

Mapping and Taking Stock of the Personal Informatics Literature

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The research community on the study and design of systems for personal informatics has grown over the past decade. To take stock of what the topics the field has studied and methods the field has used, we map and label 523 publications from ACM's library, IEEE Xplore, and PubMed. We surface that the literature has focused on studying and designing for health and wellness domains, an emphasis on understanding and overcoming barriers to data collection and reflection, and progressively fewer contributions involving artifacts being made. Our mapping review suggests directions future research could explore, such as identifying and resolving barriers to tracking stages beyond collection and reflection, engaging more with domain experts, and further discussing the privacy and ethical concerns around tracked data.

CCS Concepts: • **Human-centered Computing** → **Human computer interaction (HCI)**; *Ubiquitous and mobile computing theory, concepts, and paradigms*.

Additional Key Words and Phrases: Personal Informatics, Self-Tracking, Quantified Self, Personal Tracking, Mapping Review

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1 INTRODUCTION

As mobile phones and wearable devices continue to proliferate, people are increasingly having access to and using technology which helps them gather personal data and reflect on it. People frequently use technology to keep track of their productivity [144,193], finances [72,77,131], and learning [92,236,241]. Tracking of various aspects of health is particularly prevalent, with surveys showing 21% of U.S. adults in 2013 [282] and 41% of Canadians in 2018 [212] use technologies to track health data. Li et al. define these technologies as personal informatics systems, which “*help people collect personally relevant information for the purpose of self-reflection and gaining self-knowledge*” [168]. Since Li et al.’s 2010 characterization, the research field has become an emerging subfield within HCI, with frequent workshops on the topic at CHI, Ubicomp, and CSCW. The field has contributed new personal sensing and data collection capabilities (e.g., [11,114,129,143]), new approaches for assisting people in deriving value from the collected data (e.g., [73,135,215,274]), and new considerations of the technology’s role in everyday life and society (e.g., [37,179,294]).

In defining personal informatics systems and developing a model of their use, Li et al. uncovered types of personal information which could be collected through technology and motivations people might have for using that information to gain self-knowledge [168]. The research field has studied and considered tracking in many domains, from physical activity, sleep, and stress to video games and words read. Further studies have challenged assumptions in Li et al.’s model, such as whether people intend to act on the knowledge they gain from using these systems [77,239] or whether they use these systems for gaining self-knowledge at all [77,183].

Amidst the numerous personal informatics publications, it can be difficult to make sense of the larger picture of the field. We therefore aim to map the landscape of personal informatics within HCI, computing, and health informatics. Mapping reviews can help a research field understand what topics are frequently studied and what methods are often used to provide an overview of the field and identify missed (or future) opportunities [10,104,216]. As such, mapping reviews provide a snapshot of a broad field and can help researchers choose future directions to engage in. By describing the topics and methods used in the decade of published research on personal informatics, we point to potential topics and considerations for the next decade and beyond.

We specifically aim to understand what domains of personal data the field has studied and designed for and how, the motivations for data collection, and the goals for tool use studied and supported. We further aim to characterize how the research community has approached building knowledge by understanding the user groups being studied or designed for and the involvement of domain experts or theory. We conducted a mapping review of publications in ACM’s library, IEEE Xplore, and PubMed’s from 2010 to 2019 relevant to personal informatics, coding and categorizing a final list of 523 publications. Our analysis of these publications suggests that personal informatics research has:

- Primarily focused on studying and designing for health and wellness domains.
- Emphasized studying and designing for behavior change and self-improvement over other tracking motivations.
- Mainly understood and addressed barriers in the collection and reflection stages of Li et al.’s model, with less focus on integration and action and little focus on preparation.
- Examined people’s use of commercial trackers at a high rate, with fewer new artifacts contributed in recent years.
- Predominantly focused on individuals’ tracking needs, with some recent work starting to examine collaborative and shared tracking such as among peers and families or between patients and providers.
- Often neglected to discuss or address ethical or privacy concerns around use of self-tracked data.

By identifying the literature’s focus to date, our review identifies opportunities for future research, including:

- How does the knowledge gained in specific and frequently-studied domains (e.g., physical activity) generalize to the design of personal informatics systems in other domains?
- In addition to barriers to collection and reflection, how can tools help people address barriers to preparation, promote integration across tracking tools, and take appropriate actions after tracking?

- How can the design of personal informatics tools help promote privacy and ethical uses of data, or under what circumstances are privacy and ethics particularly noteworthy concerns?
- How can studies leverage more focused evaluation methods, such as efficacy evaluations or feedback on low-fidelity designs, to promote contributions of new personal informatics artifacts?
- How can the design of personal informatics tools better leverage theoretical techniques for promoting self-improvement and expert best practices?

Our tagged corpus of publications is available at <http://personal-informatics.depstein.net/>.

2 BACKGROUND

Our mapping review examines the nature of research and identifies gaps in the existing literature on personal informatics systems, which aim to help people collect information for the purpose of improving self-understanding [168]. The literature has examined varied personal tracking domains and motivations as well as varied approaches for producing knowledge.

2.1 Personal Informatics History

Systems for collecting and reflecting on self-tracked data have a long history in HCI. Houston [51] and UbiFit [54] aimed to help people make sense of their physical activity on their mobile devices. Early systems also examined how public displays of tracked information could help facilitate accountability and awareness, such as Fish’n’Steps for physical activity [173] and the Whereabouts Clock for location [27]. Other early systems tracked needs and challenges in other domains like diet [184,262,283] and sustainability [88,185]. Similar to the fields of study of lifelogging [95] and Personal Information Management [122], personal informatics systems often aim to support people in collecting and maintaining a record of their habits. Personal informatics also draws on conversations in health informatics research, such as around Patient-Generated Health Data [265] and Patient Reported Outcome Measures [24].

Building on previous work in personal data, information and technology design, Li et al. introduced a model with five specific stages: preparing to collect data, collecting it, integrating it across devices or platforms, reflecting on the collected data, and ultimately acting based on the reflection [168]. People often face barriers in stages which cascade, making later stages more difficult. For example, forgetting to log in the collection stage leads to incomplete data to integrate, and difficulty interpreting data in the reflection stage makes action challenging.

Since Li et al.’s characterization of personal informatics systems, commercial tools and social movements have proliferated the practice of self-tracking. The Quantified Self social movement argues that people can achieve “self-knowledge through numbers” [297], forming meetups where people share what they tracked and learned. New mobile and wearable devices with the ability to record physical activity (e.g., steps, flights of stairs), biometrics (e.g., heart rate, insulin levels), and location became popular, such as Fitbit, Apple Watch, and Foursquare. As more people have adopted self-tracking practices, the scope of personal informatics has broadened, with more domains being supported, using more tracking approaches for more motivations.

2.2 Mapping Reviews

Mapping reviews, sometimes called scoping reviews, aim to summarize the range of findings on a research topic. By comparison, systematic reviews synthesize and summarize those findings [216]. Mapping reviews are valuable for helping a research field understand what topics traditionally have and have not been studied and what methods have and have not been used [10,104,216], therefore revealing opportunities for further focus on topics or use of methods. Our review follows two of Arksey & O’Malley’s four motivations for conducting a scoping review [10]. We examine the *range and nature* of personal informatics by summarizing what, and how, the personal informatics literature has tended to study. We also *identify research gaps in the existing literature* by pointing out areas of study and methods which have typically been underexplored in current personal informatics literature.

Because systematic reviews aim to summarize prior literature, they tend to be better-suited to narrow research questions, such as characterizing common intervention approaches (e.g. technological, medical, or behavioral) or evaluating those interventions' effectiveness across studies and settings [10,104,216]. Prior systematic reviews have summarized key findings from some topics relevant to personal informatics. For example, reviews have characterized strategies for fostering engagement [107], design approaches for managing health and wellness [53,277], strategies for sharing [74], and approaches to digital health behavior change [155,288]. Books by Lupton [182] and Neff & Nafus [203] examine the quantified self and self-tracking as social and cultural phenomena, exploring potential benefits and challenges. Kersten-van Dijk et al. conducted a systematic review of personal informatics systems by considering a corpus of over 6,000 publications [133]. However, their final review excluded systems which did not experimentally evaluate self-insight or behavior change or included potential confounding features (e.g., coaching, clinical care), resulting in only 24 studies meeting the inclusion criteria. We extend these reviews to broadly characterize the research questions asked and methods used in personal informatics at large.

2.3 Review Motivations and Research Questions

The research questions of our mapping review are motivated by trends in the research literature and in commercial tracking technology.

2.3.1 Tracking Domains, Motivations, and Challenges. Personal informatics research has examined many different types of data a person can collect. Li et al.'s initial characterization of personal informatics emphasized the curation and analysis of digital logs of professional and personal activities such as bank and credit card statements, email and call history, and calendar events. Quantified Selfers traditionally tracked activities related to health and wellness such as physical activity, food, weight, sleep, and mood [42]. Although commercial tools exist to help collect and analyze personal data (e.g., summarize or download expenses, automatically collect physical activity), experts with the ability often generate their own collection and analysis tools to match their needs and goals [42,291].

