Personal Informatics and Context:
Using Context to Reveal Factors that Affect Behavior

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Abstract

Personal informatics systems help people collect and reflect on behavioral information to better understand their own behavior. Because most systems only show one type of behavioral information, finding factors that affect one's behavior is difficult. Supporting exploration of multiple types of contextual and behavioral information in a single interface may help.

To explore this, I developed prototypes of *IMPACT*, which supports reflection on physical activity and multiple types of contextual information. I conducted field studies of the prototypes, which showed that such a system could increase people's awareness of opportunities for physical activity. However, several limitations affected the usage and value of these prototypes. To improve support for such systems, I conducted a series of interviews and field studies. First, I interviewed people about their experiences using personal informatics systems resulting in the *Stage-Based Model of Personal Informatics Systems*, which describes the different stages that systems need to support, and a list of problems that people experience in each of the stages. Second, I identified the kinds of questions people ask about their personal data and found that the importance of these questions differed between two phases: *Discovery* and *Maintenance*. Third, I evaluated different visualization features to improve support for reflection on multiple kinds of data. Finally, based on this evaluation, I developed a system called *Innertube* to help people reflect on multiple kinds of data in a single interface using a *visualization integration* approach that makes it easier to build such tools compared to the more common *data integration* approach.

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In Pittsburgh, there is an annual hiking event called the Rachel Carson Trail Challenge. The goal is to hike 35 miles through roller coaster hills, lush forests, and country roads in one day from sunrise to sunset. I have participated in this event several times throughout my graduate school career and it is an apt metaphor for the Ph.D. experience. Like the event, the Ph.D. experience is long and arduous, starts with excitement, is punctuated with moments of agony and bliss, and ends with a profound sense of accomplishment. And in both cases, I have learned that the value of the journey is not so much its completion, but in sharing the experience with others. I am very fortunate to have shared my pursuit of the Ph.D. with many wonderful people. Without their love, encouragement, support, and guidance, I would not have gotten the Ph.D. or the experience of a lifetime.

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Table of Contents

Chapter 1 Introduction 1
1.1 Personal Informatics and Physical Activity 2
1.2 Stage-Based Model of Personal Informatics 4
1.3 Phases of Reflection 4
1.4 Visualization Features 5
1.5 Personal Informatics Dashboard 5
1.6 Contributions 6

Chapter 2 Related Work 9
2.1 The Self, Behavior, and Factors 9
2.2 Self-Knowledge 11
2.3 Self-Monitoring 12
2.3.1 Issues in Self-Monitoring 14
2.4 Self-Regulation 15
2.5 Transtheoretical Model of Behavior Change 16
2.6 Examples of Behavior Change 17
2.7 Personal Informatics Systems 18
2.8 Tools for Collecting Personal Information 18
2.8.1 Life-logging 18
2.8.2 Experience Sampling 18
2.8.3 Personal Information Management 19
2.9 Tools for Reflecting on Personal Information 19
2.9.1 What Information to Display 20
2.9.2 How to display information 21
2.9.3 Why display information 22
2.9.4 Where and when to display 23
2.10 Personal Informatics Systems 23
2.11 Personal Informatics for Physical Activity Awareness 25

Chapter 3 Using Context to Reveal Factors that Affect Physical Activity 29

3.1 Scenario 30
3.2 Study Approach 31
3.3 Diary Study 33
3.3.1 Method 34
3.3.2 Results 35
3.3.3 Conclusion 36
3.4 IMPACT 1.0 37
3.4.1 Study 40
3.4.2 Results 41
3.5 IMPACT 2.0 43
3.5.1 System 44
3.5.2 Study 46
3.5.3 Results 47
3.5.4 Follow-up Interviews 50
3.6 Discussion 51
3.7 Conclusion 54
Chapter 4 A Stage-Based Model of Personal Informatics Systems 57
4.1 Method 59
4.1.1 Survey 59
4.2 Participants 60
4.3 Results 61
4.3.1 Collected Personal Information 61
4.3.2 Tools Used 62
4.3.3 Reasons 62
4.4 Stages and Barriers 63
4.4.1 Preparation Stage 64
4.4.2 Collection Stage 65
4.4.3 Integration Stage 65
4.4.4 Reflection Stage 66
4.4.5 Action Stage 67
4.5 Properties of the Stages 68

4.5.1 Barriers Cascade ... 69
4.5.2 Stages are Iterative ... 69
4.5.3 User-driven vs. System-driven ... 70
4.5.4 Facets ... 72
4.5.5 Limitations of the Survey and Model ... 73
4.6 Case Studies ... 73
4.6.1 Twitter-based systems ... 74
4.6.2 Mint (finance) ... 75
4.7 IMPACT (physical activity) ... 76
4.8 Discussion ... 77
4.9 Conclusion ... 78
Chapter 5 Phases of Reflection: Discovery and Maintenance ... 79
5.1 Interviews ... 81
5.1.1 Recruitment ... 81
5.1.2 Procedure ... 82
5.2 Results ... 83
5.2.1 Participant Information ... 83
5.2.2 Reasons ... 84
5.3 Questions ... 85
5.3.1 Status ... 85
5.3.2 History ... 86
5.3.3 Goal ... 87
5.3.4 Discrepancies ... 88
5.3.5 Context ... 89
5.3.6 Factors ... 90
5.4 Phases ... 91
5.4.1 Maintenance Phase ... 92
5.4.2 Discovery Phase ... 93
5.4.3 Transitions Between Phases ... 94
5.5 Features ... 95
5.5.1 Supporting the Maintenance Phase ... 95

5.5.2 Supporting the Discovery Phase 96
5.5.3 Supporting Transitions between Phases 98
5.6 Discussion 99
5.7 Conclusions 100
Chapter 6 Visualization Features to Help Associate Behavior with Contextual Information 103
6.1 Sketches 104
6.2 Sketch Permutations 106
6.2.1 Goal Information 106
6.2.2 Instance/Context Detail 106
6.2.3 Comparisons and Associations 107
6.2.4 Summary Notes 107
6.3 Method 107
6.3.1 Scenarios 108
6.4 Discovery Phase Scenario Results 108
6.4.1 Looking Back in Time 109
6.4.2 Seeing Details to Reason What Happened 109
6.4.3 Comparison of Different Kinds of Data 110
6.4.4 Goal 111
6.4.5 Writing Summaries 111
6.4.6 Progress Bar 112
6.5 Maintenance Phase Scenario Results 112
6.5.1 Timeline is still useful 113
6.5.2 Dependent on Type of Data 114
6.5.3 Value of the Flower Visualizations 114
6.5.4 Differences between Maintenance and Discovery Phases 115
6.6 Summary 116
Chapter 7 Visualization Integration 119
7.1 Why a Personal Informatics Dashboard? 119
7.1.1 Building a Personal Informatics Dashboard 121
7.2 Data Integration 123

7.2.1 Accessing Data ... 123
7.2.2 Parsing Data ... 123
7.2.3 Generating Visualizations ... 124
7.3 Visualization Integration ... 126
7.3.1 How Does It Work? ... 126
7.3.2 Benefits ... 127
7.3.3 Limitations ... 129
7.4 Innertube ... 132
7.4.1 Dashboard ... 132
7.4.2 Widgets ... 133
7.4.3 Widgets API ... 136
7.5 Evaluation ... 137
7.6 Results ... 139
7.6.1 Usefulness ... 139
7.6.2 Ease of Use ... 139
7.6.3 Satisfaction ... 140
7.7 Conclusion ... 140
Chapter 8 Conclusions ... 143
8.1 Chapter Summaries ... 144
8.1.1 Ch. 3: Using Context to Reveal Factors that Affect Physical Activity ... 144
8.1.2 Ch. 4: Stage-based Model of Personal Informatics Systems ... 145
8.1.3 Ch. 5: Phases of Reflection ... 146
8.1.4 Ch. 6: Visualization Features ... 148
8.1.5 Ch. 7: Personal Informatics Dashboard ... 148
8.2 Contributions to HCI ... 149
8.2.1 Users ... 149
8.2.2 Developers ... 150
8.3 Future Work ... 152
8.4 Closing Remarks ... 153
References ... 155

Chapter 1
Introduction

The importance of knowing oneself has been known since ancient times. Ancient Greeks who pilgrimaged to the Temple of Apollo at Delphi to find answers were greeted with the inscription "*Gnothi seauton" or "Know thyself*". To this day, people still strive to obtain self-knowledge.

One way to obtain self-knowledge is to collect information about oneself—one's behaviors, habits, and thoughts—and reflect on them. Computers can facilitate this activity because of advances in sensor technologies, ubiquity of access to information brought by the Internet, and improvement in visualizations. A class of systems called personal informatics is appearing that help people collect and reflect on their behavior (*e.g.*, Mint for spending habits, Nike+ for physical activity). Today, there is a personal informatics system for almost any aspect of a person's life, such as moods felt, health symptoms experienced, exercises performed, computer applications used, steps taken, electricity consumed, and hours slept.

Most personal informatics systems only collect one type of data about one aspect of a person's behavior [Li *et al.* 2010]. For example, pedometers count number of steps; diabetes devices measure blood glucose level; and financial applications track purchases. This may be for simplicity's sake, but some information is missed. People's behaviors are affected by factors in their lives; one may take more steps while at work than at home, blood glucose level is affected by what one eats, and off-budget purchases may be due to unexpected purchases. Knowing the factors that affect behavior can be useful for making better decisions, avoiding unproductive habits, and changing behavior [Endsley 1997, Leary 2004].

One source of information that users can use to find the factors that affect their behavior is contextual information. According to Dey [2000], "Context is any information that can be used to characterize the situation of an entity." In this case, the entity is some behavior about an aspect of a person's life, while context are the factors that affect the behavior. Context characterizes the individual's behavior, some of which may be factors that have a direct effect on the behavior. In this dissertation, I will show the value of contextual information in personal informatics systems for revealing factors that affect behavior. I will prove the following thesis:

> *A tool that allows users to associate contextual information with behavioral information can better reveal factors within one's life that affect behavior, compared to existing systems that only show behavioral information.*

1.1 Personal Informatics and Physical Activity

To explore how personal informatics systems can reveal factors that affect behavior, I started my research with personal informatics systems for physical activity awareness. The domain of physical activity awareness is a good lens to explore the thesis because physical activity is affected by many factors [Sallis & Hovell 1990] and research has shown that awareness of these factors is critical to circumventing barriers to becoming active [Center for Disease Control and Prevention 2008]. This focused exploration will result in several studies and prototypes of a physical activity awareness tool that supports collection of contextual information and reflection on the information. I will also present an argument that the lessons learned from the exploration of physical activity can be generalized to other types of behavioral information. In the next section, I will present in more detail the argument for supporting physical activity and the plan for exploring how contextual information can reveal factors that affect behavior.

Lack of physical activity is a common problem that increases the risk of otherwise preventable diseases, such as obesity, chronic heart disease, diabetes, and high blood pressure [Pate et al. 1995]. A recent study by the Center for Disease Control found that more than half the adult U.S. population did not participate in regular physical activity [Kruger & Kohl 2008]. Lack of awareness of physical activity is one of the reasons people lead sedentary lifestyles [Tudor-Locke et al. 2004]. Many personal informatics systems for physical activity awareness help users become more aware of their physical activity levels, such as step counts, energy expenditure, and heart rate [Assogba & Donath 2009, Intille 2004, Maitland et al. 2006]. Pedometers, an example of such technology, have been shown to also help increase physical activity [Bravata et al. 2007, Tudor-Locke et al. 2004].

Most physical activity awareness systems focus on one type of behavioral information, *e.g.*, step counts, energy expenditure, and heart rate. However, physical activity levels are not the only information relevant to physical activity. Physical activity is affected by many factors, such as lack of time, choice of activities, the environment, and social influence [Sallis & Hovell 1990]. Awareness of these factors is critical to circumventing barriers to becoming active [Center for Disease Control and Prevention 2008] and may help with finding active lifestyle activities (*e.g.*, walking *vs.* driving short distances or taking stairs *vs.* elevators) that have been shown to be easier to incorporate into daily life [Levine *et al.* 2006, Pate *et al.* 1995]. People need information in addition to physical activity levels to help them understand how different aspects of their lives, such as events, places, and people, affect their physical activity.

I developed and deployed prototypes that support physical activity with contextual information called IMPACT. Major findings from each study were (in order): 1) users make associations between physical activity and contextual information that help them become aware of factors that affect their physical activity; 2) reflecting on physical activity and context can increase people's awareness of opportunities for physical activity; and 3) automated tracking of physical activity and contextual information benefits long-term reflection, but may have detrimental effects on immediate awareness.

1.2 Stage-Based Model of Personal Informatics

I observed from the study of the study of the IMPACT prototypes that people wanted to collect more information than the study had allowed them (*i.e.*, location, activity, people). Participants wanted to associate their physical activity with their mood, weather, and calendar events. I also observed that regardless of the type of data, the user had to collect the data and they had to reflect on it. I wanted to explore whether there is a general model that can describe the activity of personal informatics. Knowing this can inform us of what kinds of things people need to do when partaking in personal informatics. Also, this will inform us on what kinds of features need to be provided to support users in their personal informatics activity.

This resulted in a survey of 70 people about the process that people go through when doing personal informatics. This also resulted in a list of problems that people encountered when doing personal informatics.

In general, this exploration is useful because it provides us with a guide to designing and evaluating personal informatics systems. This exploration is important to the thesis for several reasons. First, it highlights the difficulty of collecting data. If collecting one kind of data is already hard, collecting multiple types of data is even harder. Second, it highlights the need for collecting multiple types of data (as we explored in the IMPACT work). Not only is contextual information useful for physical activity, but people also want it for different kinds of data. Third, it highlights the inter-relatedness of the different stages. This important because this has implications on how systems should be designed.

1.3 Phases of Reflection

Following the creation of the model of personal informatics systems, I chose to focus on what kinds of questions people try to answer when they are reflecting on their personal data. I interviewed people who use personal informatics tools. I identified six kinds of questions that people ask about their data, *Status*, *History*, *Goals*, *Discrepancies*, *Context*, and *Factors*, and described how people answered these questions using current tools and what problems that they encountered. I also discovered that people's information needs change between two distinct phases: *Discovery* and *Maintenance*. These phases differ by the kinds of questions people asked about their data more frequently. In the *Maintenance* phase, people more frequently asked *Status* and *Discrepancy* questions. During this phase, people already understood what was causing their problem; they just wanted to know whether they were doing well. People only collected data to determine whether they were meeting their goal. In contrast, during the *Discovery* phase, participants were trying to better understand their behavior and collected multiple kinds of data to understand how different factors affected their behavior. In this phase, participants more frequently asked *History*, *Goals*, *Context*, and *Factors* questions. They have identified that they have a problem (*e.g.*, not sleeping well, lacking physical activity, diagnosed with diabetes), but they do not know how different factors may be causing their problem. During this phase, participants collect multiple kinds of data to understand the relationship between different factors and their behavior.

1.4 Visualization Features

My previous studies showed that people want to be able to reflect on multiple types of data together and that this is especially important during the *Discovery* phase of reflection. In this chapter, I focus on the specific features necessary to better support reflection on multiple types of data together. I conducted a study to determine the specific visualization features that people need to explore multiple types of data together. In the study, I sketched prototypes of different kinds of visualizations. I presented the visualizations to users and asked them questions about their thoughts about the different visualizations. The lessons from this study guided the development of a personal informatics dashboard to help people reflect on multiple types of data in one interface.

1.5 Personal Informatics Dashboard

In this chapter, I describe my implementation of a personal informatics dashboard, which supports the viewing of multiple types of data in a single interface. I discuss the technical problems of developing a personal informatics dashboard, and then I introduce the one solution that I developed called *visualization integration*. I present my implementation of a personal informatics dashboard using the visualization integration approach called *Innertube*. Finally, I describe the interviews I conducted with participants to validate the usability of the dashboard.

1.6 Contributions

This work has several technical, theoretical, and human-computer interaction contributions:

- Evidence that people seeking to be active need to become aware of factors that affect their behavior.
- Evidence that contextual information associated with behavior is one way to help users become aware of factors within their lives that affect their behavior.
- Evidence that contextual information can increase user's awareness of opportunities for physical activity.
- Introduced a stage-based model of personal informatics systems that describes the different kinds of activities in personal informatics that systems must support.
- Listed the problems that people experience when using personal informatics tools. Such a list helps developers and designers avoid the common problems that users encounter with personal informatics tools.
- Described four properties of the personal informatics to take into consideration when developing tools for personal informatics: 1) Problems from earlier stages affect the later stages; 2) The stages are iterative; 3) Each stage can be manual or automated; 4) Many users expressed the need to reflect on multiple types of personal data.
- Identified the kinds of questions that people wanted to answer when they are reflecting on their personal data.
- Identified two phases of reflection where the importance of the different kinds of questions is different, which suggests that tools for personal informatics need to provide different kinds of support depending on which phase the user is in.

- Determined the features that need to be supported in personal informatics systems that help users through the Reflection phase.
- Presented the difficulties of implementing a personal informatics dashboard that allows people to reflect on multiple types of data in one interface. Most personal informatics dashboards approach the problem by integrating data together (*data integration*).
- Proposed a different approach to implementing personal informatics dashboards called *visualization integration*.
- Implemented a personal informatics dashboard called *Innertube* that uses the visualization integration approach.

In the next chapter, I review related work on self-knowledge and awareness of behavior, personal informatics systems in general, and personal informatics systems for physical activity awareness. In Chapter 3, I present a series of studies (a diary study and field studies of two prototypes of *IMPACT*) that explore the value of contextual information on personal informatics systems in the context of physical activity awareness. In Chapter 4, I discuss my exploration of the many problems that people encounter when they are using personal informatics systems. This exploration led to the development of the stage-based model of personal informatics systems. In Chapter 5, I focus on how people reflect on their personal data. The study identified six kinds of questions that people ask about their data and two distinct phases when people had different information needs: *Discovery* and *Maintenance*. In the Discovery phase, the kinds of questions that people ask require that they explore multiple types of data. In Chapter 6, I explore the features necessary to better support reflection on multiple types of data by validating designs that I sketched. In Chapter 7, I present the development and validation of a personal informatics dashboard, which supports reflection on multiple types of data. The implementation is called *Innertube* and is based on an approach I developed called *visualization integration*, which circumvents the problems associated with building personal informatics dashboards. In Chapter 8, I conclude and discuss the overall contribution of this dissertation.

