. Many of the designs in the e-paper visualization workshops also envisioned uses for dedicated trackers that might call for more specialized hardware including wearables, portable displays, and trackers that could easily be affixed to objects. For example, EP6 wanted to track events during their daily commute but worried about accidental button presses, proposing a portable version with a carrying case. The same request was made by participants in Vega et al.'s study in which they developed a similar self-tracking device for the

symptoms of Parkinson's Disease [46]. More dramatic suggestions included EP8's request that we remove the display entirely. IP2 echoed this sentiment, suggesting we reduce the tracker to slim bracelet that could be used exclusively for input, but in a variety of settings.

Exploring these kinds of alternative form factors represents an interesting and immediate opportunity for dedicated personal trackers. Because we focused on creating tracker designs that participants could assemble themselves, our prototype devices were much larger than the combined dimensions of the individual components. However the same elements could easily be reconfigured into a considerably smaller package more akin to the e-paper displays now used in many retail settings. The increasing prevalence of low-cost e-paper smartphones and watches also makes these a promising platform for prototyping dedicated situated trackers — either as standalone devices or integrated into custom housings with additional inputs and outputs [28].

7.4 Connecting Situated Trackers to Larger Tracking Ecosystems

Finally, a number of participants discussed a desire to connect their situated trackers to a broader tracking and analysis ecosystem which could allow them to access more complex visualizations of their tracker's data, add context and data from other sources, or access data when they were not in-situ. Interestingly, these requests reveal a clear tension between the ways participants used their I/O Bits to inform immediate decision making and the more idealized long-term reflection envisioned in many early models of personal informatics [30]. Connecting modular and situated displays like our I/O Bits to a larger tracking ecosystem could also compromise the sense of privacy and ability to abandon or reuse trackers that participants valued. Negotiating a balance between these competing constraints presents promising opportunities for future personal informatics research, particularly efforts involving sensitive and highly personal data.

8 CONCLUSION

With the rise of personal devices such as smart phones and watches, there has also been a growth of self-tracking via special-purpose applications and services, most of which automate data logging and centralize analytics. With this research we explored the viability of an alternative approach to self-tracking — using dedicated, situated, and user-driven trackers which can bring focus to personal tracking tasks and provide opportunities for reflection while engaged in those tasks. The results of our ideation workshops and the feedback from an initial deployment suggest that simple, generic interfaces and user-driven data collection can support flexible tracking that allows people to pose questions and explore personally-relevant topics more freely. Our I/O Bits represents a provocative point in the design space of user-driven and situated personal informatics systems, showcasing the potential of these tools while highlighting the need for future research on input mechanisms, form factors, supporting ecosystems, and privacy. While the results of our iterative research and design process reveal a number of open questions and challenges, our findings also underscore the unique design opportunities presented by simple, dedicated, and situated tracking tools that give individuals the power to choose exactly what to track and where to track it.

ACKNOWLEDGMENTS

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) [RGPIN2016-04564] and funding from the Canada Research Chairs Program. Portions of this work were also funded by the Inria-Calgary Associated Team SEVEN and members of the team played important roles in several workshops. We would also like to thank all of our participants.

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