Commercially and in research, apps and devices continue to broaden the kinds of data people can collect about themselves. Many tracking technologies are aligned with personal and clinical health and wellbeing goals. Pedometers are perhaps the earliest widely-adopted tracking technology, with 50% of U.S. adults having currently or previously owned an activity tracker as of 2016 [226]. The ubiquity of mobile apps have made other tracking domains prevalent as well, with a quarter or more of U.S. adults using an app to track their diet, sleep, or mental health as of 2017 [270]. Tracking outside of health and wellbeing is common as well. For example, 20% of U.S. adults reported using technology to track their personal finances in 2020 [7]. We sought to understand whether the research literature's understanding of self-tracking technologies is concentrated to one or a few domains or builds across a variety of domains. We therefore ask:

RQ1: What data domains does the personal informatics literature focus on?

People decide to track for a range of reasons, including self-improvement, a desire to keep a record, or a fascination with numbers. Although participants of the Quantified Self movement were largely driven by a desire for self-improvement or behavior change [42], Rooksby et al. argue people's practices of collecting data and reflecting on it (or choosing not to) are intertwined with the rest of their lives [239]. Many people are drawn to use tracking technologies out of curiosity, because they were given the device or app as a gift, or out of a desire to preserve a record of their activities [77].

We sought to understand to what extent people's varied motivations and uses of personal informatics tools are represented in the tools that the research literature aims to design for and studies conducted. Conceptual frameworks have suggested different phases of personal informatics tool use, such as Li et al.'s Stage-Based Model [168], Epstein et al.'s Lived Informatics Model [77], and Niess & Wozniak's Goal Tracker Evolution Model [204]. Leveraging Li et al.'s [168] framing as most widely-used, we ask:

RQ2: What tracking motivations and stage of tool use does the personal informatics literature focus on?

The rise in self-tracking also points to important privacy and ethical challenges, as the collection and use of personal and often sensitive data are core to the practice. Lupton notes that self-tracked data can be commodified, with governments, employers, and other corporate entities considering how to leverage people's data for their purposes [180]. Articles have pointed to specific cases where self-tracked data can be used by employers and advertisers for monitoring behavior, such as Ovia and Flo selling people's menstrual cycle data to employers and Facebook [110,250]. Lupton further characterizes five modes of tracking (private, communal, pushed, imposed, and exploited) to highlight circumstances where a person might be coerced or even forced to collect and disclose their self-tracked data [181]. However, people are often willing to disclose their personal data for incentives, financial or otherwise [105].

Beyond concerns around how data will be used, people also face frequent challenges when trying to use tracking tools as part of their everyday lives. People often find the process of collecting data burdensome, and some find that tracking reinforces negative behaviors [56,67,76,83]. People regularly switch tools and goals, abandon the process altogether, and resume tracking at a later time [47,72,77,160]. To understand how the literature has engaged with the potential risks, downsides, and challenges of self-tracking, we ask:

RQ3: What everyday challenges and ethical concerns does the personal informatics literature consider?

2.3.2 Research Foundations and Approaches. Wobbrock & Kientz highlight that HCI contributions are predominantly empirical studies of system use, empirical studies of people, and development of artifacts or systems [296]. The widespread adoption of tracking technology has enabled researchers to take empirical approaches to generating knowledge. For example, studies have examined people's experiences with commercial devices and apps through surveys and interviews, such as fitness trackers (e.g., Fitbit, Apple Watch) [87,204,239,279] and sleep trackers [170,233]. Studies have also used self-tracked data to better understand people's habits, such as analyzing publicly-shared records of physical activity and food logging to understand people's dieting, weight loss, and activity patterns [5,43,98,172]. We wondered whether or how the rise of commercial systems influenced the kinds of research being conducted and systems being designed and evaluated. Mapping reviews often aim to summarize methods undertaken in past work alongside characterizing the research contributions themselves [216].

Wobbrock & Kientz further highlight the value of other contribution types to the HCI literature, including theoretical and survey contributions as ways of furthering the field's thinking by summarizing or generalizing knowledge [296]. We sought to understand the relative prevalence of different styles of contribution, asking:

RQ4: What types of research contribution are prevalent in the personal informatics literature, and how have contribution types changed over time?

Many personal informatics studies aim to understand the tracking needs of the general public, aligning with the widespread use of personal tracking technology. Typical of HCI studies, the literature often approximates the general population by recruiting from the local community (e.g., mailing lists, social media). However, many studies focus on the tracking needs of people in certain circumstances, life stages or occupations. For example, studies have examined self-tracking needs of office workers [70,186,193], gamers [152,230], and people who own pets [159]. In some populations and situations, people share the data they collect or collect it collaboratively with others. For example, people often use their tracked data to facilitate advice and support from their social networks online and offline [44,74,106,132,202]. Some share the data or track collaboratively with clinicians or other domain experts, such as teachers or dieticians [178,240].

Although we know that a variety of different groups and classes of people have been studied or designed for in the literature, we were unsure to what extent publications the personal informatics literature aimed to characterize a general population or specific demographic groups. Given the multitude of stakeholders involved in collecting, reflecting, and acting on self-tracked data, we sought to understand to what extent the literature studied and designed for stakeholders beyond the individual whose self-tracked data was being collected (or whether studies or designs examined multiple individual's data being collected). We therefore asked:

RQ5: What units of analysis does the personal informatics literature tend to study or design for?

Personal informatics systems for self-improvement often draw on theories, such as for behavior change (e.g., [228]) and reflection (e.g., [254]). Some systems and designs encode support for aspects of theory (e.g., reflective practicum [266], habit alteration [218]). But in practice, many systems either do not leverage any theories or aim to support the concept generally rather than applying specific recommendations from theory [19]. We sought to understand how the personal informatics literature has engaged with theory, extending Baumer et al.'s investigation of how studies, including studies of personal informatics systems, have characterized reflection.

Personal informatics systems often must account for domain-specific needs, such as needs related to a specific setting (e.g., a workplace, a hospital) or with a specific population (e.g., older adults, a people with specific chronic condition). To help inform design, personal informatics researchers often engage with domain experts (e.g., health coaches as study or co-design participants [2,242], healthcare providers as design consultants and co-authors [222,223]). Beyond descriptions in specific projects, we have limited understanding of how frequently domain experts tend to be involved as collaborators and participants. We therefore ask:

RQ6: To what extent does the personal informatics literature involve domain experts and theory?

3 METHOD

We searched for keywords and citations in relevant search engines to identify papers, following similar methods with similar scope to other mapping reviews in the HCI literature [19,86,247]. We searched the ACM Digital Library, IEEE Xplore, and PubMed because they index many of the prominent HCI and Health Informatics venues where personal informatics work typically appears. We considered additional engines (e.g., Google Scholar, Scopus), but opted not to include them due to scale (e.g., “quantified self” returns ~16,000 articles on Google Scholar), focus on publications relating to computing and adjacent fields, and the fact that indexed articles have varying depth of peer review (e.g., posted on arxiv without review, self-hosted on university pages).

We searched for papers including keywords “self-tracking”, “personal tracking”, “quantified self”, or “personal informatics” in any searchable field. We also included publications which cited one or more of the three most-cited papers which used those keywords: Li et al.'s development of the stage-based model [168], Choe et al.'s study of the practices of Quantified Selfers [42], and Rooksby et al.'s characterization of lived informatics [239]. To our knowledge, PubMed does not include a feature for searching by citation, and our attempts to recreate such a search (e.g., searching for the title of an article) produced unsatisfactory results. Our search therefore captured citing articles from ACM and IEEE. Figure 1 summarizes our search methods.

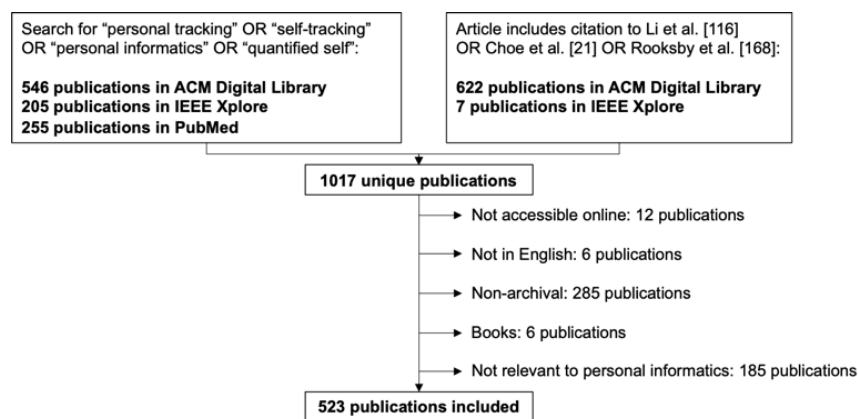


Fig. 1. We identified 523 publications relevant to personal informatics in ACM’s Digital Library, IEEE Xplore, and PubMed.