Chapter 2
Related Work

I have organized the related work into three sections. First, I will discuss current research in self-knowledge and awareness of behavior. Second, I will discuss personal informatics systems and current research on tools for collecting and reflecting on personal information. Lastly, I will discuss personal informatics systems for physical activity awareness.

This dissertation is informed by behavioral research on self-monitoring, self-regulation, and self-feedback and by technical research on ubiquitous computing, life-logging, and information visualization. The literature review below encompasses a review of related work from these multiple areas.

2.1 The Self, Behavior, and Factors

Personal informatics systems support the activity of observing oneself. People have a *reflective property* or "an ability to relate to oneself externally, as an object or an other" [Linde 1993]. To further illustrate, I use the statement "I see me", an example made by Brown [1998]. In this statement, the self is involved twice. The *I* self is the subject, the self that is doing the action of seeing. The *ME* self is the object; the self being observed. Personal informatics systems treat people as both the object and the subject of its function. These systems collect information about the user and present the information back to the user.

People can observe many aspects of themselves. According to James [1890], the self can be divided into three subcategories: 1) *the material self*, tangible objects, people, or places that people can call *my* or *mine*; 2) *the social self*, how other people see us or our social identities, and 3) *the spiritual self*, our *inner self* or *psychological self*, which includes our perceived abilities, attitudes, emotions, interests, opinions, traits, and wishes. Personal informatics systems aim to support people in observing these different aspects of the self. Below are examples of tools that track these different aspects of the self:

- *Material Self*. There are personal informatics tools to keep track of the people you are with (*e.g.*, With, http://with.me), the places you go (*e.g.*, Foursquare, http://foursquare.com), and the items you own or use (*e.g.*, LibraryThing, http://librarythings.com; Keepio, http://keepio.com).
- *Social Self*. There are personal informatics tools to keep track of how you interact with others. For example, Twitalyzer (http://twitalyzer.com) analyzes your Twitter account for impact, engagement, influence, and other metrics.
- *Psychological Self*. Paper journals or diaries have been the common way that people have recorded their attitudes, emotions, interests, and wishes. The Internet has allowed people to journal online publicly (*e.g.*, LifeJournal, http://lifejournal.com) or privately (e.g., Penzu, http://penzu.com). 750 Words (http://750words.com), an online journaling site, can analyze a person's writings for emotional content using the Regressive Imagery Dictionary [Martindale 1975]. There are also personal informatics tools to keep track of your emotions (*e.g.*, MoodJam, http://moodjam.org; Moodscope, http://moodscope.com).

Another aspect of the self is its *behaviors*, that is, the actions that a person does in relation to (or in response to) various stimuli, such as, their environment and other people [Skinner 1938]. Behaviors can be observable or unobservable. Observable behaviors are behaviors that can be sensed by the individual (seen, heard, smelled, tasted, and felt). Some observable behaviors cannot be directly sensed or measured by the individual, such as physiological signs (*e.g.*, blood sugar level, blood pressure) or unconscious or automatic actions (*e.g.*, tics, breathing rate, movement while sleeping). However, there exists devices or tests that can measure these behaviors (*e.g.*, blood glucose meters, blood pressure monitors, sleep monitors). There are also *unobservable behaviors*, such as feelings or intentions, which cannot be directly measured. However, some of these behaviors can be inferred from other observable behaviors [Skinner 1953].

This dissertation posits that awareness of behavior is not limited to information about the behavior alone; information about the factors that affect behavior may also be important. These factors may be psychological, environmental, genetic, and social. Contextual information may be important in revealing factors that affect behavior. According to Dey [2000], "Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and application themselves." Using context for self-knowledge in personal informatics systems, context *characterizes* the information collected about an individual's behavior. Context may be information about where a set of steps taken in a particular amount of time. It may be information about types of food eaten related to a person's blood sugar level. It may be information about the hours of sleep in the past week or amount of caffeine intake that may characterize a person's insomnia. In other words, contextual information answers the *five Ws (and one H)*: *who*, *what*, *where*, *when*, *why* and *how* of a person's primary data.

2.2 Self-Knowledge

One of the goals of personal informatics systems is to help people gain *self-knowledge*, people's knowledge of themselves [Wilson & Dunn 2004]. In particular, personal informatics systems aim to increase people's knowledge of their own behavior.

Gaining self-knowledge is not easy. People do not have complete knowledge about themselves or about things that affect their lives [Wilson & Dunn 2004]. This is because people have limited memory, cannot directly observe some behaviors (*e.g.*, sleep apnea), and may not have the time to constantly and consistently observe some behaviors (*e.g.*, manually counting steps throughout the day).

Another problem is that people have inaccurate memories. Research shows that sometimes people tend to remember negative events [Frijda 1988]. Remembering only the negative aspects of an activity (*e.g.*, remembering how many times one lost in racquetball, instead of the sport's health benefits) may discourage further participation in the activity [Taylor 1991]. Sometimes people also tend to remember positive events [Walker *et al.* 2003]. Remembering positive events is good for self-esteem and health [Lyubomirski *et al.* 2005], enhances evaluations and judgments [Clore & Huntsinger 2007], and leads to higher motivation and greater perseverance [Taylor & Brown 1988]. However, an overly positive illusion of the self may prevent the person from recognizing that something is wrong [Colvin *et al.* 1995, Robins & Beer 2001]. Personal informatics aims to help people gain an accurate knowledge of their own behavior.

People also have biases that prevent proper explanation of events that happen to them. When people are asked why they do something, they use common theories to explain their behavior instead of the actual causes of their behavior [Nisbett & Wilson 1977]. For example, diabetes patients have limited knowledge of the connection between their behavior and the fluctuations in their blood sugar [Frost & Smith 2003; Mamykina *et al.* 2006].

2.3 Self-Monitoring

One of the ways to gain self-knowledge is to *self-monitor*, that is, to observe and record one's own behaviors, thoughts, and emotions [Ciminero et al. 1986, Korotitsch & Nelson-Gray 1999]. Self-monitoring is relevant to personal informatics because it involves monitoring oneself or consciously observing one's behavior. However, personal informatics also includes observations of oneself by collecting data using automated sensors and devices. Personal informatics also concerns itself with helping people to explore and analyze their personal data, while the data collected through self-monitoring is assessed by clinicians. Regardless of the differences, I discuss self-monitoring because of the insights it can offer to the benefits and issues associated with monitoring one's behavior.

Korotitsch & Nelson-Gray [1999] defines self-monitoring as “an assessment procedure that involves data collection made by the client primarily within naturalistic settings”. They break down the procedure into two component responses: 1) “discriminating or noticing the occurrence of the target behavior (an action, thought, or feeling)” and 2) “producing some record of the record of occurrence as well as any additional information that is relevant to the particular goals of assessment.” Self-monitoring is relevant to clinicians because it can be used for assessment and reactivity (changing the user’s behavior), which I discuss below.

Self-monitoring has been applied in various clinical settings for assessment. First, self-monitoring can be used to diagnose the patient’s condition. The patient can self-monitor their symptoms to help a clinician arrive at a diagnosis. Second, self-monitoring can be used for functional assessment [Haynes, Leisen, & Blaine 1997]. Clinicians can use the self-monitored data to determine variables that might be affecting a particular behavior. For example, a person who had problems with chronic headaches could self-monitor occurrences of headaches along with occurrences of various factors, such as stressful situations, sleep, and diet), which clinicians could use to assess which factor has the most effect on headaches. Lastly, self-monitoring can be used for monitoring treatment. The patient can continuously record their condition during their treatment and the clinician can assess the effectiveness of the treatment. For example, as part of dialectical behavior therapy, patients with borderline personal disorder are asked to self-monitor during assessment and treatment [Linehan 1993]. Patients record frequency of suicidal thoughts and medication use, which the clinician can assess if the treatment is working.

Self-monitoring is different from other clinical methods of assessment, such as self-reports and clinical observations of a patient. With self-reports, data collection is not at the same time as the occurrence of the behavior. Instead, the person answers questions about a behavior days, months, or years after the behavior. With clinical observations, the data collection happens at the same time as the behavior, but another person (usually a clinician or a researcher) observes the persona and records the information.

Self-monitoring has also been used as an intervention in clinical settings because of its reactive effects. Reactive effects are undesirable during assessment because it biases the conclusions that clinicians can make about the data. However, reactive effects are useful when the clinician wants to use self-monitoring as part of a treatment to change the patient's behavior. Korotitsch and Nelson-Gray [1999] listed several documentations of the reactive effects of self-monitoring in various clinical settings, such as hallucinations [Rutner & Bugle 1969], paranoid ideation [Williams 1976], ruminative thinking [Frederikson 1975], insomnia [Jason 1975], alcohol consumption [Sobell & Sobell 1973], and suicidal ideation [Clum & Curtin 1993].

2.3.1 Issues in Self-Monitoring

Accuracy of data is a primary issue with self-monitoring because the data collection is highly dependent on the person. Korotitsch and Nelson-Gray [1999] listed eight variables that affect accuracy: awareness of accuracy checks, topography of the target behavior, training, compliance, accuracy-contingent reinforcement, nature of the recording device, concurrent-response requirements, and valence of the target behavior. These variables also have implications on personal informatics tools. For example, training has an effect on the accuracy of self-monitored data. Personal informatics tools may not need to worry about accuracy if the tool uses automated devices and sensors to collect personal data. However, user's still need to carry, wear, or interact with these devices, so training on usage would be helpful in maintaining accuracy.

Korotitsch and Nelson-Gray [1999] also listed eight variables that influence the magnitude and direction of reactive effects: target behavior valence, motivation for change, topography of the target, schedule of recording, concurrent response requirements, timing of recording goal-setting feedback and reinforcement, and nature of the self-recording device. These variables also have implications on personal informatics tools. For example, motivation for change has an effect on the reactive effects of self-monitoring. Lipinski [1975] showed in an experiment that self-monitoring reduced smoking only for the group that was motivated to change. The effect of personal informatics tools on changing behavior might also be dependent on the user's motivation for change. For example, feedback to encourage environmentally friendly behavior could be tailored using the Transtheoretical Model of Behavior Change, which classifies people's different levels of motivation and ability to change behavior [He *et al.* 2010].

2.4 Self-Regulation

Self-regulation says that behavior results from the exercise of control over oneself, whereby the person acts to bring the self into line with a goal or standard [Bauemeister & Vohs 2004, Carver & Scheier 2001]. Personal informatics tools can help with self-regulation by helping users observe and record their behavior, which users can then reflect on using visualizations to compare to their behavior to a particular goal or standard.

One of the basic principles in self-regulation research is the feedback loop, which comes from cybernetics [Schank & Abelson 1977]. The feedback loop is a system with 4 elements: an input function, a reference value, a comparator, and an output function. I will describe each of the elements of a feedback loop and discuss how each can be mapped to an aspect of personal informatics systems (discussed further in Chapter 4).

The *input function* is a "sensor" that brings information into the system. In self-regulation, this is equivalent to perception or observation of the effects of one's behavior. In personal informatics systems, the input function can be viewed as the time when users collect information about themselves with support from an application and/or device.

The *comparator* compares the input to a *reference value*. In self-regulation, the reference value refers to goals or standards. In personal informatics, the comparator can be viewed as the time when a user reflects on their personal information and determines whether she is or is not making progress towards a goal. A personal informatics tool may support this comparison by presenting collected information and user-specified goals back to the user.

The result of the comparison is the *output function*. In self-regulation, the output function is equivalent to taking action. In personal informatics, this can be viewed as the time when users act based on the understanding they gained during reflection and evaluation.

The model has two additional components: *environment* and *outside influences*. In self-regulation, the environment refers to anything external to the system itself, *i.e.*, what is acted upon. In personal informatics systems, the environment could also be the person herself, in that; she could take action to change her own physical, emotional, and mental state. The component "other influences" refers to other factors that might have an effect on the environment/self. Personal informatics systems tend to only track a single facet about the person. For example, pedometers track step counts. Very few personal informatics systems track other influences or *contextual factors* that might affect behavior. For example, physical activity may be affected by where you spend your time, but few pedometers track location along with step counts.

2.5 Transtheoretical Model of Behavior Change

The Transtheoretical Model of Behavior Change (TTM) is a model that describes people's motivation towards change [Prochaska & DiClemente 1983]. The model consists of five stages that depend on the differences in people's desire and ability to change their behavior. The stages are *Precontemplation*, *Contemplation*, *Preparation*, *Action*, and *Maintenance*.

The TTM is useful for classifying people based on their motivation to change their behavior. This classification is valuable because interventions can be tailored for people based on their motivation. He and colleagues [2010] described how the TTM could be used to design feedback for people who are trying to be more environmentally conscious.

Later in this dissertation, I will describe the Stage-based Model of Personal Informatics Systems (MPI). The stages in this model are different from the TTM. While both models use the word "stages", the stages in each model refer to different things. The stages in the TTM describe people's readiness for behavior change. On the other hand, the stages in the Model of Personal Informatics Systems refer to the different types of support that a personal informatics tool must provide to assist users in knowing their behaviors better.

The two models can be seen as orthogonal. Depending on what stage a person is in the TTM, they might need different levels of support for each of the stages from their personal informatics tool. For example, if a person who is in the Preparation stage of the TTM needs a personal informatics tool, the person probably needs plenty of support in selecting the right tool (Preparation stage of MPI) and collecting relevant data (Collection stage of MPI). On the other hand, a person in the Maintenance stage of the TTM probably needs more support in reflecting on their behavior (Reflection stage of MPI) and determining what changes to make in their behavior (Action stage of MPI). Note that in some cases, the user may not even need a personal informatics tool. For example, a person in the Precontemplation stage of the TTM has no desire to change their behavior yet. They may not be interested in knowing their behavior more, so a personal informatics tool will not be helpful to them.

2.6 Examples of Behavior Change

One of the applications of personal informatics systems is to help people know their behavior, so that they can change their behavior. There are plenty of explorations in the area of behavior change.

Hixon & Swann [1993] showed that knowing one's behavior can foster self-insight. They showed that knowing one's behavior can lead to insights into oneself, which can help a person make better decisions that are more true to oneself. O'Donoghue and Rabin [2001] showed that knowledge of self-control problems can lead to mitigation of self-control problems. They argued that even small amounts of naïveté regarding one's self-control problems can lead to problems later.

Some studies have shown the benefits of self-knowledge on encouraging positive behaviors. Sobell and Sobell [1973] described a self-feedback technique to monitor drinking behaviors in alcoholics that helped alcoholics reduce occurrences of drinking. Seligman and Delay [1977] did a study where they monitored the electricity usage of two groups of residential homes. One group of residential homes received feedback on their electricity usage, while the other group did not receive any feedback. After several months, the group that received feedback had reduced their electricity usage compared to the other group that did not receive feedback.

2.7 Personal Informatics Systems

In this section, I briefly discuss prior work on personal informatics systems. This section is divided into three subsections: tools for collecting personal information, tools for reflecting on personal information, and personal informatics systems, which combine collection and reflection of personal information.

2.8 Tools for Collecting Personal Information

2.8.1 Life-logging

Research in life-logging is largely focused on the sensing of data about users and the collection/storage of such data. Data collected in life-logging may be used for multiple uses, e.g., assessment, automation, in addition to personal informatics. In some ways, personal informatics is a subset of life-logging. Personal informatics also concerns itself with the collection of data, but is also focused on eventually presenting the information back to the user.

Many research areas focus on collecting personal information. Lifelogging research explores the use of sensors to collect various types of information about people's daily lives. The developers of MyLifeBits [Gemmell, Bell, & Lueder 2006] envision a future when daily activities of people, such as computing, web-browsing activity, electronic communication, and media usage, are recorded and archived. SenseCam, a wearable digital camera, takes photographs throughout the day while worn by the user [Hodges *et al.* 2006]. The device also contains other sensors, such as light sensors, an infrared detector, and an accelerometer. GPS and microphones can be added to collect additional information.

2.8.2 Experience Sampling

The Experience Sampling Method (ESM) is a method of conducting studies that are used in various disciplines, such as psychology and sociology. Experience sampling studies are different from lab studies in that they are conducted *in situ* or in the context of the lives of the participants and can last several days to several weeks. In ESM, participants are randomly prompted throughout the day via a text message, an alarm, or a mobile phone application. After prompting, participants are asked to answer questions. Researchers have developed many techniques to motivate people to participate in these time-intensive studies, such as improved questions and mobile devices that facilitate data input [Scollon *et al.* 2003]. Context-aware devices alleviate interruptions by alerting the participant at more opportune times [Intille *et al*. 2004]. However, reflection on the data collected by ESM is for the researchers conducting a study and not the study participants. Recently, some experience sampling projects have been developed that allow participants to reflect on their collected information: Track Your Happiness (http://trackyourhappiness.org) and ES+feedback, a project I worked on with Hsieh and others [Hsieh *et al.* 2008].

2.8.3 Personal Information Management

Personal Information Management (PIM) focuses on how people manage their information so they can perform their tasks more efficiently [Jones & Teevan 2007]. PIM also explores how people can retrieve their information, but the focus is less on self-reflection and more on staying organized.

2.9 Tools for Reflecting on Personal Information

Researchers have recommended using computers as a way to persuade and motivate people [Fogg 2002]. One way to use computers to persuade and motivate people as tools for reflection [Collins 1988]. Computers can help people make connections between their behaviors and the effects of those behaviors in their lives. They can form conclusions, not just facts, from images and video data [Smith & Blankinship 2000]. For example, asthma patients videotaping their daily routines realized they are in the presence of harmful allergens more often than they realized [Rich *et al.* 2000].

In the following sections, I discuss the what, how, and why of information visualization. The review also mentions the where and when of information visualization, which are less often discussed in traditional information visualization.