We conducted our search in January 2020, indexing publications from 2019 or earlier. We identified 1,017 unique publications across the three search engines and inclusion criteria. We removed 12 publications we could

not find online, 6 publications not written in English, and 285 non-archival publications (e.g., extended abstracts, magazine articles, workshops, posters, or keynotes). We removed 6 scholarly books to narrow our study to archival conference and journal publications. We finally removed 185 publications which two or more researchers agreed were irrelevant to personal informatics (e.g., tracking a person in an environment to facilitate Virtual Reality experiences, techniques for quantified self-reports, only acknowledging self-tracking as a movement or trend). We included 523 publications in total (Figure 2). 283 were indexed by ACM, 59 by IEEE, 128 by PubMed, and 53 by more than one engine. Publications have risen steadily, with under 50 publications per year before 2015 and over 70 per year since then. The indexed publications appeared in 189 different venues. 45% of publications (235) were from CHI (104), Ubicomp/IMWUT (41), CSCW (25) PervasiveHealth (25), OzCHI (16), JMIR (13), or DIS (11). 117 venues including UIST, ISWC, and GROUP contributed 1 relevant publication each.

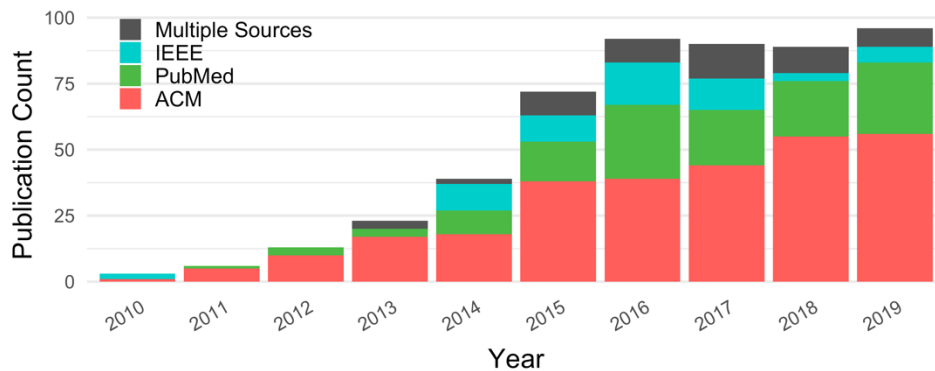


Fig. 2. Publications on personal informatics have risen steadily over the past decade.

To formulate our research questions, five researchers who have all published in personal informatics (two professors, one postdoc, and two graduate students) discussed suspected literature trends, such as a move away from systems contributions and increased study of multiple stakeholders. Each researcher then open coded 5-10 publications they knew well based on these trends. We discussed our codes and research questions and coded another 10 publications each. We refined our codes and research questions, producing 6 questions and 13 codes which we applied to the rest of the publications. We added 3 codes after coding about half of the publications (after receiving feedback from other researchers on topics to consider) for a total of 16 codes (Table 1). We re-coded completed papers for the added codes. Subsequent sections further describe how we coded each category.

When possible, we pre-populated codes with categories based on our knowledge of the personal informatics literature (e.g., popular data domains, study methods). We included open-ended response fields for all codes to allow researchers to describe the publication as accurately as possible. We occasionally added new sub-codes for topics which emerged (e.g., “mental health” as a domain). Once the coding was close to complete, we clustered the open-ended categories and uncategorized sub-codes as a group, such as the role of data domain experts or less frequently used study methods. The team then went back to each publication to resolve any open ambiguities. We aimed to be liberal in our application of codes, including all domains, stages, etc. studied or designed and involvement of theory while attempting not to judge whether they were the primary focus or contribution of the work or being critically engaged with.

We split codes roughly in half, with nine experienced researchers (two professors, one postdoc, five PhD students, one MS student) coding categories relating to tracking motivation, commentary, experts, and theory (e.g., RQ2, RQ3, and RQ6) while six more junior researchers (one MS student, five undergraduate students) coding categories relating to domain of study, study methods, and study population (e.g., RQ1, RQ4, and RQ5). All experienced researchers were actively conducting research on personal informatics, with five of the nine having participated in formulation of the research questions. Each publication was thoroughly read by one researcher from each group.

Table 1. We coded research papers according to 16 categories aligning with our research questions. Publications often included multiple codes in each category or did not include any codes for a category.

RQ	Code Category	Example codes
RQ1	Data domain tracked or studied	Physical activity, productivity, mental health
	If the domain relates to clinical health or wellbeing	Clinical health, wellbeing, neither, both
RQ2	Stage of Li et al.'s stage-based model examined	Preparation, collection, integration
	Tracking motivation	Behavior change, habit awareness, curiosity
RQ3	Discussions of people's tracking in everyday life	Abandonment or lapsing, downsides of tracking, physical burden of tracking
	Ethical or privacy implications discussed	Data control concerns, data sharing concerns, measures to protect privacy
	Depth of ethical and privacy engagement	Mentioning ethical or privacy concerns, informing a design, discussing findings
RQ4	Contribution type	Empirical, artifact, theoretical
	Kind of artifact created (for artifact contributions)	A mobile app, a website, new hardware
	Study method	Interview, survey, field deployment
RQ5	Recruitment method	Mailing lists, posts to social media, flyers
	Stakeholders studied or designed for	Individuals, families, healthcare providers
	Demographic studied or designed for	Children, teachers, general population
RQ6	Involvement of a data domain expert	Co-author, consultant, study participant
	Theory engaged with	Transtheoretical model of behavior change, self-determination theory
	Depth of theoretical engagement	Mentioning the existence of theory, informing a design, discussing findings

Whenever a new coder was onboarded, they re-coded a 3-5 publications another researcher (one of the five who helped formulate the research questions) had already coded. Initial agreement between new coders and previous researchers was strong (Krippendorff's $\alpha \geq 0.800$ [156]) for 7 of 8 codes for experienced researchers (min 0.62, max 1) and for 5 of 8 codes for junior researchers (min 0.6, max 1). Two codes were below Krippendorff's lowest acceptable limit ($\alpha \leq 0.667$): whether the tracking domain related to health/wellness and stages of Li et al.'s model. We reworked our definitions for those two codes to use the WHO's definition of health and wellbeing [298] and to clarify how different types of research contribution might discuss or design for Li et al.'s model stages. We continued to meet as a group every 2-3 weeks to further refine code definitions and to resolve any uncertainties or disagreements, often coding in working meetings and discussing questions as they arose. The lead author additionally reviewed each publication for consistency in applying codes.

3.1 Limitations

Our aim by indexing publications from ACM's Digital Library, IEEE Xplore, and PubMed was to capture the range of work studied in computing, sensing, and health informatics. However, we acknowledge that relevant work appears in venues which are not sponsored or indexed by these search engines. Other relevant search engines where self-tracking work appears include Scopus, ScienceDirect, and Web of Science. One noteworthy omission is a special issue on the lived experience of personal informatics in the Human-Computer Interaction Journal [57]. We integrate a few publications from this issue into our discussion. Our list of papers also likely overrepresents self-tracking papers relevant to health and wellbeing. PubMed as a data source focuses on health and wellbeing, and citations of Choe et al. and Rooksby et al. may also focus on these domains because the original studies discussed self-tracking opportunities around health and wellbeing.

Although non-archival articles are sometimes cited as standalone contributions, many represent in-progress work and are later published in archival venues. Only considering archival publications helped avoid over-

representing duplicate work. Including non-archival publications may make certain contribution types more prevalent (e.g., artifacts), but we leave this exploration to future work.

We are aware of relevant publications which did not include the relevant citations or keywords and were therefore not included in our sample. We particularly noticed relevant publications missing from the early 2010's, likely because terminology had not yet coalesced. For example, some research at the time described approaches as persuasive or monitoring rather than tracking, such as monitoring health and wellness via mobile and wearable devices (e.g., Health Mashups [22] and BeWell [158]), and using social support to persuade improving tracked activities (e.g., VERA [18] and GoalPost [200]).

4 RESULTS

Our mapping review uncovers areas that personal informatics literature has primarily focused on and topics which tend not to be discussed. We follow our research questions to organize our findings.

4.1 RQ1: The Literature Focuses on Health and Wellbeing

We coded the type(s) of self-tracked data being studied, designed for, or discussed in each publication, following the World Health Organization definition of health as a state of complete physical, mental, and social wellbeing [298]. Most personal informatics publications touch on an aspect of health (434, or 83%). Although a few publications examined health generally, most explored one or more specific domains related to health or wellness (Figure 3). The literature has commonly studied or designed for physical activity (181 publications), a component of mental health (89), sleep (78), or food (61). 150 publications explored multiple health and wellness domains. For example, DataMD integrated activity, food, sleep, stress, weight, and blood pressure into an interactive dashboard to be used in clinical consultations [141], while Salud! contributed an infrastructure for logging and sharing a range of health data [191]. MacLeod et al. [183] interviewed people with a range of chronic conditions to understand self-tracked data's role in management.

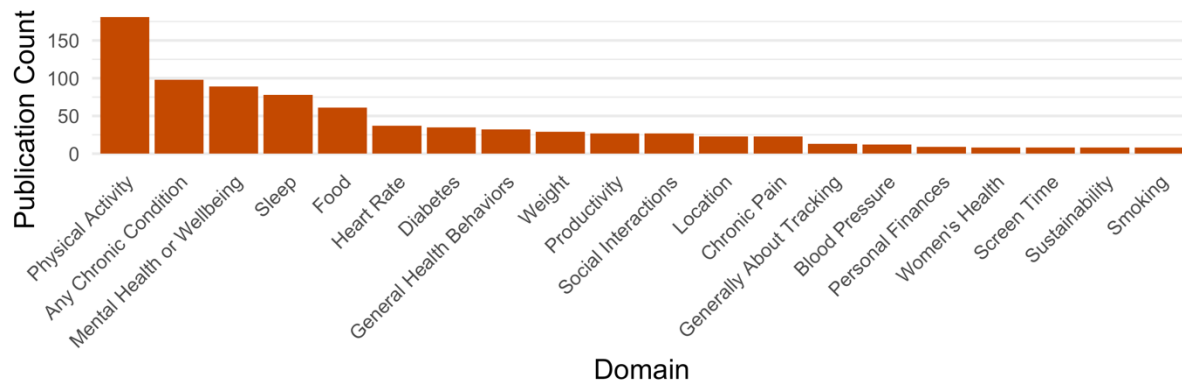


Fig. 3. The most frequent domains of study or design.

Many of the publications (204) examined health outside of clinical goals or settings, focusing on general wellbeing rather than addressing a specific condition. 172 publications considered clinical health applications, while 58 discussed both. Unsurprisingly, publications examining clinical applications were more likely to be indexed by PubMed (111 publications) than ACM (92) or IEEE (50). Physical activity and sleep were predominantly explored in relation to wellbeing, with 117 (64%) and 78 (62%) publications in those domains touching only on wellbeing. Clinical health domains included monitoring and treating chronic conditions (98 publications) such as migraine [214,255] and stroke [220,222] as well as cessation goals (13) such as with smoking (8 publications, including [210,211,267]) and alcohol consumption (4 publications, including [142,300]).

Diabetes (35 publications) and chronic pain (23 publications) were the most prevalent chronic conditions examined.

A few tracking domains were frequently studied from both clinical and wellness perspectives. Journaling of food was often discussed in wellbeing and behavioral health contexts related to healthy eating and weight loss (40 publications) as well as for diagnosis and management of chronic conditions, such as diabetes and irritable bowel syndrome (13 publications). The study of tracking tools for mental health has similarly spanned monitoring mood, affect, and stress (45) to managing bipolar disorder and depression (22).

The publications we coded as not related to health or wellbeing considered domains such as workplace productivity (27 publications), location (23), personal finances (9), sustainability (8), and teaching or learning (6). 13 publications discussed tracking broadly or did not specify a domain, such as creating a tool which participants could appropriate to track or reflect on whatever they wanted (e.g., [139,280]).

4.2 RQ2: Studies Emphasize Collection and Reflection for Behavior Change

We identified publications which studied, designed for, or discussed one or more stages of Li et al.'s stage-based model of personal informatics systems [168]. For example, any study which discussed how people decide what to track or systems supporting that decision process were coded as "preparation", while studies or systems understanding or supporting data entry were coded as "collection". Most publications (417, or 80%) examined at least one stage, and about half (248, or 47%) examined two or more stages. Figure 4 summarizes stages examined.

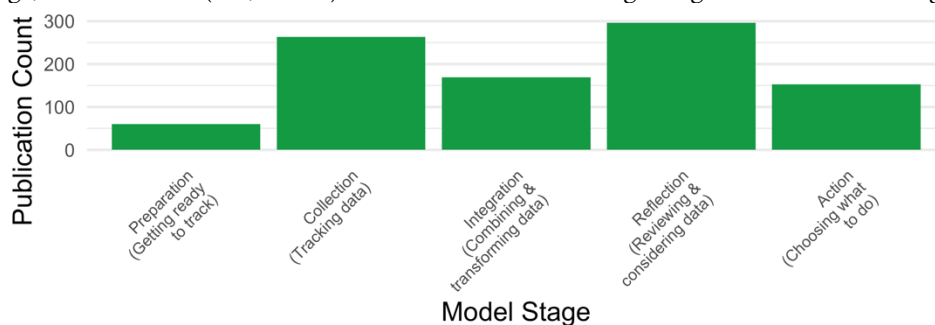


Fig. 4. Most publications focus on collection and reflection of tracked data.

4.2.1 Model Stages. Most publications study or design for people collecting data (86, or 16%), reflecting on it (119, or 23%), or both (177, or 34%). 29% (153) of publications examine or discuss how people can or do act on that data, while 32% (169) consider challenges to or propose solutions for integrating data across platforms or devices. Fewer publications consider the preparation stage (60, or 11%), where people determine what information they will record and how.

Common barriers in the preparation stage include difficulty deciding what to track and selecting effective tools [168]. Some designs and tools have used guided self-experimentation to lower the burden of identifying what to track [59,127,163]. Publications have examined the general strategies people take to find an appropriate tool (e.g., asking friends for advice, looking at online reviews [77]) and challenges people face in evaluating tools [138,217]. Although flexible configuration can help ensure tools are effective (e.g., OmniTrack [143], paper-based methods [12]), we found few studies of how people go about deciding whether a tool is a good fit or systems which help support this decision.

Integration is often studied and supported in domain-specific contexts. For example, platforms have aggregated and summarized data relevant to a domain, such as Lullaby and SleepExplorer for sleep [129,171] and ArmSleeve for stroke recovery monitoring [220]. However, we also observed many platforms which aim to aggregate a variety of health data across domains, such as 360° Quantified Self [108] and AGILE [192].

People sometimes struggle to determine how to act after reflecting on their data [168]. Most publications tended to study action in the short term, examining how commercial or research tools have facilitated immediate insights or changes (e.g., [87]). This focus aligns with Klasnja et al.'s suggestion to use HCI approaches to evaluate use of applications and tying evaluation to behavior change strategies rather than evaluate whether behavior change persists long-term [145]. We indexed a few (8) evaluative clinical trials which leveraged personal informatics systems. For example, Reichard et al. compared the impact of a weight loss interventions which leveraged self-tracking of weight, diet, and physical activity [235], and Hsu et al. compared A1c decline between traditional face-to-face diabetes care and a digital system where patients self-tracked and shared their insulin intake with their providers remotely [118].

4.2.2 Tracking Motivation. To summarize how publications study or support different tracking motivations, we coded how each publication introduced the problem space they studied or designed for or how study participants self-reported their tracking interests. Figure 5 summarizes frequently-explored motivations. Most publications aimed to study or use technology to support a self-understanding goal. 231 publications (44%) aimed to support people tracking with the goal of behavior change or self-improvement. 152 publications (29%) focused on awareness, understanding what habits people aimed to become more aware of or developing tools to support that awareness. 109 (21%) of publications focused on tracking to help manage or understand a chronic condition.

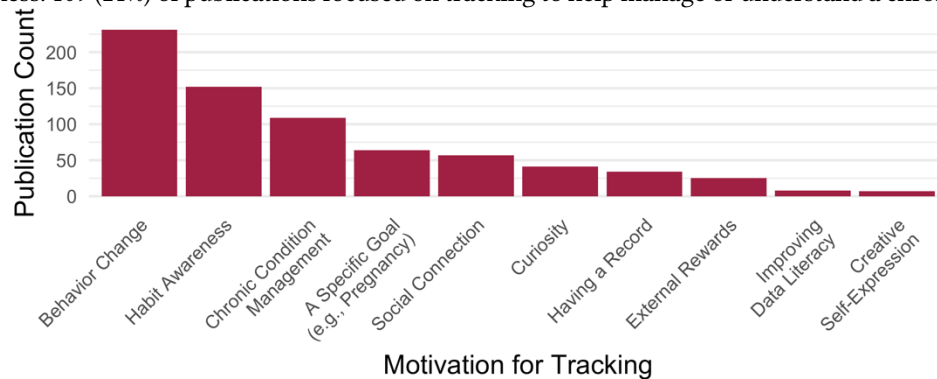


Fig. 5. Motivations of behavior change and habit awareness were frequently studied and designed for, and many publications examined multiple motivations.

Beyond understanding the self, 57 publications (11%) mentioned using data to facilitate social connectedness or social understanding, such as using data to be more aware of each other's habits [69,74,106,123,177,214]. 41 publications (8%) described or supported satisfying people's curiosity about their habits, while 25 (5%) examined external rewards such as financial payouts or discounts on insurance [46,101,119] or virtual or physical prizes [41,135,136,137]. 8 publications aimed to understand or support creative self-expression through data, such as examining artist practices with data [205] or exploring how tracked data could be incorporated into tangibles [164].

4.3 RQ3: Studies Rarely Discuss Privacy or Ethical Challenges Associated with Tracking

We described publication's discussion or study of challenges or concerns around privacy, ethics, and incorporating personal tracking in daily life in open-ended fields, later coding and summarizing descriptions.