2.9.1 What Information to Display

Information visualizations can display a variety of things in the world [Spence 2001, Tufte 1983] including information about individuals. Visualizations vary by how the data are related to each other. Information can be related spatially, temporally, and structurally [Perer and Smith 2006]. Spatial visualizations consist of information that is organized in space, such as geographical data [Hearnshaw & Unwin 1994]. Temporal data consist of information that is organized in time. Francis and Fuller [1996] describe the visualization of people's event histories. Structural data consist of information that is organized by their relationship to each other. The Themail [Viegas et al. 1999] and Soylent [Fisher and Dourish 2004] systems show relationships preserved in email histories. ThreadArcs [Kerr 2003] and Newsgroup Crowds and AuthorLines [Viegas and Smith 2004] reveal the structure in email and the relationships of participants in newsgroups, respectively.

Information presented can be current or historical. Current information refers to the current state of an object. Most awareness displays focus on current information [Plaue et al. 2004]. Awareness displays have been used most often to indicate presence of another individual [Dey 2006, Mynatt, 2001, Pederson 1997] or groups [Donath 1999, Dourish & Bly 1992]. Chat Circles display various parameters about participants in a chat room, such as most recent responses [Donath 1999]. Most physical activity monitors focus on current aggregated information about a person's physical activity [Hatano 1993].

Historical information refers to previous states of an object, usually over a range of time. Most information visualizations show data that have been collected over a range of time. Historical information can provide trends and patterns that cannot be immediately discerned from current information or actual experience [Tufte 1990]. Visualization of historical data has been an important part of various fields in the humanities [Boonstra et al. 2004]. Various projects have shown the value of visualizations in providing insights into people's lives [Alonso 1997, Francis 1996, Plaisant 1996]. Long-term recording of computer activity, calendar appointments, and email reveals patterns of work activity [Begole et al. 2002]. Long-term recording of physical environments have also been shown to provide insights into group activities [Fry 2001, Skog 2004, Viegas 2003]. As technology keeps increasing the ability to record and store more of our lives [Gemmell 2004 & 2006, Hodges et al. 2006], the need for efficient ways to display that wealth of data increases.

2.9.2 How to display information

Paper has been the way of conveying information for a long time. Tufte [1983 & 1990] exalted the affordance of paper to display high resolutions of data with higher fidelity compared to monitor screens. He presented a theory of data graphics emphasizing that every drop of ink conveys information, reduction of chartjunk (graphic decorations that merely decorate), and use of graphical elements with multiple functions.

The field of information visualization has focused on the display of information on the computer screen [McCormick et al. 1987, Spence 2001]. While computers may not have the same resolution as paper, computers allow people to interact and explore data [Gouveia 2000, Oliveira 2003]. Derthick and Roth [2000] describe a way for people to compare different views of a data with each other that is not possible with paper alone. Dix and Ellis [1998] created a method to add value to static visualizations through simple interaction.

While information visualizations are presented primarily on paper or on a computer screen, others have also explored other modalities to convey information [Ishii 1997]. Other projects have also used physical objects to convey information about people. Infotropism used live and robotic plants to convey information about recycling behavior [Holstius et al. 2004]. Breakaway used a simple structure resembling a person in a sitting position to convey information about bad posture [Jafarinaimi 2006]. Blossom [2006] envisions a representation of a plant on a screen to convey information about the users productivity level.

Information visualization excludes non-visual means of conveying information, but a few deserve mention. Tactile graphics allow blind and visually impaired people to read graphical information [Edman 1992, Ramstein 1996]. Auditory properties have been manipulated to convey information [Brewster et al. 1993]. Audio Aura [Mynatt 1998] uses sound to convey physical actions in a workplace.

While paper is primarily static, computer-based information visualizations differ by their interactivity. Presence displays tend to be static visualizations; Presence Displays [Dey 2006] and the Digital Family Portraits [Mynatt 2001] show presence information that changes in time, but are not interactive. Pedersen and Sokoler [1997] have outlined the different kinds of representation that can be used in supporting mutual awareness. Static abstract art displays have also been used to give information about an environment [Holmquist and Skog 2003, Miller 2001, Redstrom 2000]. On the other hand, scientific visualizations, business analysis tools [Selfridge 1996], and personal history tools [Francis and Fuller 1996, Plaisant 1996] emphasize interactivity and exploration.

Casual Information Visualization [Pousman, Stasko, & Mateas 2002] and Slow Technology [Hallnäs & Redström 2001] help people reflect on everyday patterns. Casual Information Visualization aims to expand the definition of Information Visualization beyond work-related and analytical tasks to include non-experts. Slow Technology is a design agenda aimed at encouraging the development of systems that foster users to slow down to reflect, rather than speeding up performance. Static abstract art displays have also been used to give information about an environment [Holmquist & Skog 2003, Miller 2001, Redstrom *et al.* 2000].

2.9.3 Why display information

Information visualization can be used to explain and show causation [Tufte 1997, Tufte 2006]. For this reason, information visualizations are often used in scientific computing to gain insight into large amounts of data [McCormick et al. 1987], such as geographical applications [Hearnshaw and Unwin 1994] and simulation studies of computer systems [Keller and Keller 1992]. Selfridge et al. [1996] described improvements in analysis of business data by incorporating exploration and analysis. Visualizations that show causation can also help users associate their behaviors with their effects. For example, Frost and Smith [2003] built a system that helps users associate eating behavior with blood glucose level fluctuations.

Information visualization can also be used to provide awareness. Displays provide awareness for awareness's sake or to encourage and motivate positive behavior change. Awareness displays show information about availability [Dey 2006] and health [Mynatt 2001] so people in one's immediate social network can be aware of the information. Other awareness displays attempt to motivate positive behavior changes, e.g., recycling behavior [Holstius 2004], and exercise [Lin 2006, Maitland 2006]. Other systems have augmented awareness with suggestions to motivate healthier food choices [Mankoff 2002].

2.9.4 Where and when to display

Traditional information visualization assumes that information is displayed either on paper or in a monitor at any time ignoring the context of where and when the information is received. The detail of where and when the information is received is especially critical for displays that inform people; people may only be receptive or be willing to reflect on the information at particular places and times [Intille 2004]. Many research projects have placed information in the environment to be perceived peripherally [Hallnas and Redstrom 2001]. Intille has done plenty of research [2003 & 2004] on providing just-in-time information, that is, at the point people are making decisions when information is most crucial. Nawyn et al. [2006] describe a system that displays exercise information at particular times.

2.10 Personal Informatics Systems

Personal informatics is a class of systems that *help people collect personally relevant information for the purpose of self-knowledge* [Li *et al.* 2010]. While the research areas mentioned in the previous sections examined collection and reflection separately, personal informatics takes collection and reflection as a whole process. That is, the user is involved in both collection and reflection because the data is *about* and *for* the person,. Effective personal informatics systems help users collect the *necessary* personal information for *insightful* reflection. Personal informatics goes by other names, such as "living by numbers", "quantified self", "self-surveillance", "self-tracking", and "personal analytics" [Wolf 2009; Yau & Schneider 2009]. Personal informatics systems provide an advantage over simply trying to remember information about the self, because pure self-reflection is often flawed. These systems help people by facilitating collection and storage of personal information, and by providing a means of exploring and reflecting on the information.

There have been a number of research personal informatics systems that have combined collection and reflection on personal information. There are research personal informatics systems for computer-mediated communication. Viegas and colleagues [Viegas *et al.* 2006] developed Themail, a visualization that shows users how their relationships with others changes over time as reflected in their email correspondences. Perer and Smith [Perer & Smith 2006] developed visualizations that allow users to reflect on hierarchical, correlational, and temporal patterns stored in their email repositories. There are also research personal informatics systems for sustainability. PEIR (Personal Environmental Impact Report) is a mobile phone and web site system that tracks GPS location to inform users of four environmental impact and exposure scores: carbon emissions, impact on sensitive sites, fast food exposure, and particulate exposure [Mun *et al.* 2009]. StepGreen is a web site where people can report their sustainable actions and see visualizations of their progress [Mankoff *et al.* 2008]. UbiGreen is a mobile phone system that tracks and visualizes green transportation habits [Froehlich *et al.* 2009]. Mycrocosm is a visual micro-blogging site that allows users to collect and reflect on various types of personal information [Assogba & Donath 2009].

Many commercial personal informatics systems have leveraged the ubiquity of access to information afforded by the Internet and mobile devices to help people in various domains such as finance, health, physical activity, and productivity (*e.g.*, Mint: http://mint.com, CureTogether: http://curetogether.com, DailyBurn: http://dailyburn.com, and Slife: http://slifelabs.com, respectively). There are also systems that allow collection of various types of personal information (*e.g.*, Daytum: http://daytum.com, Grafitter: http://grafitter.com, and your.flowingdata: http://your.flowingdata.com). I have created a web site where people can find commercial personal informatics systems (http://personalinformatics.org/tools).

2.11 Personal Informatics for Physical Activity Awareness

Many devices exist that measure physical activity. Heart rate monitors measure heart rate to gauge the intensity of physical activity. The BodyMedia SenseWear armband (http://bodymedia.com) monitors acceleration, galvanic skin response, skin and ambient temperature to calculate calories burned. Pedometers or step counters are the most affordable and easiest to use [Bravata et al. 2007; Tudor-Locke et al. 2004]. Recently, mobile phones equipped with accelerometers have included step-counting software, e.g., Nokia 5500 SportsTracker and Samsung SPH-S4000. Table 1 provides an overview of several commercial products and research activities in the domain of physical activity awareness.

The awareness of physical activity can offer several benefits. First, awareness can help users make better decisions. Awareness of one's environment has been shown to be critical in decision-making [Endsley 1997]. Begole and Tang [2003] used patterns of activity to help office workers plan work activities and communication. Many physical activity awareness systems leverage this. Second, feedback about exercise can help users prevent problematic behaviors. Discontinuing one's exercise regimen is a common occurrence among people. Martin and colleagues [Martin *et al.* 1984] showed that feedback is one of the several behavioral and cognitive procedures that can enhance

Name	Monitoring Device	Information monitored	Feedback	Social
Pedometer	Pedometer	Aggregate step counts	Device	No
Nokia 5500 SportsTracker	Mobile phone	Aggregate step counts	Device	No
Shakra[Maitland et al. 2006]	Mobile phone	Duration of different activities	Device	No
UbiFit Garden [Consolvo et al. 2008]	Mobile phone & Intel MSP	Duration of different activities	Device	No
Fish'n'Steps [Lin et al. 2006]	Pedometer	Aggregate step counts	Device & public display	Public display
BodyMedia SenseWear	SenseWear armband	Time-stamped activity level	Desktop application	No
Nike+iPod	iPod and in-shoe device	Distance walked/ran	Device & web site	Share in web site
First IMPACT prototype	Pedometer & journal	Step counts & context (manual)	Device & web site	No
Second IMPACT prototype	Mobile phone and GPS	Time-stamped step counts& context	Device & web site	No

Table 1.Overview of commercial products and research activities in physical activity monitoring.

adherence to an exercise program. Annesi [1998] found that members of a fitness center who received exercise feedback attended the fitness center more and were less likely to drop out. Lastly, information about one's self can be used as a motivational tool. Paschali and colleagues [2005] used simple accelerometers to track activity among adults with Type 2 diabetes and showed that feedback promoted exercise. Body and environment sensors are here today and more are being created. They just need to be applied to the problem of exercise adherence and their information offered as motivational tools to users.

Research has also been conducted on the use of novel visualizations for displaying physical activity levels. UbiFit Garden [Consolvo *et al.* 2008] displays physical activity levels using a garden metaphor in a glanceable display on the phone. The Shakra system used GSM signal strength to detect minutes of physical activity (*e.g.*, sitting, walking, and driving) and displayed cartoon visualizations of activity on a mobile phone [Maitland *et al.* 2006]. Fish n' Steps explored motivating physical activity by using visualizations of fish in a tank [Lin *et al.* 2006]. The BodyMedia SenseWear armband comes with software that creates visualizations of users' step counts and energy expenditure. Walking Spree (http://walkingspree.com) uses a pedometer that can upload data online for visualizations. The Nike+iPod system (http://nikeplus.com) monitors step counts using a device embedded in Nike shoes. Like WalkingSpree, users can upload and share data. Guidelines for designing physical activity awareness devices have been discussed by several projects [Consolvo *et al.* 2007; Jafarinaimi *et al.* 2005] and I leverage these principles in the design of the prototypes. While these systems allow users to reflect on their physical activity using visualizations, they do not go beyond physical activity levels. My work builds on these systems by integrating contextual information.

Finding opportunities to be physically active remains a challenge for people [Levine *et al.* 2006]. Awareness of opportunities for behavior change is critical to circumventing them and making lasting behavior changes [Centers for Disease Control and Prevention 2008; Sallis & Hovell 1990]. Focusing only on the amount of physical activity may be insufficient to help find opportunities for behavior change because there is a gap in understanding between the facts about such a physical state and what causes that state

[Frost & Smith 2003]. For example, knowing the number of steps in a given day does not answer where those steps were taken: Did I take the most steps at home or at work? Did walking outside for lunch contribute enough steps to my overall count?

Other research projects have stated the importance of helping people make connections between their behavior and factors that affect their behavior. For example, diabetes patients are taught to be aware of their blood sugar level, but blood sugar levels alone do not show the behaviors that contribute to those levels [Frost & Smith 2003; Mamykina *et al.* 2006]. By showing people images and video, they can form conclusions, not just facts [Smith & Blankinship 2000]. For example, asthma patients videotaping their daily routines realized they are in the presence of harmful allergens more often than they realized [Rich *et al.* 2000].

Chapter 3
Using Context to Reveal Factors that Affect Physical Activity

People use physical activity awareness systems to perform personal informatics on their physical activity, but it would be great if these systems also allowed them to see the factors that affect their physical activity level, so that they can better understand their situation and help them improve or change. Unfortunately, most physical activity systems only track performance information, so people have to depend on their memory to know and understand the effect of different factors. A solution is to use contextual information, which may represent factors that affect physical activity, such as location, activities, and companions. However, there are several open questions regarding using contextual information to inform people of factors that affect their physical activity:

- How does a system appropriately support the tracking of contextual information?
- How effective is contextual information in informing users of factors?
- How do users use contextual information to learn/understand the factors that affect their behavior?
- Would this new awareness lead to increase in physical activity?

In this chapter, I discuss my exploration of the use of contextual information for personal informatics in the domain of physical activity awareness. I developed prototypes that supported tracking of and reflecting on both physical activity and contextual information. I deployed the prototypes in a series of field studies that explores the value of contextual information in revealing factors that affect physical activity. The studies consist of a diary study, a field study of an activity journaling prototype, and a field study of a prototype using mobile phones. The prototypes counted steps, supported recording of contextual information, and were deployed over long periods of time. I employed iterative, user-centered human-computer interaction methodologies and took the lessons from each iteration to improve the next.

In the following sections, I describe a scenario to illustrate concepts relevant to the three studies. Next, I outline the general approach that guided the three studies. I describe each study and prototype I created and identify problems that people experienced monitoring both physical activity and contextual information. I explain the lessons learned and how they led to each subsequent prototype and study. Finally, I discuss the implications of these lessons and make recommendations on the design of personal informatics systems that integrate contextual information to help people gain more self-knowledge.

3.1 Scenario

To illustrate how contextual information might help with understanding factors that affect physical activity, I present the following scenario:

Alice, a college student, uses a pedometer to track her step counts, which she records in a spreadsheet at the end of each day. After a month of collecting data, she creates a graph of her step counts. She sees that she is more active on the weekends except on Sundays, and she wonders why? What was she doing during those past Sundays? Where was she spending her time? Who was she spending time with? Contextual information, such as her activities, location, and companions, could have helped her answer these questions. If Alice had written down her step counts with contextual information, she could have discovered that she spent most of her Sundays *watching TV* at *home* by *herself*. Alice did not consider collecting contextual information related to her physical activity, but if she wanted, how could a system support her? Would it help her identify the factors that affected her physical activity? Alice did not have the right tools to support collection of contextual information. But if she did, I believe contextual information could have helped Alice identify the factors that affected her physical activity.

There is little support for people interested in the factors that affect their behavior; they have to use an *ad hoc* collection of websites and devices to collect data. The responsibility lies on them to put together the pieces of their personal data puzzle. People have to go through the tedium of organizing, formatting, and integrating their data together. Worse, they are left to remember, infer, or guess how the different factors affect their behavior. How can a personal informatics system appropriately support people in tracking and reflecting on the factors that affect their behavior?

The studies that I describe in the following section explore the questions posed by the above scenario.

3.2 Study Approach

I conducted three studies of physical activity and context. In this section, I discuss the general approach that guided how I conducted the three studies.

I worked primarily with sedentary people because research suggests that they are less aware of how active they are and they need more information about how to become active compared to active individuals [Sallis & Hovell 1990]. Consequently, I focused on walking as a physical activity because walking is easier to integrate into one's daily life than other forms of physical activity [Norman & Mills 2004]. I recruited a wide swath of people with different backgrounds within the city proper using various recruiting tools: Craigslist, an experiment recruiting web site, online newsgroups, and flyers. I screened participants using a pre-questionnaire that included the Stages of Behavior Change Items [Marcus *et al.* 1992] based on Prochaska's Stages of Change Model [Prochaska & DiClemente 1983]. The model describes that people progresses through five stages of behavior change: *Precontemplation* (no intention to change), *Contemplation* (intention to change), *Preparation* (prepare to change), *Action* (involved in change), and *Maintenance* (sustain change). All participants in the studies were sedentary, that is, the Stages of Behavior Change Items identified them as being in the first three stages of behavior change: *Precontemplation*, *Contemplation*, and *Preparation*. For this study and the subsequent studies, I recruited a different batch of participants because I wanted all participants to have fresh experiences monitoring their physical activity.

While there are many kinds of information that can be added to step counts, I focused on three different kinds of contextual information that have been explored extensively by the ubiquitous computing community: *activity*, *place*, and *people*. As technologies that monitor this information become more robust, they can be more readily integrated into physical activity awareness devices.