4.3.1 Everyday Self-Tracking Challenges. About half of publications (223, or 43%) explicitly studied or discussed everyday challenges related to self-tracking. Challenges often related to difficulty integrating tracking practices with daily life (71, or 14%) or abandonment or lapsing (48, or 9%). 70 publications (13%) discussed challenges involving making sense of data (e.g., [229,253]), self-experimenting (e.g., [58,127]), and making decisions based on tracked data (e.g., [128]). These challenges resulted from issues with data accuracy or quality, tools that did not track the right data for the user's needs, or data that was difficult to interpret or act upon. A

few publications discussed difficulties collecting data due to physical or social appropriateness of tracking in certain settings (e.g., in public [32,56,210]), concerns balancing tracking with other time demands and commitments [46,58], and tracking not accounting for practices (e.g., certain meals are more difficult or impossible to record [40,55,56]). For example, patients and clinicians often have different expectations regarding what data they find relevant, accurate, or worth collecting [15,21,150] and how that data should be used in consultations [8,45].

31 publications reported other downsides to tracking, either due to obsession with collecting or checking data (e.g., [83,100,152]), due to feelings of guilt or shame based on the data (e.g., [8,50,67,144,227]), or tracking encouraging undesirable habits (e.g., [37,56]). Difficulties around sharing data (23), lack of motivation or engagement (17) and evolving goals (11) were also reported by several publications as barriers that limit use and reduce tracking benefits.

4.3.2 Privacy and Ethical Challenges. Although some publications explicitly stated that personal informatics systems should respect privacy (e.g., [49,194,224,225]), only 36% of papers (187) explicitly mentioned ethical or privacy concerns. 69 of those (37%) referred to concerns broadly, typically mentioning that privacy is an important consideration for future systems or future study. For example, two publications briefly mentioned that privacy concerns might impact adoption or use of tracking technology [107,134]. Other publications discuss concerns around informing participants that their self-tracked data may be used in research studies [238,246] or that tracking technologies may embed power relations [153] or manipulate people's behaviors [112]. Other publications pointed to privacy and ethics as potential concerns for the future of systems they design [108] or open questions for the field at large [61].

73 papers (39%) which mentioned privacy or ethical considerations used them to inform the design of an artifact contribution or in process of analyzing participant data. For example, systems allowed participants to remove data which the system automatically collected but that they felt was too sensitive to share with researchers [102,129]. Others discussed measures taken to ensure participant privacy, such as altering potentially searchable data such as posts to public forums [83] or using pseudonyms on displays [92].

90 papers (48%) brought up privacy or ethical considerations when describing or discussing study results. 41 of these papers mentioned privacy violations in the context of data access. These publications typically examined how sharing data with doctors, family members, or others can lead to deeper insights but can also invade one's privacy (e.g., [71,165,217,284]). 3 publications involving sharing tracked data on public displays described similar tradeoffs [40,186,268].

55 publications mentioned adverse consequences of collecting or sharing data. Publications warned about what tracked data could reveal or how it could be used against individuals, including consequences to employment [28,193], changes in health insurance rates [43,148], and use in legal affairs [125]. Additionally, some publications also discussed potential negative consequences of engaging in tracking or data being tracked, such as changed social dynamics and relationships [123,285], and reinforcement of stereotypes and power dynamics, such as gender roles [13,67,76,78,271]. These concerns were particularly mentioned in contexts where stigma often surrounds a condition, such as HIV [31,32] and mental health [246]. 41 publications discussed questions of privacy in the context of data ownership. Publications questioned whether individuals or device and app developers own the rights to self-tracked data [138,231], expressed concern that a company may make tracked data public in the future [116,152], or examined how designs do or can support data access control [231,263,281]. Other publications examined privacy and ethical tensions and potential benefits around data donation, where researchers could leverage contributed self-tracked data to facilitate population-level understanding of conditions [3,23,151].

48 publications discussed how people or personal informatics systems could mitigate privacy concerns. User-developed approaches included disabling particular features [6] or uninstalling or abandoning tools [72,154]. System suggestions included limiting the type of data captured (e.g., audio, video, location) [1,91,102,195], keeping data abstract or aggregated [71,81,93], and encrypting data [234]. A few systems proposed new protocols or architectures for secure data transfer among wearable devices [96,176,237].

4.4 RQ4: Fewer Artifact Contributions in Later Years

To understand the types of research contributions typically made by personal informatics publications, we followed Wobbrock & Kientz's categorization of contribution types to code each publication [296]. Wobbrock & Kientz enumerate seven contribution types: empirical, artifact, methodological, theoretical, dataset, survey, and opinion. We allowed publications to have multiple contribution types, aiming to be inclusive in labeling contributions. For example, we labeled any publication which included a design or system developed by the research team as an artifact contribution, regardless of the artifact's fidelity (e.g., paper, implemented). For empirical contributions, we also coded the style(s) of study or studies conducted (e.g., survey, interview, deployment of a system).

Most publications (406, or 78%) included an empirical contribution, while many (215, or 41%) included an artifact contribution, similar to Wobbrock & Kientz's overview of the CHI 2016 proceedings [296]. We coded 201 publications (38%) as having more than one type of contribution, with most combining empirical contributions with artifacts (174 or 201, or 87%). Table 2 shows relative frequency of contribution in total and by search engine. Empirical work was most prevalent in ACM publications (90% of all indexed publications), while artifacts tended to appear in ACM or IEEE venues (48% and 44% of publications, respectively). Survey and opinion contributions were disproportionately more prevalent in PubMed (14% and 16% of PubMed publications), aligning with a medical culture where literature reviews, meta-analyses, and opinion pieces are common contributions. We did not observe any publications which primarily made dataset contributions.

Table 2. Number of publications by contribution type. Sum of percentages exceed 100% because publications could be coded for multiple contribution types and some publications were indexed by multiple search engines.

Contribution Type	# of ACM Publications (% of ACM)	# of IEEE Publications (% of IEEE)	# of PubMed Publications (% of PubMed)	Total # of Publications (% of total)
Empirical	299 (90%)	62 (63%)	93 (63%)	406 (78%)
Artifact	159 (48%)	44 (45%)	32 (22%)	215 (41%)
Survey	13 (4%)	3 (3%)	24 (16%)	39 (7%)
Opinion	9 (3%)	6 (6%)	20 (14%)	33 (6%)
Theoretical	18 (5%)	4 (4%)	3 (2%)	23 (4%)
Methodological	6 (2%)	3 (3%)	3 (2%)	11 (2%)
Dataset	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total # of publications	332	98	147	523

Figure 6 shows the rate of empirical and artifact contribution styles by year, normalized to the number of publications that year. Although the number of personal informatics publications per year has risen (Figure 2), the rate of empirical contributions has remained relatively steady, with 70-90% of publications including empirical work (excluding 2010, where only 3 publications were indexed). The rate of artifact contributions made has steadily dropped over the past decade. 45 of the 84 relevant publications (53%) from 2010 to 2014 included an artifact contribution, versus 171 of 439 publications (39%) from 2015 to 2019.

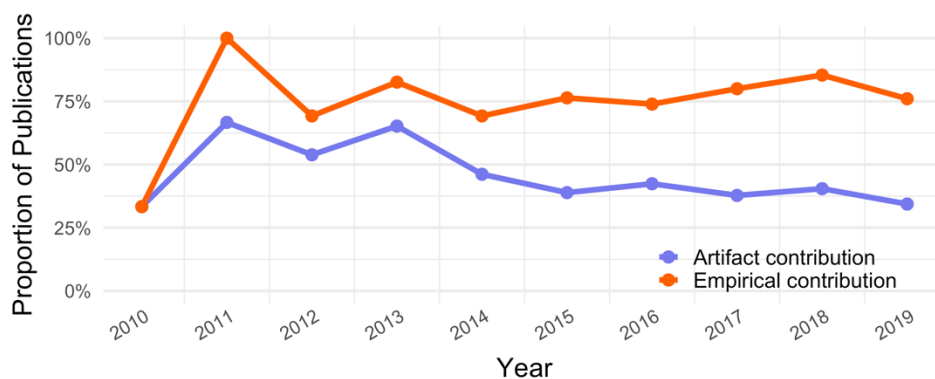


Fig. 6. Fewer recent publications contribute artifacts, while empirical contributions remain prevalent.

Among the empirical studies, most involved interviews (126, or 31%), surveys (63, or 16%) or a combination (58, or 24%). 131 publications (32%) included a deployment study, where participants used either a researcher-developed artifact (89, or 22%) or a commercial artifact (42, or 10%). Deployment studies typically also involved interviews or surveys with participants. 47 publications (12%) incorporated lab studies (e.g., of a new tool for reflection [268,273,274], of a new data collection technique [130,292], as a data source for development of a clustering or recognition algorithm [63,126,199,292]) and 39 (10%) involved participatory design activities (e.g., providing participants artifacts or scenarios to inform design of future tools [25,115,165,301], co-creating tools with participants [140,178,245]). 37 empirical studies (9%) leveraged publicly-available data, such as videos of Quantified Self talks [42,291], social media posts [12,43,74,98,213,287], posts to forums [84,189,207,219], or app reviews [36,76,233].

About half of the artifacts created were mobile apps (91, or 42%). Websites (41, or 19%), desktop apps (16, or 7%), apps for wearable devices (13, or 6%), and lower-fidelity paper prototypes or digital mockups (13, or 6%) were also prevalent. These artifacts often incorporated novel approaches to visualize data, including abstract or artistic representations [81,136] or techniques for extracting useful or interesting feedback [73,82,149]). Others contributed new hardware, such as devices for presenting data publicly [188,268] or for collecting new kinds of data [11,114,292]. 6 publications contributed toolkits or architectures to ease creation of other self-tracking tools, such as for semi-automated tracking [143] or single-case experiments [276]. Other artifacts included conversational agents [149], large-scale displays [40], and live theater productions [264].

Researcher-developed artifacts were frequently empirically evaluated (174/215, or 81%), and about half of these were evaluated through field deployments (94/174, or 54%). Roughly half of publications with each artifact type conducted a field deployment: 53% of mobile apps (48), 41% of websites (17), 46% of novel hardware (13), 61% of wearable apps (8), and 44% of desktop apps (7). The relatively minor differences between deployment rates suggests that artifacts types tend to be developed at similar levels of maturity. Study durations have ranged from a single day for deployments around a special event the researchers organized (e.g., a race, a hike, a presentation [80,90,188]) to nearly a year [62,198], with a mean of 40.7 days and a median of 21 days.

Most survey publications contributed reflections on the potential role of self-tracking technology, such as in clinical care or disease prevention [9,16,30,272,289,295] or described situations where personal informatics data could be useful socially [74,221]. Others summarized literature where personal informatics is one of many strategies (e.g., reflection [17,19], behavior change [218,277]), or opportunities for tracking in specific data domains (e.g., affective health [246]). A few summarized prior literature on important methods for personal informatics systems, including how to foster engagement [107], how to provide feedback [251], and the accuracy of data from wearable devices [157,260,261].

Opinion contributions also suggested that self-knowledge or self-understanding through numbers may be impossible [37,271] or undesirable [294], or emphasized opportunities for computing to better connect with other

disciplines (e.g., sociocultural or political dimensions [179], intelligent computing [208], art [205]). Method contributions provided approaches for engaging marginalized groups in design activities to inform the design of self-tracking tools [124,150] and understanding people's in-situ habits with self-tracked data [99,167].

We identified 23 publications making theoretical contributions, including models of personal informatics [4,77,168,204], frameworks describing how tracking technology can best support a domain or practice (e.g., transformative reflection [266], serious mental illness [202], diabetes [128], productivity [290]), and defining terms (e.g., adherence [275]). The 11 methodological contributions offered new strategies for analyzing self-tracked data (e.g., Bayesian analysis for self-experimentation [256], personalized models for event detection from self-tracked data [169]) and approaches for using self-tracked data to understand people's everyday experiences [48,99,117].

4.5 RQ5: Studies Are Mainly Individual-Focused, More Recently Beyond Individual Stakeholders

To understand what unit of analysis tend to be studied in the literature, we labeled the stakeholder(s) each publication studied or designed for (e.g., individual trackers, families, caregivers) and targeted populations (general population, students, patients).

To date, empirical research has primarily focused on the needs of individuals tracking by themselves, for themselves (341, or 84%). However, study and discussion of stakeholders other than individual trackers has increased in recent years (Figure 7). The primary stakeholders studied or designed for other than individuals were tracking in collaboration with healthcare providers (36, or 9%) or other domain experts such as teachers (6, or 1%) and family members or caregivers (27, or 7%). Other relationships were present in 17 papers, most often friends.



Fig. 7. Number of publications for stakeholders beyond individuals that have been studied or designed for, by year.

In many publications (219, or 42%), researchers did not focus on a specific demographic, instead aiming to study or design for the population at large. 131 (60%) of these publications discussed applications of wellness-focused tracking such as physical activity, sleep, or food tracking. Empirical studies of general populations followed HCI norms of recruitment from mailing lists (42, or 23%), social media (36, or 20%), snowball samples (35, 19%), or flyers (20, or 11%). Study sizes typically aligned with local standards for HCI [34], with field deployments ranging from 1 [64,290] to 365 participants [174], with a median of 21 and a mean of 38.5.

Around half (241, or 46%) of publications have focused on a particular population, such individuals with a certain illness or students. Most prevalent populations studied and designed for include patients (105, or 20%), students (38, or 7%), and office workers (25, or 5%). The tracking needs of students were sometimes studied in an educational context (e.g., towards improving their attention in the classroom [236], and exercise at recess [166]). More often, studies recruited students out of convenience (e.g., [120,201]). Among workers, studies investigated tracking performance or productivity (e.g., [111,227]), workplace wellness programs (e.g., [46,100]), and wellness with the goal of increasing productivity (e.g., [70,193]). Other studies examined specific age groups

such as children (e.g., monitoring ADHD [94] or sleep [123,217]) and older adults (e.g., to support aging in place [35,60,66], self-monitoring [20,190], and monitoring functional abilities [165]). A few publications examined the needs of people with specialized hobbies or occupations (e.g., amateur and elite athletes [38,232,279] and gamers [152,230]) or with specialized goals (e.g., smoking cessation [210,211,267], trying to conceive [83,84,253]).

4.6 RQ6: Studies Occasionally Involvement of Domain Experts and Theory

In surveying involvement of domain experts and theory in personal informatics publications, we sought to understand how the HCI community has leveraged intellectual domain knowledge. We coded whether and how each publication involved a domain expert, inclusively defining experts as anyone with formal training who a person might go to for professional advice (e.g., a personal health coach, a classroom educator, a clinician). To identify domain experts, we investigated the affiliations of authors (e.g., medical collaborators), descriptions of study participants, and involvement of any consultants or assistants in the study methods. We similarly coded the role of theory, labeling theories which served as guides for artifact design, lenses for analysis, or motivations for studying a topic.

4.6.1 Domain Experts. About a third of the publications related to health and wellness mentioned involvement of a domain expert such as a clinician, dietician, coach, or psychologist (164 of 434, or 38%). Publications involving clinical health domains involved experts at a higher rate (89 of 172, or 52%) than those relating only to wellness (51 of 204, or 25%). A higher rate of publications indexed by PubMed involved a domain expert (90 of 142, or 63%) than those indexed by ACM (73 of 259, or 28%) or IEEE (19 of 81, or 23%). Most publications involving experts included them as publication authors (119 of 164, or 73%), with affiliations in schools of medicine, public health departments, and hospitals.

59 publications involved experts as study participants, such as an interviewee or to get feedback on a developed system. These publications were typically indexed by ACM (47, or 80%). For example, Hong et al. use clinician interviews to inform topics to explore in a co-design process with parents and patients involved in pediatric care [115]. Experts were also occasionally consultants (12) or collaborators who helped recruit patients in hospitals or clinics (5). Domain experts were sometimes involved in tracking domains outside of health and wellness (14 of 89, or 16%), such as teachers and students when tracking in educational domains (e.g., [248,264]).

4.6.2 Theory. Roughly a quarter of publications (140, or 27%) described using a theoretical lens for examining a personal tracking phenomena or theoretical approach to developing personal tracking technology. Artifact and empirical contributions drew on theory at similar rates. 41 publications only mentioned the existence of a relevant theory, such as describing the theoretical foundations that self-monitoring technology are based on [47,137,269]. 75 publications utilized theory to inform an artifact design or analytic lens, while 39 showed how study results were explained by theory or expanded on a theory. Figure 8 shows widely-mentioned theories.

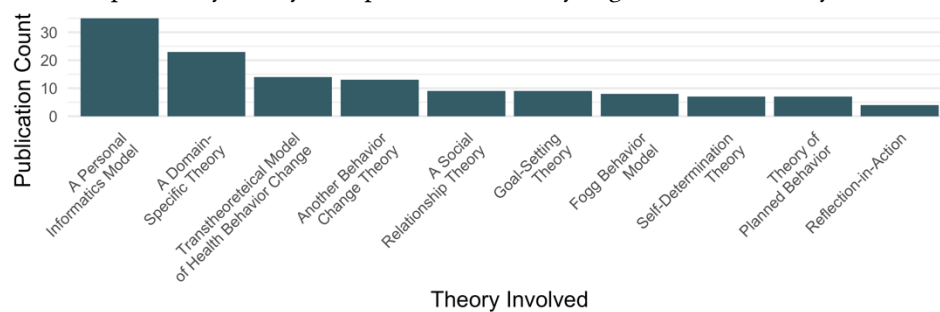


Fig. 8. Theories commonly mentioned by publications included models of personal informatics, domain-specific theories, and behavior change theories.

35 publications used a model of personal informatics systems as a theoretical framing, such as by examining how people track in a new domain at different stages in those models [44,84,217]. Commonly-used theoretical

perspectives from other bodies of literature included the Transtheoretical Model of Health Behavior change [228] (14 publications), Goal-Setting Theory [175] (9), the Fogg Behavior Model [85] (8), Self-Determination Theory [243] (7), and Reflection-in-Action [254] (4). 10 publications drew on and expanded on theories of how people engage socially, such as Bond's [26] or Goffman's [97] theories of self-presentation [188] or Bandura's [14] social learning theory [121]. 23 publications leveraged theories relevant to the specific domain being tracked, such as suggesting that tracking tools use the SATED framework [33] to measuring sleep quality [233] and appraisal theory [252] to make sense of how algorithmic framing in an interface might influence a person's reaction to seeing emotion data [113].