I also took a user-centered approach in conducting the studies. I started with the needs of the users and then created a series of prototypes to observe how users reflect on their information. There were three reasons for this. First, the primary goal of the studies was to understand how increasing awareness of context about physical activity affects the user and what the benefits are compared to existing systems *before* investing time and money on developing more sophisticated technology. Second, I wanted to make sure that the deployed technologies were robust enough to be used for a long period of time. Finally, the current state of most systems to track activity and people require wide infrastructure changes or require more devices than most users were willing to wear. The approach is similar to technology probes [Hutchinson *et al.* 2003], where low-fidelity prototypes are used to observe how people might use a new technology. As I progressed through the studies, I addressed the lessons learned from the earlier trials.

I conducted studies that spanned a long period of time and were *in situ* for two reasons. First, if reflecting on information about oneself is going to be useful, users will need to have monitored their behavior for an extended amount of time and the data they view needs to be their own data (as opposed to synthetic data or someone else's data). Second, I wanted the studies to be ecologically valid. Consolvo and colleagues [2007] further described the value of *in situ* deployments for computing technologies.

In the following sections, I describe the three studies that I conducted. Each section is organized in the following manner. First, I explain the motivation for the study. Next, I describe the methods I used in the study and any prototypes I developed. Then, I report how people used information about their physical activity and contextual information. Finally, I discuss the implications of the results and how it guided the next study and prototype iteration.

3.3 Diary Study

In this study, I explored what people would do if they had to collect contextual information along with their physical activity and what they would do if they could reflect on multiple kinds of information together.

As a first study, I conducted a diary study [Rieman 1993], instead of building a prototype system and conducting a field study. Conducting a diary study allowed me to focus on the question of what role contextual information might play when reflecting on physical activity. If I had built a prototype, I expect that it would have taken a significant amount of time and resources because tools that track physical activity and associated contextual information would have to satisfy the following requirements:

- People's physical activity is not limited to one location, so these devices and sensors have to be where the person is.
- People's physical activity can happen any time during the day, so these devices and sensors have to be on throughout the day.
- People may want to collect their physical activity information for a long time to find trends and patterns, so these devices and sensors have to be robust enough to continue working for several days and weeks.

At the time of this study (2006), there were already several physical activity devices in the market that met the above requirements. Additionally, they were affordable and comfortable to wear. On the other hand, the devices and sensors that tracked activities, people, and location comfortably and reliably over a long period of time were more difficult to find. There were several GPS devices during this time, but they were used for navigation, instead of personal tracking. Unfortunately, the then state-of-the-art devices and systems to track activities and people were not as robust enough to last a long deployment, would have required wide infrastructure changes (*e.g.*, embedding sensors at home and in the office), and prohibitively expensive given the speculative nature of the study.

In this diary study [Rieman 1993], I asked participants to collect data about themselves. They used physical activity awareness tools, such as pedometers and the Bodymedia Sensewear armband, to help record the number of steps they take. The collection of contextual information (*i.e.*, events, location, and people they spent time with) had to be done in a diary. Writing in a diary is similar to self-monitoring (as discussed in the Related Work chapter) in that the user had to observe themselves. The difference from self-monitoring in this case is that the data they are collecting will eventually be reflected upon.

3.3.1 Method

The diary study had three conditions, which differed by the kind of feedback participants received about their physical activity and contextual information: *no feedback*, *real-time feedback*, and *end-of-day historical feedback*. Each condition lasted a week. In total, the study spanned 3 weeks in which participants carried a paper journal (4.25 in × 5.5 in) to record their activities. Participants also wore the BodyMedia SenseWear armband (http://bodymedia.com), which senses acceleration, galvanic skin response, skin and ambient temperature to calculate calories burned and to count steps. In the first week (*no-feedback*), participants did not see their physical activity data, since the armband has no display. In the second week (*real-time feedback*), participants also carried a pedometer along with the armband, so that they saw aggregated step counts in real time. Participants used the Omron HJ-112 Digital Premium Pedometer because it is highly accurate, can be worn comfortably on the waist or carried in a pocket, and is silent as it has no mechanical parts [Consumer Reports 2004]. In the final week (*end-of-day historical feedback*), I took away the pedometers and gave participants printouts of daily reports of their physical activity from the desktop application that synchronizes with the armbands. The reports showed graphs of time-stamped step counts for every minute of the day.

Participants used the journal to record every time they changed activities. The journal had fields for time, type of activity, location, and people. At the end of the day, the journal asked participants about their day: unusual events, awareness of activity, and other notes.

I recruited 4 participants who were trying to be physically active (A1-A4, ages 25, 50, 44, and 36, respectively). A1 was a college student, while A2, A3, and A4 worked as staff in various university departments. A2 was married with children, while the rest were single. Participation included 4 audio-taped face-to-face interviews: at the beginning of the study and at the end of each week. I also collected responses from questionnaires and handwritten notes. Regardless of their step counts, participants received $150 for completing the study.

3.3.2 Results

Participants had excellent compliance over the 3 weeks of the study; they recorded at least one activity per hour. Participants liked the detailed daily reports of time-stamped data from the SenseWear armband for reflection. Interviews indicated that this detailed data helped users to better understand the times and days at which they were physically active. They *routinely matched segments on the graph* with activities they recorded in the journal to better understand how much physical activity they were performing while engaged in different activities. A1 said that the graphs were useful "because I was able to quantify my physical activity" and that she compared "the peaks on the charts to see what I was doing."

Participants *became more aware* of their physical activity level and were often surprised when they discovered that a particular activity could be physically active. For example, A2 identified the impact of little activities throughout the day: the graph and journal "told me when the intensity was greater than other times, so I was able to gauge my activities like if I just walk upstairs to get a cup of coffee." Other participants voiced the same sentiment:

"I realized that walking up the hill on my way home burns a lot of calories, and that going shopping makes me walk a lot." (A1)

"It was nice to see that I walked more than I thought I did. There was one day when I was babysitting. I walked so much with the baby. I walked all over campus." (A3)

"Housework and walking to the bus stop can contribute, really. I mean, I take that for granted in terms of energy expenditure. I mean I don't even count it when I write down what I do. But it really does make a difference." (A4)

Participants also *found opportunities* for physical activity. A2 said that the information from the journal and the device "caused [her] to incorporate mini-bursts of activity into my day." A4 said "The feedback really makes me realize that walking makes a difference, even if it's just errands."

While participants appreciated the detailed time-stamped data from the SenseWear armband, they missed the real-time feedback that the pedometer provided. They specially missed seeing the numbers increase as each day progressed.

3.3.3 Conclusion

People found value in both real-time and historical feedback. They each offered complimentary benefits that people found them valuable. The value of real-time feedback is that they could see what was happening immediately, which guided some people's decisions. The value of the historical feedback, especially, with the contextual information is that people could look back at their data and see what happened. They noticed things they never did before. For example, one of the participants found that an activity was active. Thus, I think physical activity awareness systems should provide both options instead of having to choose one.

I found that people would find associations between their physical activity and contextual information. They used the contextual information to explain why they were active or inactive. In the last week (end-of-day historical feedback), people found relationships between their physical activity and contextual information, despite the rudimentary nature of looking at paper graphs and booklets. While looking at multiple kinds of data together, people matched interesting data points (*e.g.*, peaks) with times in their booklet.

They went back and forth to see what happened at the peaks. Which activity were those that gave them a lot of steps?

To summarize, this study suggests that when given access to contextual information during reflection, people could and would associate them with their physical activity helping them become more aware of factors that affect their physical activity. This study encouraged me to build prototype systems that help people find associations between their behavior and contextual information. I describe the development and deployment of the prototypes in the following sections.

3.4 IMPACT 1.0

I developed the first prototype of IMPACT (Integrated Monitoring of Physical Activity and ContexT). I wanted to build a prototype that helped people easily see associations between their physical activity and contextual information, so I focused on the visualizations feature of the prototype, instead of how people tracked information about themselves.

The participants in the last study had such good compliance in collecting data that I maintained the same procedure for collecting physical activity and contextual information. I had the choice to use a pedometer or a BodyMedia SenseWear armband. I chose the pedometer because their easier to use (the armband can be uncomfortable); they display real-time information (the armband did not have a real-time display); and they were affordable (the armband was $500 apiece). I used the same brand pedometer as the previous study (Figure 1a). I also modified the journal from half the US Letter size (5.5 x 8.5) to a quarter of the US Letter size (2.75 x 4.25 in). This made the journal easier to carry because it can be place in one's pocket. The journal was similar, but it had an additional field to record step counts and it was smaller (2.75 in × 4.25 in, a quarter of the US Letter size), so that it could easily fit in a pocket and be carried easily (Figure 1b).

a b

Figure 1. a) The Omron HJ-112 pedometer, b) a two-page spread of the diary booklet with fields for time, steps, and context.

I used Ruby On Rails (http://rubyonrails.org), an open-source web framework, to develop the IMPACT website. The website had a form where participants can transcribe data from their completed journals for storage online. The website also had pages where participants can see visualizations of their step counts and the association between their steps and contextual factors. I created the visualizations using Java applets and the Processing library. I built three versions of the website for the three phases of the field study: *Control*, *Steps-Only*, and *IMPACT*. The versions differed from each other by their visualizations.

Control. This version did not have visualizations; users only had access to a web page to enter their step counts from their journal. I deployed this system to establish a baseline for the participants' physical activity levels. Users carried journals with fields for time and steps. This version is similar to what would happen if they were just tracking their physical activity using a pedometer.

Steps-Only. In this version, participants could also access visualizations of their step counts by day and by week (Figure 2). There were three visualizations with different levels of granularity in time: a) step counts in a day, b) step counts in a week, and c) detailed step counts per day for a whole week. Again, users carried journals with fields for time and steps. This version is similar to services like Nike+iPod and RunKeeper, where users can see graphs of their physical activity over a long period of time. One difference of this system from existing tools is that physical activity is tracked all day, so the graphs represented physical activity all day.

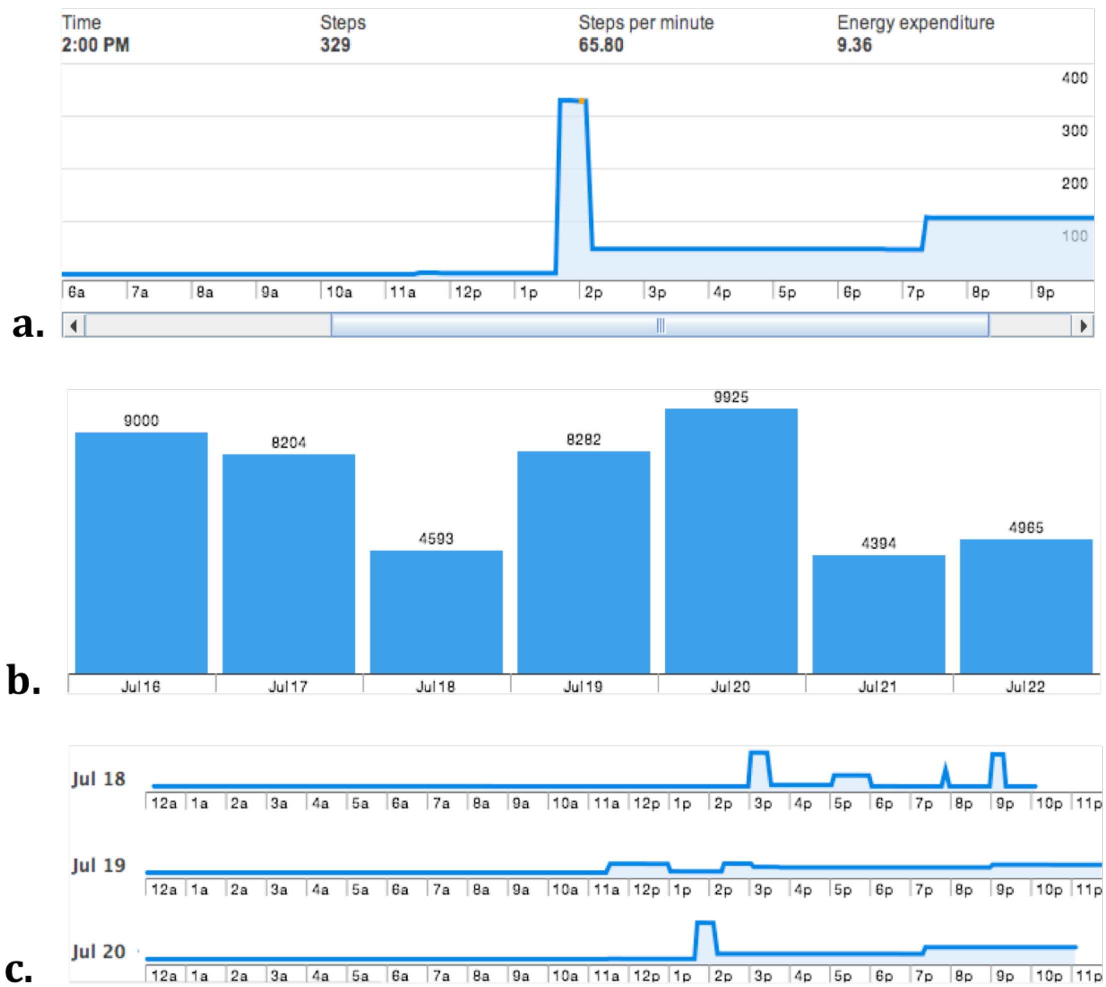

Figure 2. Visualizations in the Steps-Only version of the IMPACT web site. a) Day view of step counts; b) Aggregated daily step counts during a week; and c) Detailed daily step counts per during a week.

IMPACT. In addition to the visualizations in the *Steps-Only* version, this version had an interface to label time segments with contextual information (activity, location, and people). In addition to visualizations of step counts by day and by week, this version had visualizations showing the association between daily activities and step counts (Figure 3). Users carried journals with additional fields for recording contextual information.

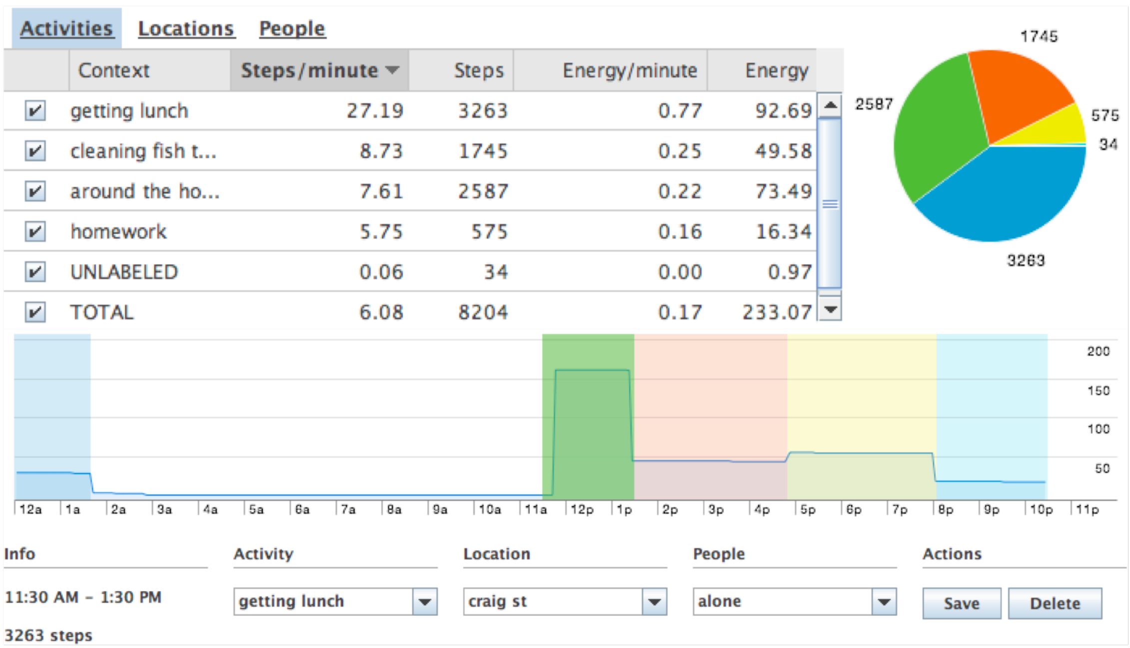

Figure 3. Additional visualizations in the *IMPACT* version of the IMPACT web site showing step counts with contextual information.

3.4.1 Study

I expected that the prototype would help users better associate contextual information with their physical activity. With this awareness, I hypothesized that users would increase their awareness of opportunities to be physically active as I observed in the diary study.

I recruited 43 sedentary individuals (B1-B43, 14 males and 29 females) with various backgrounds from around the city proper. Regardless of step counts, participants received $100 at the end of the study.

I conducted a 7-week study of the prototype: one week for the *Control* version and 3 weeks for each of the *Steps-Only* and *IMPACT* versions. The last two phases were counter-balanced.

I interviewed the participants four times during the study: at the beginning and after each of the phases. I also gave them surveys in which they rated their awareness of physical activity, awareness of opportunities for physical activity, system usefulness, and ease of use on a 5-point Likert scale.

3.4.2 Results

Thirteen participants were dropped from the study because of sickness (1), lost pedometers (2), not responding to surveys (3), and unlike Study A, poor compliance in recording (7). I analyzed the data on the remaining 30 participants.

Results from the survey supported the hypothesis about the value of contextual information: participants reported greater awareness of opportunities for physical activity after the *IMPACT* phase (mean: 3.93, s.d.: 0.74) compared to after the *Steps-Only* phase (mean: 3.57, s.d.: 0.86) ($F[1,58] = 5.32$, $p<.05$). I asked participants to describe how IMPACT increased their awareness and they explained that the contextual information helped them see the factors that they did not realize had an effect on their physical activity. Below are some examples:

"The field [in the journal] I used the most was noting who I was with during my most inactive periods. I was surprised by the results—I hadn't realized that I was so sedentary most of the time I spent with my friends." (B1)

"It turns out I get the most walking done to and from work…and walking around my neighborhood for an hour or two made such a difference." (B25)

"It helped me realize which activities were more important. For example, I didn't understand the importance of walking home versus taking the bus." (B8)

I also coded the responses whether they mentioned any contextual information and what type. Table 2 shows further proof that people actually used the contextual information that they collected. Eighteen participants mentioned context after using *IMPACT* compared to 13 (*Steps-Only*) and 11 (*Control*). If I remove mentions of time as context, the number of participants that mentioned context after using IMPACT (13) is twice more than after using Steps-Only (7) or after using Control (6). Participants' awareness of their physical activity remained the same for each of the phases, which makes sense since all participants used pedometers throughout the study.

	Control	**Steps-Only**	**IMPACT**
Mentioned Context	11 participants	13	18
Mentioned Context Excluding Time	6	7	13

Table 2. Number of participants who mentioned context (including and excluding time) after using each of the systems.

Participants also rated the *IMPACT* version as most useful. B11 actively used the contextual information provided by IMPACT; she said, "I used the contextual information to identify those activities that generated the most steps and if possible, I would increase those activities during the day." B24 appreciated seeing what she was doing exactly; she said, "Being able to see what exactly I was doing at what times of the day showed me how I could work in extra walking during my breaks, and exactly how long it took me to get to work."

While the *IMPACT* version was useful, it was rated the least easy to use. Participants gave several reasons why the IMPACT version was difficult to use. B4 said, "IMPACT gave a lot of cool information, but having to input all of the various factors was a hassle and made me less likely to do it on time." B11 said, "IMPACT was too time-consuming. Sometimes it made me feel like it is actually having a negative effect! I wouldn't want to do something different because then I had to record it. It could be really exhausting at times."

The poor compliance during the study (the study lost 7 participants because of non-compliance) suggests that all the different versions of the system had to be easier to use. In retrospect, the assumption that participants would be willing to manually record step counts and contextual information for a long time as I saw in the previous study was misguided. This study was more than twice as long as the previous study (7 weeks *vs*. 3 weeks). Fortunately, the problem is addressable; 90% of the participants reported they would continue using the system if collection of context information were more automated.

There were no statistical differences in step counts between phases; the *IMPACT* version performed as well as the *Control* and *Steps-Only* versions, which are similar to regular pedometers. This may be caused by the realities of running field studies: 1) there are many factors that can affect physical activity throughout a month that the study cannot control; 2) the study only had few participants per condition; and 3) the variability of the step counts by each user and between users is too high to get a significant result. All that can be concluded about the effect of contextual information on level of physical activity from this study is that, the extra load of recording contextual information did not deter physical activity.

Another limitation of the study concerns the length of the 1-week-long *Control* phase compared to the 3-week-long *Steps-Only* and *IMPACT* phases. The brevity of this phase may have resulted in unrealistic baseline step counts because of the novelty effect [Clark & Sugrue 1988]. The *Control* phase should have been the same length as the other phases. Despite this concern, if there were a novelty effect, I expected the *Control* step counts to be significantly more than the other phases, but this did not occur.

This study provides empirical evidence that associating contextual information with physical activity can increase participants' awareness of opportunities for physical activity. Additionally, the extra load of recording contextual information did not deter physical activity. While participants found the IMPACT system useful, they commented that it was hard to use, due to the need for manual collection of context and transcription to the web site. I addressed this problem with a more automated prototype, which I describe in the next section.

3.5 IMPACT 2.0

IMPACT 1.0 showed that contextual information could help participants become more aware of factors that affect their physical activity. However, participants noted that having to manually record information over such a long period of time is too difficult.

This is a problem because if people did not collect their data consistently, then the data that they reflect on will be incomplete, which will affect how aware people are of the factors that affect their behavior. This becomes even more critical when the amount of time that the user spends collecting data becomes longer.

Another aspect of the IMPACT 1.0 system that the user had to manually do was to transcribe the data to a web site. This was problematic because the user had to record data twice: 1) write their contextual information on a booklet, and 2) copy what they wrote in the booklet into the web site.

Clearly, the collection and integration problems need to be resolved. One way to do this is to make the data collection and integration more automated.

I created a second version of the IMPACT system that addresses the problems identified with IMPACT 1.0. Instead of using a pedometer and journal for manual recording, this version uses a mobile phone and GPS to monitor step counts and the user's location. The mobile phone also has an easy-to-use interface that allows users to input what he/she is doing and whom he/she is with.

3.5.1 System

The mobile phone I used in this prototype is the Nokia 5500 Sport, which has a built-in 3-dimensional accelerometer. The phone contains software to count steps, but the algorithm

Figure 4. Monitoring device for the second version of IMPACT. Nokia 5500 Sport (left) and detailed view of the display (right).

is not as accurate as the Omron HJ-112 used in the previous trials. Instead, I wrote a pedometer application in Python to run on Nokia's Symbian OS (Figure 4). I modified a step-counting algorithm from the Robert Bosch Corporation to match the accuracy of the Omron HJ-112 pedometer. I tested this with 5 users over several days of routine use and tuned the algorithm until it matched the Omron pedometer within ±5%. The pedometer application stores the user's step counts per minute and displays the user's aggregate step counts for the day and for each of the past 5 minutes.

The Nokia 5500 Sport does not have an internal GPS, so I used a separate Bluetooth GPS module (Nokia LD-3W) to collect location information. The GPS module scans the user's location every minute, which is then stored by the phone application.

The phone application collects additional contextual information using activity-triggered experience sampling [Froehlich *et al.* 2007]. When the user is active or inactive, the phone vibrates to prompt the user to select from a list: what they were doing (events) and whom they were with (people). The list is pre-filled with 5 common activities (*e.g.*, grocery shopping, walking) and 5 usual companions (*e.g.*, friends, family, co-workers), but users can enter new labels. I did not implement automatic labeling of events and people because such classification requires additional sensors that may not be robust enough for a long-term field study or are still not mainstream and widely available. For example, the UbiFit Garden [Consolvo *et al.* 2008] used a combination of a mobile phone and the Intel Multi-Sensor Platform research prototype to partially automate recognition of exercise activities, such as walking, running, biking, and stair machine.

I also implemented a new version of the web site (Figure 5), which showed the association between daily activities and step counts on 1) a timeline of the user's steps with time segments labeled with contextual information; and 2) a histogram of the total number of steps associated with a particular label (*e.g.*, 400 steps at work, 1300 steps at the grocery store). Instead of manually entering step counts and contextual information on the web site, a desktop application synchronized data between the phone and the new web site. If the user needs to add more contextual information after uploading, they can label periods of time on the visualizations.

I also implemented 2 other versions of the system: *Steps-Only* and *Control*. The *Steps-Only* system only monitored step counts and the web site only showed daily step counts without any contextual information (Figure 6). The mobile phone still alerted users when they have been active and inactive, but they were just asked to rate how active they were on a 5-point Likert scale (not at all active to very active), to make the interruption comparable to the *IMPACT* version. The *Control* system also only monitored step counts, but I removed visualizations on the web site. Essentially, it is similar to an off-the-shelf pedometer.

3.5.2 Study

Similar to the first IMPACT prototype, I expected that the second version would help users better associate contextual information with their physical activity. I hypothesized that users would increase their awareness of opportunities to be physically active.

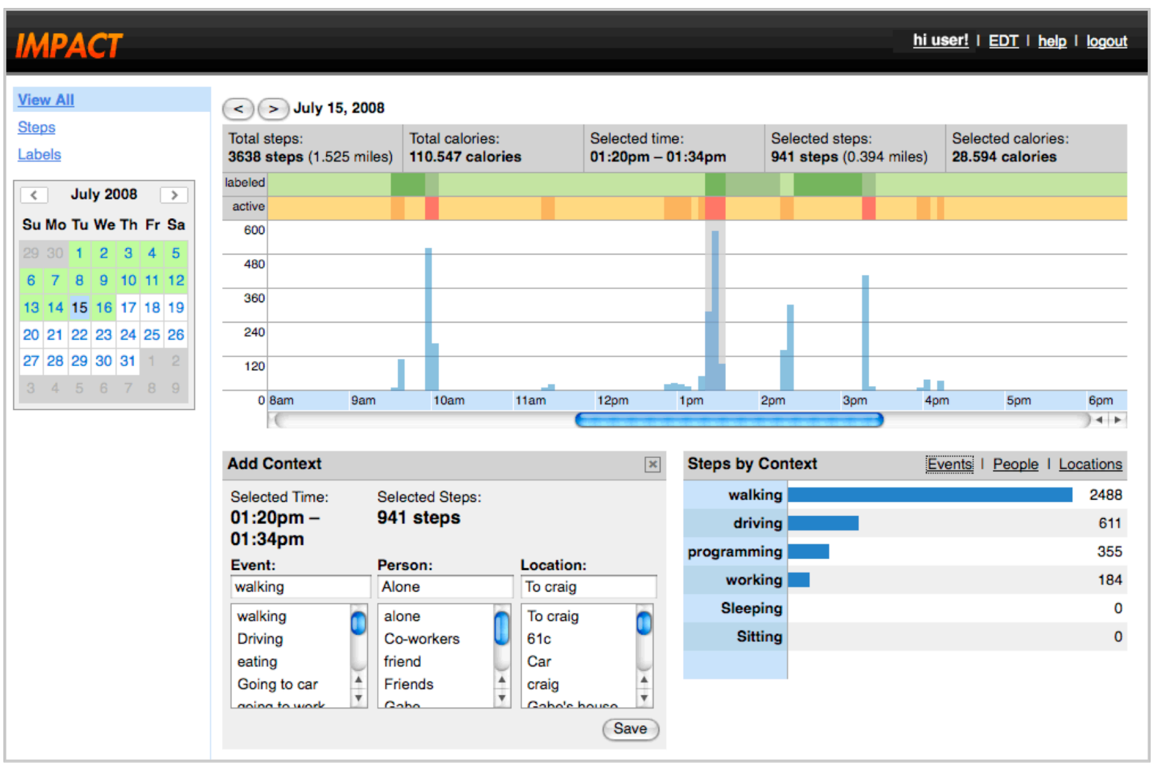

Figure 5. Visualizations in the IMPACT website showing step counts with contextual information. Detailed step counts graph with contextual annotations (top) and context graph (bottom right).

I conducted an 8-week long study: four weeks for a *Baseline* phase and four weeks for an *Intervention* phase. During the *Baseline* phase, all participants used the *Control* system. During the *Intervention* phase, participants were randomly assigned to three types of interventions: *Control*, *Steps-Only*, and *IMPACT*. I told participants to synchronize their data at least every other day, so I could ensure usage and promptly see any technical issues with the system.

I recruited 49 participants (C1-C49) aged 18 to 60 using the same recruitment method as the previous study. Regardless of their step counts, participants received $50 for completing the baseline phase and $75 for completing the intervention phase. Successful completion meant that data was uploaded on a consistent basis.

I met the participants three times: at the beginning and after each phase. During the meetings, I introduced participants to the system they would use, interviewed them, and gave them surveys similar to the previous study.

Participants did not use the IMPACT phone as their primary phone. This prevented frustration with having to use a new phone and interoperability problems between phone communication and monitoring functions. However, this risked users not carrying the device. I experienced problems with some participants, but most were compliant.

3.5.3 Results

I performed the analysis of the data I collected on 35 out of the 49 participants that started the study. Thirteen participants dropped during the *Baseline* phase because of family issues and scheduling problems (4); not wearing the devices for several days (4); disappeared and never returned the phones (3); losing the phone (1); and not responding to emails (1). One participant dropped out during the *Intervention* phase because she got into an accident. Despite the attrition, the remaining participants were still evenly distributed between the interventions: 12 participants in *Control*, 12 in *Steps-Only*, and 11 in *IMPACT*.

3.5.3.1 Average Step Counts

I prepared the physical activity data by removing days where participants did not wear the device for more than nine hours. Days with more than six hours with zero steps in the middle of the day (suggesting the phone was not worn) were also removed.

Adding the total steps for each day and dividing it by the number of days produced the average steps for each phase. I performed a repeated-measures analysis of the differences over the two phases between the groups. There were no significant changes over the course of the study between the different groups (no interaction, $F[2,32]=0.15$, $p=0.86$). I also ran the analysis with the phases broken into weekly segments, but found no differences. In general, participants maintained the same amount of physical activity between the two phases. Again, recording contextual information did not deter physical activity and the IMPACT system performed as well as the *Steps-Only* and *Control* versions, which are like pedometers.

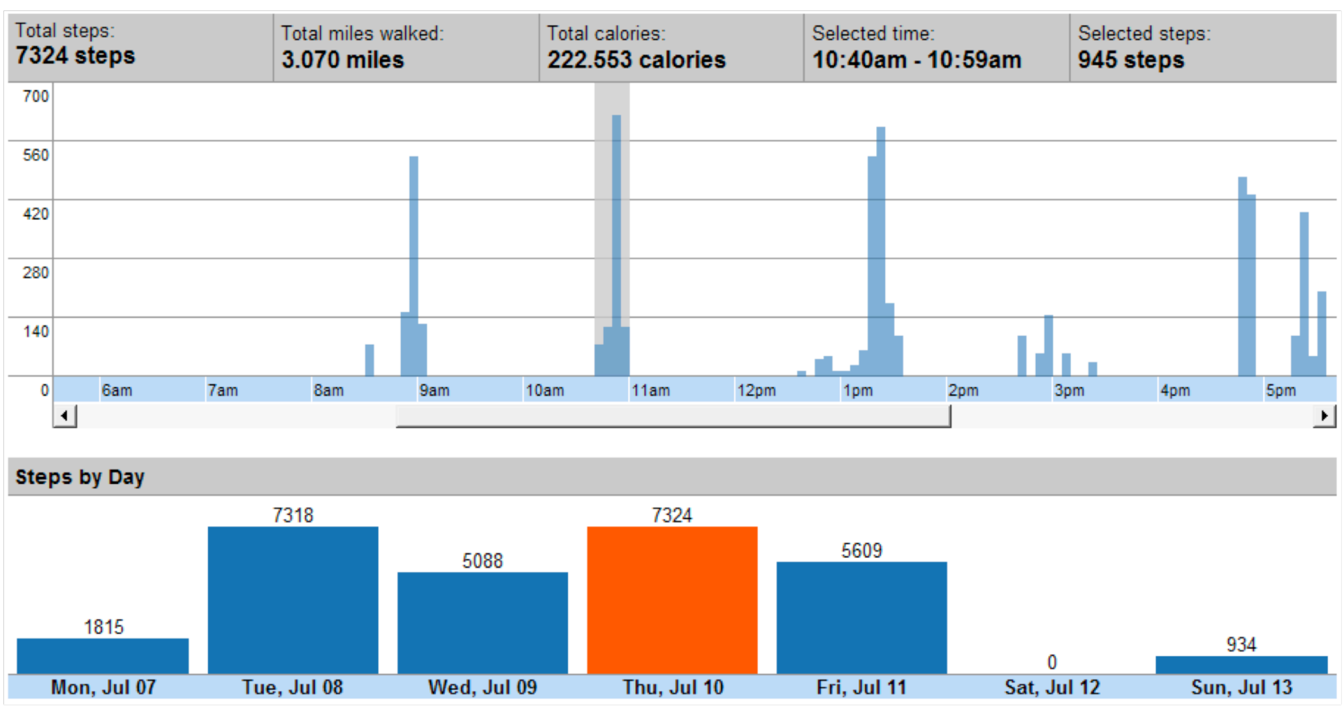

Figure 6. The *Steps-Only* version of the system only had the visualizations above. Top: day view of step counts. Bottom: aggregated daily step counts during a week.

3.5.3.2 Awareness of Opportunities

I checked to see if the IMPACT system helped participants increase their awareness of opportunities to be active. There was a marginally significant main effect of phase on the awareness of opportunities ($F[2,32]=3.98$, $p=.0547$). Awareness of opportunities increased for all groups, which is *not* what I expected. Similar to the analysis in the second study, I coded participants' responses to how the systems increased their awareness of how/when they can be active. Unlike the previous study, contextual information did not make users of IMPACT more aware of how/when they can be active compared to the other versions (Table 3). Eight participants who used IMPACT mentioned context compared to eight (Steps-Only) and six (Control). Even after removing time as context, the number of participants who mentioned context after using IMPACT (6) is similar to after using Steps-Only (3) or after using Control (5).

	Control	Steps-Only	IMPACT
Mentioned Context	6 participants	8	8
Mentioned Context Excluding Time	5	3	6

Table 3. Number of participants who mentioned context (including and excluding time) after using each of the systems.

One explanation why awareness increased with the first version of IMPACT but not the second is that users of the first version were more engaged; they had to physically write down their contextual information. On the other hand, the second version of IMPACT eased the burden of collection of contextual information, thus engaging the users less. I also have evidence from the interviews that simply carrying around the extra device, being confronted with real-time information about steps taken, and knowing that they were being monitored, were enough to give all users some idea of opportunities for physical activity:

"I have tried to make a point of making more trips across the office rather than waiting to make one trip." (C34, Control)

"I began to see the contribution of a short-distance walk to my overall emotional and physical health. I used to be a very sedentary person. I realize if I do not walk on purpose, my physical exercise will be zero. So I take a short walk whenever possible, then I feel good about it." (C12, Steps-Only)

"The system helped me realize how exercise can be built into your daily schedule. I tried to maximize those opportunities by walking whenever possible instead of taking the bus." (C24, IMPACT)

Contrasting this result from the results of the study with IMPACT 1.0 (described in Chapter 4) suggests an important implication for applications that integrate contextual information to increase awareness. It suggests that *user engagement is very important and that taking away too much of the responsibility for monitoring from the user may have a detrimental effect on immediate awareness*. However, this is a difficult issue to balance. As I saw in the previous study, some form of automation is necessary because it relieves the burden of monitoring on the user. What good can the application provide if the user will not use it? I conducted a follow-up interview with participants to explore this issue further.

3.5.4 Follow-up Interviews

I conducted follow-up interviews with participants six months after the study to see if people could revisit, reflect, and use their collected data in the study to learn about opportunities for physical activity. 14 participants responded to the request: 5 from *Control*, 6 from *Steps-Only*, and 3 from *IMPACT*. During the interviews, I asked them about their physical activity and their experience with the different systems. I also had them reflect on their physical activity during the study by exploring their data on the web site.