5 DISCUSSION

In summarizing frequent areas of study in the personal informatics literature, we aim to map the current landscape of the literature and point to underexplored opportunities for future research. We revisit our six research questions to point to opportunities for future research. Our opportunities primarily speak to HCI research, though we highlight some opportunities which overlap with engineering and medicine.

These suggestions for the personal informatics field represent less-studied areas and less-used methods that we have uncovered in reviewing publications in the computing literature that focus on self-tracking. They overlap with other disciplines with long histories of HCI research including sustainability, privacy, and recommender systems, and intersect with other broader conversations around incentivizing depth versus novelty and promoting interdisciplinary scholarship. Aspects of these opportunities are already being discussed in these disciplines, and personal informatics researchers should participate in these communities and movements to translate the scientific knowledge back to the study and design of personal informatics tools, rather than reinventing design strategies as though they are the only community facing such issues.

5.1 Expanding Domain Exploration and Generalizing Findings

Our review points to opportunities to broaden the domains frequently studied in order to help generalize our takeaways on how to design personal informatics systems. When Li et al. described personal informatics, participants primarily tracked their financial statements, conversational history, and calendar events [168]. Our analysis surfaces that the study of personal informatics has diverged, focusing primarily on data collected for personal health or wellness. In many ways, this change in focus reflects society's desire to pursue health and wellness as the practice of self-tracking has moved from experts to the general public. The widespread adoption of commercial tools which reduce the burden of collecting health and wellness data (e.g., fitness trackers, mobile apps for domain journaling or chronic condition management) has made personal informatics for health appealing and easy to study.

Within health, physical activity specifically was a case study for over a third of the publications we reviewed, over twice as common as the next most-prominent single domain (mental health and wellbeing). Our review suggests that physical activity is often used as an exemplar domain for studying people's relationships to self-tracked data and evaluating generally-applicable personal informatics design strategies. Focusing solely on physical activity can make studies and designs more tractable, but can miss out on how people's experiences and reactions change in domains which vary on any of a number of dimensions. For example, other domains may be more or less personal, more or less meaningful, harder or easier to collect, more or less accurate, or have more or fewer clinical implications. Relatedly, the field typically not explored differences between the domain (e.g., physical activity) and the data which systems often support collecting (e.g., steps).

Future studies could explore what strategies or principles we have developed to promote physical activity do or do not translate to other domains. For example, Gouveia et al. show that glanceable feedback on activity progress can encourage people to initiate walks [103]. However, such feedback may not have the same positive outcomes in tracking domains where people desire more privacy or people make decisions less frequently, like diet and finances. Opportunities or challenges in adapting interventions should similarly be examined in other principles established around physical activity, like the utility of push feedback [39], strategies for accounting

for lapsing [75], social reflections [244], adherence-based interfaces [274], accuracy assessment [299]. To better understand the impact of domain on research findings, researchers can also explore multiple domains in single studies or design explorations when aiming to contribute to the personal informatics literature more broadly.

Personal informatics research has naturally focused on understanding and benefitting the self. But personal behaviors are situated in larger social contexts, and there are opportunities to track and potentially improve behaviors relating to people's interactions with the outside world and with others. For example, technology could better assist people in tracking and understanding their personal finances, their communication and entertainment habits, or their energy expenditures. People desire support in these areas; for example, three quarters of U.S. adults feel they could use more advice on their finances, while over half do not monitor their spending [7]. Similarly, in reviewing eco-feedback technology, Froehlich et al. articulate common personal informatics principles like goal-setting, feedback, and support for behavior change theory [89]. Considering how tracking technology in helping people live more fulfilling lives, not just healthy ones, could lead to designs for people to monitor and maintain social relationships or participation in hobbies they enjoy [11,68,206].

Research has started to examine how personal informatics can help support reflection in financial, communication, or sustainability and identified ways in which data that is easy to collect insufficiently describes people's habits [131,258,278]. Particularly in sustainability, people's circumstances are often too complex to be fully characterized by personal informatics systems because some factors are often beyond individual's control (e.g., renters can rarely control their heating, focusing on individual barriers rather than societal ones), and designs could support reflection over goal-setting [29]. The few publications at the intersection of personal informatics and these thriving HCI research areas suggest opportunity to apply the knowledge that personal informatics has acquired about supporting reflection or collecting data which acknowledges or addresses factors out of individual's control. Alternatively, learning to address these barriers in domains like sustainability, finances, and communication can create transferable knowledge.

Conversely, there certainly continue to be worthwhile challenges to explore within often-explored health and wellness domains like physical activity as tracking technology becomes available to people in more socioeconomic and cultural situations around the world. However, the often-unfortunate focus on novelty within the HCI community can lead researchers to seek out new situations or circumstances where health tracking technology has not been seriously studied or designed for, or new health domains which have not been explored in depth by prior work. There is also a need to design and develop new approaches to core personal informatics challenges such as helping people find a tracking tool appropriate to their needs, helping them set an achievable and measurable goal, helping people derive insight from their self-tracked data, and helping them use collected data to express themselves to others.

5.2 Addressing Barriers to the Preparation, Integration, and Action Stages

Considering the stages of Li et al.'s model of personal informatics [168], the literature has primarily focused on understanding and addressing barriers to collection and reflection with less attention paid to integration, action, and particularly preparation. Barriers to collection and reflection are natural HCI problems, as entry and display of information are central to many interfaces. Addressing barriers to the other stages will help improve the utility of tracking tools.

The continued increase in tracking tools available to people and their decreased cost will make barriers to preparation more challenging. When preparing to track, Li et al. point out that people face challenges determining what information to collect and what tool to use. These challenges then cascade to barriers in collecting information which turns out to not be useful in later attempts to reflect [168]. With more tracking tool options released frequently, people may struggle to identify what tracking tool(s) best support their needs or are effective in conjunction with apps or devices they are already using. Literature highlights that people have diverse goals and information needs, but there has been limited examination of how designs can support preparation beyond flexible configuration of tracking tools [143,257]. To address this, personal informatics could further examine how redesigned apps, app stores, recommender systems, or peer advice could further facilitate preparation, connecting with foundational literature on the topics. Given that people frequently turn to online

searches and app reviews to identify what app is best-suited for their personal tracking needs [77], the community could design platforms which help people more easily identify whether a tool collects the data they want, how they want it.

The siloed nature of tools for self-tracked data continues to make integration challenging [77,79,231], which will become more of a challenge as people adopt more tools and switch between them. Research has offered techniques for aggregating data in shared repositories, such as leveraging open data standards [79] and semantically linking data [293]. As Wiese et al. describe, challenges around integration often manifest over longer-term self-tracking where people leverage many tools and have higher expectations for how data should be able to assist them with reflection [293]. Beyond technical challenges of getting data from disparate sources together, people also face substantial everyday and sociotechnical challenges when integrating data. These include involving multiple stakeholders (e.g., collectors of data, people who want to view different aspects of self-tracked data), mixing paper-based tracking with digital logs, and supporting simultaneous integration and reflection [202,291]. The rise of commercial aggregators such as Apple Health and Google Fit provide opportunities to study people's current experiences with integration and offer platforms for bootstrapping future designs. Whooley et al. also point out that people's integration of data are often driven by curiosity (e.g., understanding facets that they were previously unaware of) [291]. Our review points out that the literature often examines integration in domain-specific contexts. Understanding what curiosities people aim to satisfy themselves could suggest domain combinations which are worthwhile for designs to support integrating.

To offer value, personal informatics tools must support people in acting on their data to change their habits, satisfying their curiosity, preserving the history they desire, or otherwise helping people achieve their stated goal. Towards evaluating health apps that support behavior change goals, Klasnja et al. proposed HCI researchers evaluate the efficacy of tools supporting specific strategies [145]. However, we found few efficacy studies in our review. We generally agree with past work suggesting more focused contributions demonstrating the utility of new features or strategies. For example, rather than conducting evaluations of long-term goals such as weight loss or stress management, Klasnja et al. argue that HCI systems evaluate proximal outcomes which, if enacted over time, can lead to behavior change (e.g., going for a walk, connecting with a friend) [147]. To support and evaluate action, aggregators and open-source tracking tools can also serve as useful starting points to avoid needing to recreate all aspects of a personal informatics tool.

5.3 Highlighting Privacy and Ethical Concerns Further

Although some papers discuss privacy and ethical concerns, with the focus on risks associated with personal data and self-reflection, these concerns are no doubt a necessary area of continued focus for personal informatics. Recent conversations have highlighted how corporations are or could be leveraging personal data when determining insurance premiums or targeting advertisements [28,259]. Although a few research publications point to people's concerns about how companies might use their tracked data [46,101], the community tends to predominantly focus on the potential opportunities for personal informatics data to help individuals or points to design problems which need to be addressed to achieve those opportunities.