Participants repeated what they said about finding opportunities to be physically active during the study. However, there were some important observations while reflecting on their data that suggest automatically collected contextual information may still be useful. All participants were curious about the peaks that they saw in their graphs; they wanted to know what they were doing during those times of peak activity. Participants in the *IMPACT* group had no problems finding out what they did because the peaks were labeled. They were often surprised to find out that they had performed such an activity during the study. On the other hand, participants in the *Control* and *Steps-Only* groups could only guess at what they did. For participants with regular routines, they were able to deduce what they did by looking at the time of the peak. Interestingly, some participants pulled out their electronic calendars to see what they were doing on a particular date to deduce what the peak meant. One participant said that she would look back at her email and instant messenger history to find out how she was feeling during the days of peak activity guessing that her mood had an effect on her physical activity.

These observations imply a few design considerations for systems. First, automatic labeling of contextual information is useful for reflection, especially, at a *later time* when the user has likely forgotten their history. In fact, most participants told us that they *wished the study ran longer than the two months*; they were interested in finding out how their physical activity compares six months ago compares to their current activity. This suggests that physical activity awareness applications that provide information in the long-term can benefit from contextual information. Second, existing records, such as electronic calendars and email, can be leveraged to provide contextual information. A recent paper by Schwarz and colleagues [2009] suggests that financial records can be used to infer activity and location. Since many people have financial statements, this may be a ready source of contextual information. Lastly, the use of contextual information that is important to physical activity should not be limited to activities, places, and people. Other information, such as mood, and weather, may also be important. This makes sense since there are many kinds of barriers to being physically active [Centers for Disease Control and Prevention 2008; Sallis & Hovell 1990], including lack of motivation and weather conditions.

3.6 Discussion

In this section, I present three major findings from the studies. First, when given access to contextual information and physical activity information, users can and do make associations between the information helping them become aware of factors that affect their physical activity. Second, reflecting on physical activity and contextual information can increase people's awareness of opportunities for physical activity. Lastly, automated tracking of physical activity and contextual information increases the amount of data collected by the user, which benefits long-term reflection, but may be detrimental to immediate awareness. I believe these results are applicable to the use of contextual information to reveal factors that affect other types of behaviors, for example, diabetes management and energy conservation. These contributions suggest that personal informatics systems should further explore incorporating contextual information.

The studies showed that contextual information offers value in reflecting on physical activity levels. The diary study showed that people could and would associate contextual information with their physical activity to become aware of factors that affect their physical activity. The field study with IMPACT 1.0 provided empirical evidence that reflecting on contextual information can increase people's awareness of opportunities to be physically active.

Physical activity awareness systems were among the first tools used for personal informatics. However, most have not grown beyond physical activity levels. I showed that contextual information adds richness to the data. While I studied a tool for personal informatics that incorporated contextual information for physical activity, there may be opportunities for adding contextual information in personal informatics systems for other domains as well. The work of Mamykina and colleagues [2006] and Frost and Smith [2003] suggest extra information about factors that affect blood sugar levels would be appropriate for people with diabetes. In addition, contextual information in personal informatics systems to assist with living sustainably and smoking cessation may also be useful.

The second implication is that collection of and reflection on the data have to be well-integrated in personal informatics systems. In all the prototypes, the users were active participants in both monitoring (they had to wear a device and record other information) and reflecting on the data (they had to actively explore the information to find patterns and trends). The diary study suggested that people need an easy way of associating their physical activity with contextual information. I resolved this with the IMPACT 1.0 prototype that has a web site for visualizing this information. There are other approaches that warrant further exploration. For example, making a system that finds conclusions from the users' data can make the exploration more automatic. However, building such a system first requires identifying what information people want to know more about. Additionally, I can reverse the relationship between the system and user. Instead of the system passively displaying information and the user actively seeking information as in the prototypes, a system may proactively provide suggestions based on observed patterns of user activity, like a virtual coach or physical trainer.

Easing the burden of monitoring is complicated. I found in the IMPACT 1.0 field study that monitoring needed to be easier. I addressed the problem with the IMPACT 2.0 prototype that uses a mobile phone for tracking step counts and a GPS tracker for monitoring location. I found that the *IMPACT 2.0* version, which automatically collected contextual information, was not better at improving users' awareness of opportunities for physical activity compared to the *Steps-Only* systems, which only collected step counts. In fact, they both increased users' awareness of opportunities for physical activity. I attribute this problem to the automation of the monitoring contextual information. Whereas participants in the IMPACT 1.0 field study were engaged in recording their contextual information, participants in the IMPACT 2.0 field study were less engaged. Interestingly, this poses a tricky trade-off between ease-of-use and the value of contextual information. This trade-off requires further exploration.

While automation may have had a detrimental effect on immediate awareness, automated tracking of physical activity and contextual information benefits long-term reflection. In the IMPACT 2.0 field study, participants indicated that they wanted to record for longer periods of time; they wanted to be able to compare their physical activity between months, seasons, and even consecutive years; and most importantly, they wanted integrated contextual information that would help them make sense of their data months after it was collected. If the cost of collecting information was high (*e.g.*, manually collecting several pieces of information like in the diary study and the IMPACT 1.0 field study), users may not provide labels for such a long period of time and they would not be able to effectively reflect on their past history. Future systems can explore other ways of keeping users active with their data while automatically collecting contextual information using better monitoring devices or through indirect information, such as calendaring systems. The long-term field studies suggest that there is an interaction between time and the value of contextual information. How people's experiences with physical activity awareness systems change with time needs to be explored more. I do not know whether this is important for all personal informatics systems, but for systems that provide information about one's physical activity, it seems that it is important.

3.7 Conclusion

These studies are related to the thesis in that I demonstrated that showing contextual information with behavioral information could help people find opportunities to be more active. In this chapter, I presented the prototypes that I built and the studies I conducted that explore how contextual information can reveal factors that affect physical activity.

As we saw in the field studies, the features of the prototypes affected their effectiveness in helping people become more aware of the factors that affect their behavior. In the following chapters, I will discuss the studies I conducted to explore improve the design and development of personal informatics systems that support reflection on contextual information. First, I did not know what features are necessary to support in a personal informatics system. The features I developed in each of the prototypes were reactions to problems from the previous prototypes. In Chapter 4, I will describe the study I conducted that explores some of these issues. Second, I did not know what kinds of questions people wanted to answer about their physical activity and what role contextual information would play in answering these questions. I explored this in a study that I will discuss in Chapter 5. Third, the types of visualizations that I implemented were based on the interactions that I saw in the diary study, that is, looking at the contextual information at a particular time in a day. What other visualization features should be supported when reflecting on multiple kinds of data? I explored this question in a study described in Chapter 6. Lastly, people requested other kinds of data that the prototypes did not support. As the prototypes were implemented, they were rigid in what kinds of data the participants can collect. How do we make it easier for these systems to include other types of contextual information? I explored this question in a study described in Chapter 7.

In the next chapter, I expand my exploration of personal informatics tools beyond physical activity. I describe a study that explored the problems that people experience with personal informatics systems. From this study, I developed a model that will help design and evaluate such systems.

Chapter 4
A Stage-Based Model of Personal Informatics Systems

We saw in the previous chapter a series of studies that show the value of collecting contextual information with one's physical activity information. As noted before, I believe the value of contextual information is not just limited to physical activity; other personal information might benefit from being able to reflect on them with other types of data. Therefore, the next question that needs to be tackled is how to create personal informatics tools that better support analysis of multiple types of data together.

The kinds of personal data that can be collected are increasing. The limitation on the kinds of data collected in the previous studies was an artificial one imposed by the constraints of the study. The studies and prototypes were rigid in the kinds of data that were collected: only physical activity, location, events, and people they were with. However, participants reported that they wanted flexibility; they wished they had collected other kinds of data that may have been relevant to their physical activity, such as mood, weather, and calendar events. We now live in a world where many kinds of data about us can be collected, *e.g.*, blood glucose levels, amount of sleep, food intake, *etc*. Each of these might potentially be relevant to physical activity and vice versa. And even if they are not relevant to physical activity, they might be relevant to some other behavior for which the user cares about. For example, Alice is ambivalent about how much physical activity she does, but she is curious about how the amount of coffee she drinks every day affects her productivity and sleep.

If personal informatics tools are going to support collection and reflection on multiple types of data, we need to be aware of the problems that people experience when using personal informatics tools. While these different personal informatics tools collect different types of information in different ways, I believe there are similarities in the kinds of support they need to provide. For example, personal informatics tools need to provide a way to collect data and to reflect on the data, regardless of whether the data is physical activity, blood glucose level, or moods.

There are many ways that different kinds of data may be collected or reflected upon. For example, participants in the previously discussed studies collected and reflected on the data through various combinations of means: paper, wearable device, mobile device, and web site. We do not know all the problems that people may experience with personal informatics systems. We know that people want to get information about themselves to reflect on, and that systems that support this activity need to be effective and simple to use. Identifying problems that people experience in collecting and making sense of personal information while using such systems is critical for designing and developing effective personal informatics.

To date, there is no comprehensive list of problems that users experience using these systems. Toward this end, I conducted surveys and interviews with people who collect and reflect on personal information. From this, I derived a model of personal informatics systems organized by stages, which emphasizes the interdependence of the different parts of personal informatics systems.

I provide three main contributions: 1) I identify problems across personal informatics tools, 2) I introduce and discuss a model that improves the diagnosis, assessment, and prediction of problems in personal informatics systems, and 3) I make recommendations about how to improve existing systems and build new and effective personal informatics systems.

In the next section, I present the method and findings from our survey, and use them to introduce a stage-based model of personal informatics systems. I describe the barriers encountered in each stage and highlight opportunities for intervention within each stage. I also compare and analyze existing systems to demonstrate the use of the model for diagnosing and assessing problems. I conclude with a discussion of design guidelines for personal informatics systems and directions for future research.

More systems are being created today, but there is no comprehensive list of problems that users encounter when they collect and reflect on personal information. There is also no common vocabulary to compare and contrast these systems. This paper identifies problems in existing systems and defines a model of personal informatics to help designers and developers create more effective systems.

4.1 Method

To better understand personal informatics systems and their users, I conducted a survey of people who collect and reflect on their personal information.

4.1.1 Survey

The survey asked participants to list the types of personal information they collect and reflect on. From their list, participants selected one that was the most interesting and relevant to them. The rest of the survey focused on the participant's selection and had three sections. In the first two sections, participants answered questions about collection and reflection: what tools they used, when and how often, their motivation for use, problems they encountered, and suggestions for improvement. In the last section, the survey asked what patterns, trends, and surprises participants found from reflecting on their information. The survey ended with demographics questions (*e.g.*, gender, age range, marital status, employment, education, and technology use). The following are example questions from the survey (http://personalinformatics.org/lab/survey):

- *How difficult is it to collect this personal information?*
- *What was your initial motivation to reflect on this collected personal information?*

- *What patterns (repeating events) have you found when exploring this collected personal information?*

4.2 Participants

I recruited participants from a blog dedicated to personal informatics (http://quantifiedself.com), a blog about general information visualization (http://flowingdata.com), and forums at two personal informatics web sites (http://slifelabs.com and http://moodjam.org). I chose these web sites because their readers and users were more likely to have used one or more personal informatics systems. Survey participants were entered into a raffle for a $25 Amazon gift certificate. I interviewed a subset of these participants using instant messenger to collect additional details about their responses. Interviewees received an additional $10 Amazon gift certificate.

The study had 68 people complete the surveys, and 11 agreed to participate in the follow-up interviews. 37 participants were male. Ages ranged from 18 to 64 with a median age range of 26 to 30. About half had graduate degrees and another half were in college.

automatic	#	manual	#
bank statements	54	calendar events	27
email history	52	status updates	22
credit card bills	38	work activities	22
phone call history	26	blog posts	21
SMS history	25	weight	21
IM history	25	exercise	20
financial software	23	browser bookmarks	20
electricity bill	23	time at work	18
browsing history	23	social bookmarks	18
search history	20	mood	17

Other automatically collected: heating bill (12), travel (2) **Other manually collected:** journal/diary (16), pictures taken (14), sleeping habits (12), food consumption (12), productivity (10), health (9), medication intake (7), caloric intake (5), symptoms (5), miles ran (4), sports activities (4), blood pressure (4), blood sugar level (2), dream journal (2), step counts (2), relationship status (2), books read (1), habits of newborn baby (1), transportation (1)

Table 4. Top 10 types of personal information, automatically and manually collected by the participants.

More than half worked full-time. Participants were technologically savvy. 90% of participants used email or instant messenger daily to communicate. 60% of them used social networking sites daily. Most read news websites and blogs, ordered products online, and managed bills and bank accounts online.

4.3 Results

I created affinity diagrams to analyze the survey and interviews. I did not determine a coding scheme beforehand; instead I identified themes from the data as I processed the responses. During the analysis, I identified the types of personal information collected and reflected on by participants, motivations for collection and reflection, and problems experienced. Next, I analyzed the survey and interviews for experiences with tools and barriers that users encountered, identifying a model of personal informatics.

4.3.1 Collected Personal Information

Participants reported a wide variety of information that they collected and reflected on (see Table 4). Many participants reflected on automatically collected information such as bank statements and email history, since they are readily available. Automatically collected information was split between those recorded by industry infrastructures, such as financial transactions from banks and energy consumption from utility companies, and those recorded by computing applications and services, such as search history and email history. Since manually collecting information requires more time, fewer participants reflected on them. However, there is a greater variety of manually collected information because many types of information cannot be recorded automatically. The most popular was calendar events, since it is critical for time management. Status updates were also popular because of the rise of micro-blogging services (*e.g.*, Twitter) that facilitate input using various media.

The remainder of the discussion will focus on the personal information that participants selected as *the most relevant and interesting to them*. The four categories of information most relevant and interesting to participants were finance, journaling, exercise, and general health. Finance is the prevalent information type since there is a strong incentive to keep track of where one's money goes, and there is a reliable infrastructure for tracking the information. Journaling is a common activity for recording one's thoughts and experiences, and people are using new tools such as blogs and microblogs (*e.g.*, Twitter, Facebook status updates). Exercise is also popular because it is an activity for which people want to track their progress, and many devices and web sites exist for collecting such information. General health information, such as food consumption, weight, symptoms, medication, amount of sleep, and alcohol/caffeine intake is also of strong interest. As for the outliers, there are people who collected information on productivity, status of relationships, computer usage, transportation, the habits of a newborn baby, and books read.

4.3.2 Tools Used

People used a variety of tools to collect information. Some used pen and paper because of their flexibility and ease of use; people can take them anywhere and they are easily accessible when a note needs to be written. This group faced a problem in having to transcribe their data to an electronic format in order to visualize their data. Some used Excel spreadsheets for graphing. Many used existing personal informatics web sites for collecting and reflecting on various information, such as finance, food consumption, mood, and physical activity. Some used physical devices such as pedometers, the WiiFit, and a continuous positive airway pressure (CPAP) machine for tracking sleep apnea. Some activities had an infrastructure that automatically records information such as financial transactions, search history, and communication tools (e.g., email, instant messenger, and IRC), which people later explored for personal information. Some with programming backgrounds devised their own way of exploring data (e.g., statistical packages for analysis, and programming languages to organize and cull information).

4.3.3 Reasons

Participants gave several reasons for collecting and reflecting on personal information: natural curiosity, interest in data, discovery of new tools, suggestion from another person, and trigger events.

Some people cited curiosity about themselves prompted them to collect personal information. P22 said, "Curiosity: Q: how much would I walk if I didn't ride my bike? A: kind of a lot, but not as much as you'd think." Some people identified themselves by their interest in quantitative data. Some participants used the terms "data nerd", "a student of information visualization", and "geekiness" to describe themselves. There is also the added value that the data is about them. P40 said, "I'm an engineer, so numbers and trends and stuff just interest me in general. Plus this data is about ME (her emphasis)."

Finding personal informatics tools also encouraged people to start collecting information. P48 said, "I've been following Nick Felton's annual reports so when he started Daytum, I joined to start tracking which restaurants I ate at." Others cited trigger events, such as problems in relationships (P60, P1), sleep patterns (P44), and weight (P21, P23, P37). Sometimes, the trigger event is combined with an extra push from another person. P49 started collecting blood sugar level and blood pressure information because of "a doctor's recommendation (new medical issue, new medications)."

4.4 Stages and Barriers

I will now introduce the stage-based model of personal informatics that I derived from analysis of the survey and interview data. The model is composed of a series of five

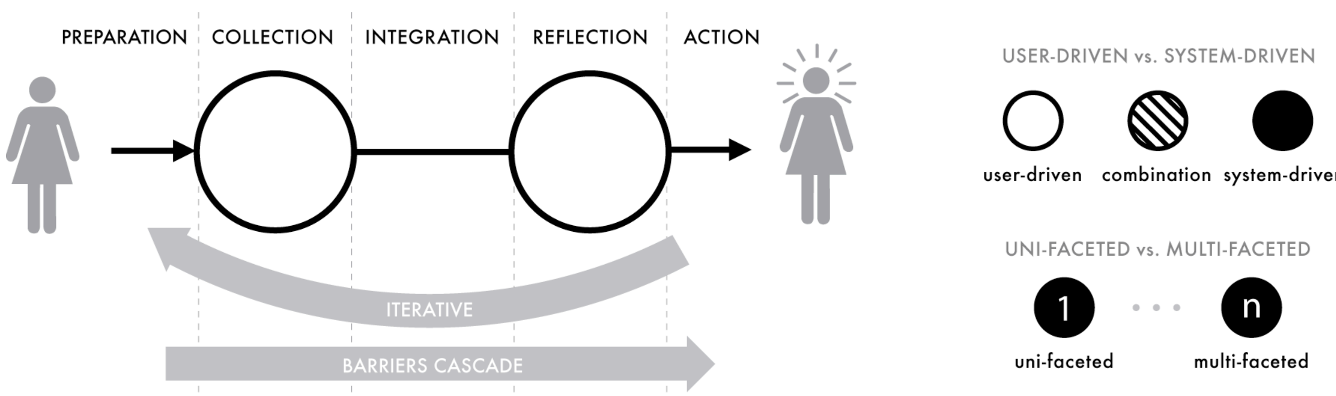

Figure 7. The Stage-Based Model of Personal Informatics Systems and its four properties: 1) barriers in a stage cascade to later stages; 2) stages are iterative; 3) stages are user- and/or system-driven, and 4) uni- or multi-faceted. The visuals for 3) and 4) can be used to show these properties for a particular system.

stages (Figure 7): *Preparation*, *Collection*, *Integration*, *Reflection*, and *Action*. I define each stage and, for each one, describe the barriers that participants experienced.

I identified this model by classifying the problems that people encountered when using personal informatics tools. I started this research intuitively thinking that there are two activities that personal informatics systems must support: collecting data and reflecting on data or the Collection and Reflection stages, respectively. The survey specifically asked about the problems people encountered during these activities. However, during the analysis of participants' responses I noticed that people experienced problems before, between, and after Collection and Reflection. Thus, I created new descriptions for each one of them, which corresponded with the stages: Preparation, Integration, and Action.

4.4.1 Preparation Stage

The *Preparation* stage occurs before people start collecting personal information. This stage concerns itself with people's motivation to collect personal information, how they determine what information they will record, and how they will record it.

Barriers in the Preparation stage are related to determining what information to collect and what collection tool to use. As noted, some people stumble upon tools, which drive them to start collecting. However, this becomes a problem when the tool does not satisfy their information needs. This causes them to switch to another tool, which has two negative consequences: 1) they abandon their previous data because most systems do not support data exporting, and 2) if they can export data, the formats between the applications may not be the same. For example, P48 used Google spreadsheets to record food and drink consumption then she switched to Daytum where she recorded restaurant information instead. When she discovered your.flowingdata, she returned to recording actual food items. Better preparation in tool selection would have helped her avoid a gap in her data. Another example is P23 who used spreadsheets to record jogging and biking times before switching to DailyBurn, She did not transfer data from the spreadsheets to DailyBurn, because she would have had to manually transfer the data, which takes time. This is a lost opportunity for more longitudinal reflection about her physical activity.

4.4.2 Collection Stage

The *Collection* stage is the time when people collect information about themselves. During this stage, people observe different personal information, such as their inner thoughts, their behavior, their interactions with people, and their immediate environment. Participants reported different frequencies of collection: several times a day (*e.g.*, food consumption), once a day (*e.g.*, amount of sleep), several times a week (*e.g.*, exercise), or a few times a month (*e.g.*, symptoms, books read).

People encountered several barriers in the collection stage (Table 5). Many of the problems are because of the tool used for collecting information. Some problems occurred because of the user, either because they lacked time, lacked motivation, or did not remember to collect information. Other problems are data-related: 1) data may rely on subjective estimation (*e.g.*, how many calories were expended when lifting weights? P23); 2) data may rely on subjective ratings with no standard for entering data (*e.g.*, P1 wanted to rate his relationship satisfaction, but noticed that his ratings were not consistent); 3) data may be hard to find (*e.g.*, P54 said, "Sometimes life isn't interesting enough to make me want to write it down, other times I can't find any worthy writing material.")

4.4.3 Integration Stage

Integration is the stage that lies between the Collection and Reflection stages, where the information collected are prepared, combined, and transformed for the user to reflect on. In Figure 7, the Integration stage is represented as the distance between the Collection

Collection Barriers	Example Quote
Tool (13/68)	"not having ready access to a computer at the time symptoms happen" P6
Remembering (12/68)	"Forgetting to record it. Because I am often not at my personal computer." P57
Lack of time (11/68)	"not difficult, time consuming at times." P16
Finding data (7/68)	"Sometimes life isn't interesting enough to make me want to write it down, other times I can't find any worthy writing material." P54
Accuracy (6/68)	"Guestimating mass of food matching homemade or restaurant foods against database entries" P5
Motivation (5/68)	"keeping up the motivation to do so, finding payback for the investment of time and effort." P4

Table 5. Collection barriers.

and Reflection stages. This distance is determined by how much effort the user has to put into preparing the collected data for the reflection stage. The Integration stage can be *long*, meaning that the user has to do many things to prepare the collected data for the reflection stage. An example of this is when the data to visualize is collected on paper. In such a system, the user has to gather all of his notes and transcribe the data into a graphing application such as Excel. The Integration stage can also be *short*, meaning that the user bears little responsibility in preparing the collected data for reflection. An example of this is Mint, which automatically integrates financial data from bank accounts and credit card companies. Another example is Nike+, which automatically synchronizes runs between an iPod and the Nike+ website.

Integration barriers prevent users from transitioning from collection to reflection of data (Table 6). Users encountered these problems when collected data comes from multiple inputs, reflection of data happens in multiple outputs, and the format of collected data is different from the format necessary for reflection.

4.4.4 Reflection Stage

The *Reflection* stage is when the user reflects on their personal information. This stage may involve looking at lists of collected personal information or exploring or interacting with information visualizations. Users may reflect on their information immediately after recording the information (*short-term*) or after several days or weeks involving extensive self-reflection (*long-term*). Short-term reflection is valuable because it makes the user

Integration Barriers	Example Quote
Transcribing data (10/68)	"It'd be neat if I could graph it straight from the website instead of manually typing in the data to a spreadsheet" P41
Organization (8/68)	"Collecting is simple. Organizing it takes some time." P29
Scattered visualizations (4/68)	"A bit cumbersome going to so many different sites [for visualizations]" P6
Multiple inputs (3/68)	"Difficult to keep organized because sometimes data are kept in separate places" P31

Table 6. Integration barriers.

aware of their current status. For example, pedometers show a current aggregate count of steps. In contrast, the BodyMedia SenseWear armband (http://bodymedia.com) does not have a display, so the user is not aware of the amount of calories they have expended until they synchronize with the desktop software. Long-term reflection is valuable because it allows users to compare personal information between different times and it reveals trends and patterns.

Barriers in the Reflection stage prevent users from exploring and understanding information about themselves. These problems occurred because of lack of time or difficulties retrieving, exploring, and understanding information (Table 7).

4.4.5 Action Stage

The *Action* stage is the stage when people choose what they are going to do with their newfound understanding of themselves. Some people reflect on the information to track

Reflection Barriers	Example Quote
Lack of time (10/68)	"Having time to go through everything, but that is also one of my biggest pleasures is finding that time." P19
Visualization (6/68)	"It's hard to get a holistic view of the data since the time filters are at most one month and I'd like to look at several months at once." P48
Self-criticism (5/68)	"It's extremely difficult (psychologically) to look back on my earliest journals. Much of that information is very emotional and innocent." P12
Interpretation (5/68)	"Sometimes its very difficult to interpret the media" P54
Search (4/68)	"not too tough. sometimes have to wait while search occurs... but it's a couple minutes at most" P14
No context (3/68)	"Not having an overlay of changes in circumstance" P11
Sparse data (3/68)	"Not enough; My collection of data has been intermittent enough that I don't get good time series." P44
Data is not useful (3/68)	"it's really not very useful and it's kind of annoying. I mean, I walk a lot. What else do I really want to know?" P22

Table 7. Reflection barriers.

their progress towards goals. From the understanding of their information, people may tailor their behaviors to match their goals. Some systems alert the user to take actions. For example, Mint alerts users when their bank account reaches a minimum amount. The WiiFit shows an avatar that acts like a personal trainer; P37 said, "The WiiFit avatar gets excited (or crestfallen) at my progress, which is kind of cool, since s/he acts as a personal trainer." Some systems provide incentives to motivate users to take action. For example, Slife introduced Slife Rewards, which uses donations to selected charities to encourage users to achieve their productivity goals.

Some people reflect on the information to inform them on what actions to take. Most systems do not have specific suggestions on what to do next, which is a barrier to applying understanding of personal information. Different systems have resolved this in multiple ways. Some systems are more explicit such as Mint providing suggestions about bank and credit card accounts with lower fees. Some systems involve input from others. For example, some people collect data and share them with their doctor for advice on next steps (P1, P40, P49). Some systems with sharing capabilities allow feedback from one's social network, *e.g.*, SparkPeople (http://sparkpeople.com), DailyBurn (http://dailyburn.com). P23 said about DailyBurn, "they have forums, which is good to get advice from others."

The stage-based model extends our view of personal informatics systems beyond a pairing of collection and reflection tools. I have just defined the specific stages of personal informatics systems. I will now describe the properties of the model as a whole.

4.5 Properties of the Stages

Here I talk about the holistic properties of the stages and their implications on the development and design of personal informatics systems. I will discuss four properties of the stages: cascading barriers, iteration, user-driven vs. system-driven, and uni-faceted vs. multi-faceted information. I describe the implications of these properties on the design of personal informatics systems.

4.5.1 Barriers Cascade

An important property of personal informatics systems that the stage-based model reveals is that barriers cascade, *i.e.*, problems in earlier stages affect the later stages. Problems in the Preparation stage, such as not using the right tool or not collecting the right data, lead users to change tools, which wastes their time. Since users cannot go back in time and collect the right kind of information, their collected data are rendered somewhat, if not totally, useless. Problems in the Collection stage may lead to sparse datasets that are insufficient for reflection. P44 lacked time and motivation during the Collection stage because he did not have enough data to get a good time-series visualization. When thinking about what he learned from his data, he said “I wish I could report successes on this front, but my lack of regular collection has made this difficult.” Problems in the Integration stage, such as scattered visualizations and difficult organization, make reflection harder. P6 noted that “each website has their own way of organizing [data]” and that it was “a bit cumbersome going to so many different sites.” Problems in the Reflection stage, such as having trouble using visualizations effectively, prevent users from transitioning to the Action stage. P64 said, “I waste too much time exploring the variations of presentation rather than considering personal changes that might be necessary.”

Cascading barriers suggest that a holistic approach to the design of personal informatics systems is critical. Focusing only on one stage ignores the whole experience of the user with the system. While we can take inspiration from different fields to resolve barriers within each stage (*e.g.*, visualization techniques from information visualization research), creating an effective personal informatics system requires the consideration of *all* of the system's parts.

4.5.2 Stages are Iterative

Another property of personal informatics systems is that the stages are iterative, *i.e.*, users incorporate new data, tools, and/or processes as they progress through the stages. I asked the interviewees whether they knew what personal information to collect when they *first* decided to collect information. Many said they knew, but some changed their minds when they found a different collection method. For example, P37 switched between multitudes of tools (whiteboard, spreadsheet, WiiFit) to collect physical activity information. As mentioned before, P48 changed tools as she found new ones (Google spreadsheets, Daytum, your.flowingdata). The iterative process was not supported well in either case. For example, P48 did not transfer her spreadsheet data because Daytum did not support importing data (at the time she used the system). When she switched to your.flowingdata, she could not import her Daytum data.

Some participants changed what personal information they needed while going through the stages, which resulted in tool changes. P23 changed collection tools because of changes in the types of physical activity she performed: 1) spreadsheet for biking and running several years ago; 2) she got a WiiFit last Christmas for physical activity games; 3) she uses DailyBurn now for her gym attendance. P44, who programmed his own visualizations to learn about his sleeping habits, continually added new information (*e.g.*, caffeine consumption, meal times, weight) into the reports depending on his hypotheses (*e.g.*, what is the effect of caffeine consumption on my sleep patterns?).

The iterative property of personal informatics systems suggests that systems should be flexible to support users' changing information needs. Systems could be flexible by 1) supporting importing data from other systems, as well as, exporting to other systems; and 2) supporting different kinds of information. Since tool changes may render previously collected data useless, systems should support rapid iteration, so that users can quickly hone in on the questions they want to answer and select the appropriate tools to collect the necessary information.

4.5.3 User-driven vs. System-driven

Each stage can be classified as *user-driven, system-driven*, or a combination of both. When a stage is user-driven, the user is responsible for the activity in the stage. In the Preparation stage, the user decides what type of information to collect and what tools to use. User-driven collection is when users record information on paper or enter information into a spreadsheet, an application, or a website form. User-driven integration is when users have to transcribe collected information, so that they can reflect on it. In the

Reflection stage, the user reflects on the information without the aid of visualizations or other tools for exploring the data. In the Action stage, the user is responsible for deciding on actions to take depending on their conclusions from the data without aid from the system.

User-driven stages demand time and attention from the user. This is problematic when the demand becomes too much (*e.g.*, high frequency of collection). There are ways to facilitate user-driven stages. For example, systems that use user-driven collection can motivate the user to collect the information. Hsieh and colleagues [2008] have explored this in the context of experience sampling; they encouraged participation in an ESM study by showing reflective visualizations. An alternative way to dealing with the burden of user-driven stages is to transfer the responsibility completely to the system, *i.e.*, making them system-driven.

When a stage is system-driven, the system takes on the responsibility of performing the tasks in the stage. In the Preparation stage, the system can suggest to users the appropriate tools and information that will help them answer their questions about themselves. In the Collection stage, the system can collect personal information by using sensors (*e.g.*, pedometers), or keeping a record of transactions (*e.g.*, bank statements, search history). System-driven collection can also involve other people, *e.g.*, a nurse writes the data for the patient into a web site. In the Integration stage, the system can aggregate and prepare the information for reflection, *e.g.*, Mint aggregates data from different banks and credit card companies. In the Reflection stage, the system can help users reflect on and explore their information using visualizations. In the Action stage, systems can alert the user to take action, *e.g.*, Wakoopa (http://wakoopa.com) suggests new applications and websites depending on the person's computer usage.

This property of the stages suggests that there are opportunities within each stage of a system to use a system-driven approach to alleviate the demands on the user. However, designers should consider the tradeoffs between a system-driven approach (*e.g.*, inaccuracies of automated analysis, and loss of user control) and a user-driven approach (*e.g.*, burden and complexity). Developers and designers can select which stage could be facilitated by the system to benefit the user the most.

4.5.4 Facets

People's lives are composed of different facets. For example, people have their home life, their work life, their daily interactions with other people, their physical activity, *etc*. Personal informatics systems can be *uni-faceted* or *multi-faceted*. Currently, most systems are uni-faceted, showing only one facet of a person's life (*e.g.*, Mint for financial matters, Nike+ for physical activity, and Slife for productivity). Facets are not necessarily correlated with the number of pieces of information collected by a system. For example, the BodyMedia SenseWear armband is uni-faceted because all the data it collects (*e.g.*, galvanic skin response, ambient temperature, skin temperature, acceleration) represent only one facet of life, *i.e.*, physical activity. An example of a multi-faceted system is MyLifeBits [Gemmell et al. 2006], which collects information about computing activity, web-browsing activity, communication (voice, email, and IM), and media usage (radio and television). Research projects in diabetes management have shown the value of associating multiple facets (*e.g.*, blood sugar level and food consumption) in patients' health [Frost & Smith 2003, Mamykina et al. 2006].

Uni-faceted systems simplify the collection and integration of personal information because there is less data to manage. However, uni-faceted systems limit the type of information that people can understand about their life. For example, the WiiFit shows people progress toward their physical activity goals, but there is no awareness of the effect of food consumption, mood, sleeping patterns, and work on physical activity. Systems with multi-faceted collection stages such as MyLifeBits and Daytum allow collection of multiple types of information, which makes collection of data harder, but offers greater potential for becoming aware about different facets of life. Unfortunately, such systems usually present information about multiple facets in separate visualizations. Many participants expressed their desire to see associations between multiple facets of their lives. P26 described his motivation to collect multiple types of information as "to understand trends in symptoms, behaviors, and circumstances." There is an opportunity here for personal informatics systems to provide visualizations (Reflection Stage) that show people the relationships between different facets of their lives. However, the benefit of multiple facets has its cost. P49, talking about tracking medication intake, said, “I suppose if it were easily collected, information on food intake, calories, fat, cholesterol, sodium, *etc*., would make an interesting starting point for analysis. However, if it is too difficult to collect, I have better things to do with my time.”

This property of personal informatics systems opens several opportunities for research and applications. Many existing technologies are capable of collecting various types of personal information, and researchers in ubiquitous computing and lifelogging are developing new collection tools. How can personal informatics systems leverage these new technologies to inform people about different facets of their lives? What would visualizations that show multiple facets of people's lives look like? How should they be designed so that non-experts (most people) can gain insights about their lives?

4.5.5 Limitations of the Survey and Model

The study recruited participants from a blog dedicated to personal informatics, a blog about general information visualization, and two personal informatics web sites, so most survey participants were familiar with personal informatics. Since even these interested users had plenty of problems with different systems, I suspect that the problems they encountered may be a subset of problems that common users may experience. I think it would be interesting to study users with little or no prior experience with personal informatics systems to find specific barriers that they may encounter.

4.6 Case Studies

Having identified the stages model, the properties of the stages, and the barriers experienced within the stages, we can evaluate the value of the model by using it to analyze personal informatics systems. There are other ways of evaluating the model, such as creating a taxonomy of personal informatics systems based on the model or conducting a field study to observe if users actually seek support for each of the stages. The former can be explored by doing some case studies, which I will do below. The latter on the other hand is not feasible in the context of this thesis because it will require running longer field studies with more participants and deployments of several personal informatics systems.

In this section, I evaluate existing personal informatics systems to demonstrate the use of the model. I only highlight some aspects of each system. I describe barriers that users may encounter and suggest potential solutions to explore further.

4.6.1 Twitter-based systems

There are several personal informatics tools that use Twitter as a collection tool. Some collect specific types of information such as eating (http://tweetwhatyoueat.com) and smoking (http://qwitter.tobaccofreeflorida.com), while some collect multiple types of information (*e.g.*, Daytum, Grafitter, Mycrocosm, and your.flowingdata). Users manually enter data into Twitter, but the cost of collection is reduced because users can collect information using different applications and devices (*e.g.*, browser, instant messenger, mobile phone) in different contexts. The Integration stage is also simplified because all data are funneled through Twitter. There are two areas that could be further explored for improvements:

Scattered visualizations. The uni-faceted Twitter-based systems do not have the data to associate multiple facets together. However, the multi-faceted systems have multiple data collected, but do not visualize the data together. P27, who used your.flowingdata, suggested that "relating many datasets at once" would improve the system. This design suggestion could be as simple as associating two pieces of information together. For example, a person who collects information about expenditure and eating locations may see directly how her eating habits are affecting her finances.