We found relatively few proposed solutions to promote privacy or understood circumstances where such privacy is desirable in the literature, such as protecting individuals from others looking over their shoulders (particularly in stigmatized domains [31,67,76]) or designing architectures which appropriately restrict access of data to individuals or trusted others. A few publications did point to designs or methods that researchers have taken to preserve privacy when designing tools, such as Consolvo et al.'s abstract visualization of activity in UbiFit Garden [52] and the practice of developing middleware to ensure self-tracked data is anonymized and encrypted prior to cloud storage [281,293]. More broadly, personal informatics research could critically engage with perspectives on how governments and companies use self-tracked data, and ideally help form and perpetuate business models for personal informatics systems which do not require self-tracked data be sold or shared. Connecting more with the security and privacy expertise within HCI, as well as with business scholars who study markets around personal data, would be valuable.

Our community's perspectives on people's willingness to share or disclose their data could better connect to policy conversations around data privacy regulations, learning from other public policymaking efforts in HCI [161]. We were heartened to find regulatory discussions in health ethics and bioethics venues, for example around personal informatics technology in the workplace [28] and closed-loop systems which combine self-tracking with drug delivery (e.g., for diabetes) [148]. The HCI literature has much to add to this conversation.

We also call for the HCI community to think more about our own ethical responsibilities, particularly how we can promote study of a participant's self-knowledge and self-understanding when we are deploying self-tracking systems for our own gains. For example, large-scale deployments of location and activity-monitoring applications have contributed important insights into the behaviors of students (e.g., StudentLife [286]) and of office workers (e.g., the Tesserae Project [187]). It is worth considering whether the self-tracking tools we use to collect data can provide individual study participants insights into their own behaviors without interfering with the study's integrity. Providing participants with feedback from their data could also benefit these studies, facilitating higher study compliance and thus higher-quality insight into their activities.

5.4 Informing Artifact Design

We offer four potential interpretations for why artifact contributions in personal informatics have been declining, though others likely exist. (1) As the technology has matured, it has become more challenging to design research prototypes which demonstrate a core concept, but also include the wider array of features that people have come to expect from personal informatics tools. (2) The field is demanding more from evaluations, expecting long-term deployments of artifacts or controlled experiments comparing techniques against baselines. (3) The proliferation of commercial tracking tools has led the field to study their use to form design insights (though we rarely take the step to translate these insights into new tracking tools or techniques). (4) This is perhaps a natural progression of the research field, as the topic moves from an era of inflated expectations towards productive implications for society [109].

Regardless of why artifact contributions have declined, we believe the community should discuss what we can do to continue to promote artifact contributions. One approach is to encourage use of platforms which lower the burden to evaluating design ideas by enabling researchers to design and deploy self-tracking tools (e.g., OmniTrack for Research [143,209]). Another is to consider whether evaluation approaches besides long-term deployments are permissible, such as using demonstrations to show what a new artifact could support [162] or understanding how and why a system is used (or not used) in shorter evaluations [145]. Our review also suggests that publications in personal informatics could conduct more evaluations of lower-fidelity prototypes to get feedback on early-stage design ideas, such as Luo et al.'s use of configurable paper-based food diaries to explore potential design opportunities [178]. Reports of sketches produced or evaluations of lower-fidelity prototypes during the process of designing higher-fidelity tools could contribute tradeoffs people considered and reasons why they were not pursued further.

Although artifact contributions are prevalent in HCI, it is important to acknowledge that implications for design are not an appropriate metric for evaluating many styles of HCI contribution [65]. Although the field often does a good job generalizing and comparing empirical findings between tracking domains, we may be able to further develop models and theory spanning domains and contexts. As previously discussed, the field typically evaluates design strategies for one domain and circumstance at a time. The field would benefit from developing guiding principles for how and when to use common personal informatics strategies such as glanceable displays for awareness, notifications for reminders, and dashboards for individual and collaborative review. One model for this is critical reflections [249], where designers of artifacts retrospectively consider the design rationale and lessons learned from designing their systems.

5.5 Exploring Tracking Beyond the Self

We were encouraged to find that the field is beginning to examine opportunities for tracking beyond the individual, exploring how tools can better support collaborative tracking or inform conversations between families, educators, clinicians, and peers. We echo suggestions of other work (e.g., [132]) pointing to a need to

examine how personal data is used in diverse social arrangements and design to support those arrangements. Our review suggests that clinical care teams, including clinicians and family members, are increasingly being studied and designed for. There is substantial opportunity for research which further understands and supports the role of self-tracked data in supporting diverse care teams and circumstances, including in-person versus remote care or support from large families versus individuals without family support.

In literature that examines tracking beyond the self, other stakeholders were largely seen as recipients of shared tracked data. A few publications examined collective tracking, where multiple stakeholders collaboratively tracked data of shared interest or one stakeholder collected data about another [196,197,217,285]. There are opportunities for the field to think more about collective tracking, particularly in domains where success is measured by the contributions of groups and teams rather than the contributions of individuals. For example, tracking productivity is perhaps more meaningful when thought of as an entire team or company. In sustainability, each individual's influence similarly contributes to the challenge as a whole. Supporting people in tracking and understanding their efforts as well as their role within a larger system is crucial for personal informatics to be useful in tackling organizational or societal challenges.

We also highlight that opportunities for supporting tracking beyond the self can undermine people's privacy and sense of control over their lives and their data. As one example, Jørgensen et al. gave children wearable activity trackers and observed that parents began to question their children about activities and resulted in lower levels of trust among the family [123]. Although we often discuss privacy concerns around data disclosure to corporate entities or governments, risks also emerge when sharing data socially.

5.6 Involving Experts and Theory

Our mapping review points to relatively limited engagement with experts and theoretical foundations. HCI researchers and medical experts each have much to contribute to the design and study of personal informatics systems for health and wellbeing. There remain gaps in our how we incorporate experts and theory into design in many, but not all, kinds of contributions.

Too often, HCI researchers suggest or create compelling tracking tools but lack the domain knowledge to design those tools effectively or influence behavior how they hoped. Conversely, tracking tools created or studied by domain experts often lack necessary design expertise and do not achieve the desired results (e.g., [146]). We were particularly encouraged to see the interest in personal informatics technology in publications indexed by PubMed, and the often-interdisciplinary teams assembled to make a technology-driven contribution in health sciences. But as Klasnja & Hekler discuss, tracking technology interventions in health sciences often do not follow the best practices in the HCI literature, which impacts their efficacy towards health outcomes [146]. It is challenging to assemble a team with enough interest and expertise in relevant areas to conduct multidisciplinary research, and recommendations for how to assemble these teams is unfortunately beyond the scope of this work. However, it is worth considering whether publication venues and funding opportunities can more effectively incentivize these collaborations.

Although we found reasonably high rates of expert involvement in publications related to clinical domains, we hoped to see more experts involved in the design and study of systems designed for wellbeing given the widespread adoption of self-tracking devices and tools aiming to promote wellbeing. A few publications have explored co-designing data collection and review with dietitians and fitness coaches [178,242]. We believe the design of personal informatics systems could further incorporate the best practices and theoretical principles that experts follow when helping clients change their behaviors (e.g., how experts support goal setting, how goals evolve as clients gain experience) and could increase access by incorporating the practices of experts into the design of self-tracking tools [2]. Designs could collaborate with domain experts both within health (e.g., sleep specialists) and outside (e.g., financial planners).

Our takeaways support Kersten-van Dijk et al.'s argument that the design of personal informatics artifacts for supporting behavior change would benefit from further incorporating strategies discussed in theory [133]. However, our review also highlights that many people's desires for and uses of personal informatics systems are not associated with behavior change, echoing Rooksby et al.'s notion of lived informatics [239]. Continued building of theory on

people's use of technology with tracking capability will be valuable for designing interventions which aim to support people's everyday needs alongside the healthy practices we often try to promote.

We acknowledge that many contributions would not benefit from engagement with domain experts or theory. For example, artifact contributions which span tracking domains may not benefit as much from expert engagement, such as advances in interaction techniques for journaling or platform approaches to data integration. Additionally, involving experts from health or medical domains in the design of our personal informatics tools runs the risk of promoting some self-tracking goals (behavior change, chronic condition management) at the expense of others (satisfying curiosity, preserving a record, creative self-expression). As Lupton articulates [182], this may have the impact of self-tracking technologies further medicalizing our personal lives. As we continue to investigate new domains and improve design in current ones, it is worth considering whether our findings would benefit from deeper understanding of the domains or concepts we are studying or designing for and whether we are promoting some self-tracking goals over others.

6 CONCLUSION

In mapping the personal informatics literature, we point out current areas of focus such as health and wellness domains, understanding and overcoming barriers to collecting and reflecting on data, and studies of individuals' self-tracking needs. We surface trends in how the field's contributions have changed over time, highlighting less emphasis on artifact contributions and more focus on self-tracking opportunities for families and clinicians. We also suggest areas for future exploration, such as better supporting tracking preparation, engaging more with domain experts, and further discussing the ethical concerns such as around corporate use of self-tracked data. The explored areas, trends, and underexplored areas we have surfaced suggest potential research agendas for the next decade of personal informatics research.

To help facilitate researchers in searching the literature, we have made our labeled corpus of personal informatics publications publicly available at: <http://personal-informatics.depstein.net/>.

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