Lack of time to collect data. These systems also suffer from the tedium of manually collecting information. P48 said, of her experience with your.flowingdata and Daytum, “I just find it hard enough to track food regularly, so I haven’t tracked other things that I would like to.” A design suggestion to address this is to automate some of the data collection. Not all collection can be automated, but some data can be. One inspiration is the concept of *tweetjects* [Alleyne 2009], sensors and devices that post to Twitter. Some tweetjects post personal information, such as @gareth_laptop (nearby devices), @andy_house (electricity usage), and @kickbee (baby activities in the womb).

4.6.2 Mint (finance)

Mint is a personal finance management website. Mint is mostly system-driven. Mint provides some support in the Preparation stage by helping users select the banks, credit cards and investments that the system will integrate. The Collection stage is completely system-driven, supported by the bank and credit card infrastructures that record financial transactions. Mint integrates your transaction records from multiple bank, credit card, and investment accounts. P9 noted that one of the flaws of Mint is that it "automatically categorizes [transactions], which works 95% of the time, but not always. I need it to be almost perfect to use it for more than curiosity." The system-driven integration is not perfect, so manual integration is still needed to provide category labels for unlabeled transactions and to fix mislabeled transactions. It supports reflection with visualizations of a user's spending between different categories. Mint is one of the few personal informatics systems that have system support for the Action stage; it provides suggestions on how a user can save money by finding banks with discounted services and credit card companies with low rates, and alerting users of low balances and unusual activity.

No support for multi-faceted reflection. Reflection within Mint is uni-faceted. P12 noted: “I now want to record all the minutiae of my personal life that aggregates into interesting data. I want to graph the people I see, the things I do, the hours I devote to every significant task, and the money I spend and *why* (our emphasis). I want to have yearly data that shows, for example, that I spent 1,000 hours on programming, but only 400 on reading, or that I spent twice as much in coffee shops as I did on groceries.” She does not use Mint, but would have found it useful for comparing her expenditures at coffee shops and groceries; however, Mint's visualizations would not help her answer the “why” question. She speculated that there are associations between different facets of her life; allowing input about different life facets in Mint may help her. Since Mint is largely system-driven, adding extra information to associate with spending may be a small burden to users, even if manually collected.

4.7 IMPACT (physical activity)

IMPACT is a mobile phone and web site system for collecting and reflecting on physical activity, with which I had first-hand experience in deploying to users for several weeks [Li et al. 2009]. I highlight two problems with IMPACT that could be further explored for solutions.

No support for Preparation stage. The IMPACT system did not have support for the Preparation stage. The IMPACT system collected four types of information: step counts and the context in which those steps were taken (location, type of activity, and whom the person was with). The system imposed these types of information without determining whether the user might find all the information useful. I learned that users were interested in the effects of mood and weather on physical activity, but IMPACT did not support these types of information. Problems in the Preparation stage affected the Collection stage leading to barriers such as too much information to collect. Collecting the three types of context unnecessarily burdened the user, when other types of information may have been more useful (*e.g.*, mood, weather). There were other collection barriers such as intrusiveness (experience sampling type alerts), and the use of separate devices for monitoring step counts (mobile phone) and location (GPS device).

User-driven Integration. An initial version of IMPACT required users to transcribe step counts, time, and contextual information from a notebook to a web site. I fixed this in the current version with a system-driven integration, where the system automatically transfers data collected on a mobile phone to a web site. I could have avoided the problem with the initial prototype if I had considered the Integration stage earlier.

Notice that the two problems described above could have been avoided if I had analyzed IMPACT using the stage-based model of personal informatics systems earlier in its development. Addressing these problems may improve users' experience with the system and yield results for the use of context in improving monitoring of physical activity.

4.8 Discussion

I have defined a stage-based model of personal informatics systems and identified a comprehensive list of the problems that people experience in each of the stages. I also described the properties of the stages, which have implications in the design of personal informatics systems. To build effective personal informatics systems, developers and designers should consider the following:

- Since barriers cascade to later stages, designers and developers should consider the system as a whole. This holistic approach requires integrating innovations and applying lessons from different areas of research, such as lifelogging, ubiquitous computing, information visualization, and persuasive technologies.
- Since users iterate in the kinds of questions they ask and the tools they use, flexibility within a system and between systems is important. Systems should allow users to easily change what kind of data they collect dependent on their needs and to transfer data from one system to another.
- There are opportunities within each stage to use a system-driven approach to reduce the demand on users and to make the experience more enjoyable and useful. Similarly, a user-driven approach is appealing because it leaves control in the hands of the user. Insights from the field of human-computer interaction should play a big part in the development of mixed-initiative approaches for effective personal informatics systems.
- Currently, most personal informatics systems are uni-faceted. Participants expressed desire for associating different aspects of their lives together. Creating multi-faceted systems may be difficult because of the extra data that need to be collected, however the insights gained may be worth it. There are opportunities to leverage the increasing ability of ubiquitous computing and lifelogging technologies to collect various types of information and show users multiple facets of their lives. These multiple facets must be displayed in ways that users can understand them and gain valuable insight into their lives.

4.9 Conclusion

This study is relevant to the thesis because the model makes us aware of all the aspects of personal informatics systems that need to be supported. This means that we should not think of personal informatics systems in parts as just collection of data or just reflection on data. Instead, design of personal informatics systems must be holistic. If the model were available to me during the development of the IMPACT prototypes, the model would have informed me of the important parts of the prototypes that needed to be supported. Instead, during the development of the IMPACT prototypes, I did not have a formal guide to what features to implement and problems to avoid. I hope that the model would be a guide for others who are developing personal informatics systems.

Additionally, the stage-based model of personal informatics systems provides a common framework for designing, comparing, and evaluating such tools. By studying how people use personal informatics systems for different kinds of personal data, I gained an understanding of their practices and the problems they encountered. I also saw that people expressed a need to associate different aspects of their lives together. Designers and developers can use this knowledge to better design personal informatics and, consequently, better support users who want to collect multiple types of personal data. In the next chapters, I present my explorations on how to better support reflection on multiple types of data.

Chapter 5
Phases of Reflection: Discovery and Maintenance

In the previous chapter, I conducted a study that explores the different kinds of support that a personal informatics system must provide to help users through the process of collecting the necessary personally relevant to data to better understand themselves. In this chapter, I focus primarily on the issues of reflection on personal data. I believe current personal informatics tools were not designed with sufficient understanding of users' self-reflection needs. For example, some personal informatics tools only show the user's current status, ignoring the user's long-term self-reflection needs. To appropriately design these tools, we need a comprehensive understanding of what kinds of questions people want to answer about their data, why they ask these questions, how they answer them with current tools, and what kinds of problems they encounter. By doing so, developers and designers can better take advantage of technology to help users self-reflect.

To explore these issues, I conducted a study in which I interviewed people who use personal informatics tools. I identified six kinds of questions that people ask about their data: *Status*, *History*, *Goals*, *Discrepancies*, *Context*, and *Factors*. I discuss how people answered these questions using current tools and problems that they encountered.

I also discovered that people's information needs change. I identified two distinct phases when people had different information needs: *Discovery* and *Maintenance*. These phases differ by the kinds of questions people asked about their data more frequently. In the *Maintenance* phase, people more frequently asked *Status* and *Discrepancy* questions. During this phase, people already understood what was causing their problem; they just wanted to know whether they were doing well. People only collected data to determine whether they were meeting their goal. For example, participants with diabetes only tracked their blood sugar level to make sure they were staying within the healthy levels. In contrast, during the *Discovery* phase, participants were trying to better understand their behavior and collected multiple kinds of data to understand how different factors affected their behavior. For example, participants with diabetes tracked their food consumption and physical activity level to determine how these factors affected their blood sugar level. In this phase, participants more frequently asked *History*, *Goals*, *Context*, and *Factors* questions. They have identified that they have a problem (*e.g.*, not sleeping well, lacking physical activity, diagnosed with diabetes), but they do not know how different factors may be causing their problem. During this phase, participants collect multiple kinds of data to understand the relationship between different factors and their behavior.

An important aspect of the phases that we found is that people transitioned between them. Participants transitioned from *Maintenance* to *Discovery* when they were unable to reach their goals or when they have to redefine their goals because they experienced a new set of problems. They transitioned into the Discovery phase because they needed to understand their behavior. On the other hand, participants transitioned from *Discovery* to *Maintenance* when they have identified their goal and have learned the steps they need to take to achieve their goal.

The importance of this work is threefold. First, this work describes details about the questions that people ask about their data. Knowing the questions that people ask about their data is critical in providing appropriate support for users. We now live in a world where there is so much data about us. The problem is not whether the data can be collected, but how the data can be provided to users in a way that is valuable to them. Awareness of the questions that people ask helps us select what kinds of data to collect and tailor the presentation of the data. Second, this work identifies specific features that tools should support to help users better reflect on their data. This feature list we describe is a starting point for explorations into developing these tools and evaluating them for their effectiveness. Lastly, this work describes how technologies can appropriately support people to answer the questions they ask within the phases and help them transition between the phases. Ubicomp technologies have been applied to various kinds of applications; this work shows that these technologies can play an important role in helping people become more self-aware, which is valuable in making good decisions and changing behavior.

The information in this chapter will be organized in the following way. First, I describe our interviews, which explore what people ask about their data and how people answer them with current tools. Then, I discuss our findings: the six main questions people asked about their data and the two phases of reflection that they transitioned between. I present a list of features that tools should support to help users with reflection, and discuss their implications.

5.1 Interviews

The goal of this study was to ask participants how they explore and reflect on the data they collect with personal informatics tools. I conducted interviews with people who were already self-tracking and reflecting on collected data. This helped us see behavior in a natural setting where people's routines around tracking and reflecting were focused on their own needs, rather than forcing participants to use a system I designed and focusing on our study goals. In the following sections, I describe how I recruited participants and conducted the interviews.

5.1.1 Recruitment

I advertised the study on Craigslist, the Quantified Self blog, and a campus recruiting web site. The recruitment letter stated that the study was looking for users of self-tracking/personal informatics tools, such as Mint, Nike+, MoodJam, *etc*. People were also directed to our project web page for a bigger list of tools that might match their self-tracking habits.

People interested in the study completed a pre-questionnaire that asked what type of data they collect, for how long, and contact information. They had to be currently using their personal informatics tool and must have used it for a month or more at the time of the study. I recruited a diverse group of people from around the nation and our city. Given that I was only going to be able to talk to a limited number of people, the pre-questionnaire helped me ensure that I recruited a set of participants using a range of personal informatics tools for a range of types of data.

91 people responded to the pre-questionnaire (local: 76, remote: 15). From all the respondents of the questionnaire, I selected 15 people (P1-P15) to participate in the study. Ten lived locally within the city limits and five lived remotely. A third of the participants were male (5 vs. 10 females). The age ranges of participants and their respective counts were 20-25 (6), 25-30 (4), 30 (1), and over 50 (4). Additionally, half of the participants were professionals (8) and the rest were students (graduate: 4, undergraduate: 3).

5.1.2 Procedure

I invited participants for a one-hour interview in either our lab or over Skype, depending on whether they lived locally or remotely. Local participants who used a desktop or mobile personal informatics tool were required to bring a laptop or mobile phone to the interview. I also asked them to bring other materials they used for self-tracking, such as notebooks or devices (*e.g.*, pedometers, blood glucose meter). Remote participants used Skype's Screen Sharing and Video features to show us the personal informatics tools they use.

At the beginning of the interview, I introduced participants to the study. Participants signed the study consent form and completed an online survey that asked about their general personal informatics usage. The questionnaire is a condensed version of the survey described in [Li *et al.* 2010].

I sat with the participants in front of their laptop or mobile phone and asked them to describe their general usage. I observed participants as they used their personal informatics tool(s). I asked them how they reflected on their data and to show us how they reviewed their data: What were they looking for? What questions did they have? Why did they ask these questions? How did they answer their questions using their tools? What problems did they experience while trying to answer their questions?

Participants were compensated $10 (in cash or as Amazon gift certificates) for the one hour they spent with us. The interviews were videotaped.

5.2 Results

We transcribed the interview recordings and analyzed them by coding the responses. We organized the codes into groups to identify themes. Our analysis focused on the reasons people reflected on their data, what questions people were trying to answer when reflecting on their data, how their personal informatics tool supported or prevented finding answers to their questions, and what design features in their personal informatics tools supported this activity.

5.2.1 Participant Information

To help focus our interviews, we asked participants to describe the *primary data* about themselves that they collected [Table 8]. The participants varied in the types of information they collected. The primary data that participants collected were: financial expenditures (3), sleep (3), weight (2), blood glucose level (2), exercise (1), productivity (1), web history (1), books read (1), and life events (1). Half the participants collected one or more types of data. For example, P7, who collected the widest variety of data, used Daytum and your.flowingdata to track television shows and movies that she watched, restaurants she dined at, and places she visited. She recorded her eating habits with DailyBurn. Because of periods of insomnia, she used Fitbit to record her sleep patterns and physical activity levels. She also complemented her sleep tracking by taking notes about the quality of her sleep in YawnLog. There was also a diversity of experiences in self-tracking. Four participants had been self-tracking for a month or two;

seven participants, for a year or two; and three participants, for more than three years. P3 who has diabetes had been tracking her blood glucose level for 15 years.

5.2.2 Reasons

Participants cited different reasons for collecting personal data. Many participants (11 out of 15) self-tracked to reflect on the data, because they wanted to change or maintain a behavior. For example, P1 used Mint to maintain a budget after moving to a new city. P8 tracked her sleep patterns and various factors that might affect the quality of her sleep using the Sleeptracker watch and laptop application. Four participants collected data for other uses. P14 collected his web history with Google Web History for *later retrieval*. P15 collected book information in GoodReads to *share* with other people. P12 recorded his grocery and utility expenditures in Buxfer to easily *coordinate* expenses with his roommates. P10 wrote about life events in online journals to better *remember* her past. These four participants' usage of personal informatics tools is more closely in line with other types of applications (in order): personal information management, social networking, coordination, and reminiscence. In the following section, we focus our discussion on the 11 participants who wanted to change or maintain their behavior,

ID	Primary Data	Multiple Types?	Reason
P1	expenses	No	Behavior Change
P2	weight	Yes	Behavior Change
P3	blood glucose	Was	Behavior Change
P4	exercise	Was	Behavior Change
P5	expenses	Yes	Behavior Change
P6	blood glucose	Was	Behavior Change
P7	sleep	Was	Behavior Change
P8	sleep	Yes	Behavior Change
P9	sleep	Yes	Behavior Change
P10	life events	No	Reminiscence
P11	weight	Was	Behavior Change
P12	expenses	No	Coordination
P13	productivity	No	Behavior Change
P14	web history	No	Retrieval
P15	books	No	Sharing

Table 8. The participants, their primary data, whether they collected multiple types of data, and their reasons for collection.

because personal informatics tools are useful when they help people gain self-knowledge that improves decision-making and assists in behavior change.

5.3 Questions

In this section, we discuss the 6 main questions that people asked about their personal information: *Status*, *History*, *Goals*, *Discrepancies*, *Context*, and *Factors*. We describe in detail what participants were looking for and how they answered their questions.

5.3.1 Status

People were interested in knowing how they were doing right now. For example, P7 checked her Fitbit device several times a day to determine her current physical activity level. Checking one's status doesn't have to happen several times a day; P5 checked her finances using Mint and her bank web site at the end of each day.

People also checked their current status to determine whether they were meeting their current goal and whether they should act to correct their behavior. For example, P7 checked her step count to determine whether she should take more steps. If not, she would go out for a walk. P5 checked her finances to make sure that she is staying within her daily budget. If not, she tried to spend less the following day.

How often people checked their status is dependent on what kind of data they were tracking and how they were tracking it. For example, P3 and P6 have diabetes, and used blood glucose meters to measure their current blood sugar level. P3 wore a sub-dermal blood glucose meter, which measured her blood sugar level every 5 minutes. However, P6 used a pin-prick device, so he could only check 3 to 6 times a day.

For some kinds of data, participants did not use a device to measure their current status; instead, they used their own senses. For example, P9 who was interested in her sleep quality recorded the quality of her sleep and whether leg cramps occurred. P8 used the SleepTracker watch to measure her sleep, but she used her senses to record information related to sleep, such as mood and stress.

5.3.2 History

Beyond looking at one's current status, participants were also interested in seeing their data over the long term. Instead of looking at one piece of data or a short time's worth of data (an hour to a day), people wanted to see their data over a long range to find trends and patterns. Trends (whether the data is going up, going down, or remaining steady) are especially important to figure out whether they are making progress towards a particular goal. For example, P4 looked for trends in her physical activity data to make sure that she was maintaining her goal of regular physical activity over a long period of time. P5 also looked at trends to make sure that she was reducing her monthly expenditures to save for a trip abroad.

People experienced different kinds of problems in understanding their history. One problem is that the ability to see trends and patterns largely depends on having collected data over a long period of time. Thus, the person has to first put in the effort of collecting data before the value of the data becomes evident. For example, P5 started using Mint when her mom introduced her to the site. She could not make any significant conclusions regarding her spending trends because she had only been collecting data for a month prior to the interview.

Another problem is that tools do not provide adequate support to allow reflection over the long term. P8 experienced this problem with the SleepTracker watch, which she had been using for several months. The watch had a desktop interface to review her past history. However, the software just listed her sleep quantity on a spreadsheet-like interface, which made it difficult to see trends. She said a simple bar graph would have been helpful.

A related question is: *how does data from one time range compare with another?* Viewing one's data over a long period of time allows the person to answer this question. For example, P1 compared her spending between two different months. She was particularly interested in seeing how her recent move affected her spending.

5.3.3 Goal

In addition to wanting to know their status and their history, people also wanted to figure out what goals would be appropriate to pursue. Sometimes, people started self-tracking without knowing their goal and they used self-tracking as way to 1) determine what actions they should take to fix a problem or 2) establish a "baseline" of their activities to determine whether they have a problem.

Before we go into detail about this question, we need to define what kind of goals we are talking about, because the distinction between the different kinds of goals is important. Powers [1973] described goals as a hierarchical structure ranging from abstract to more specific. The four levels are *system concept*, *principle*, *program*, and *sequence*. The *system-concept goal* refers to the sense of an idealized self, an idealized relationship, or an idealized society, and, as such, is very abstract. The next level of goals is the *principle level*, which refers to the set of goals (or guiding principles) that one tries to achieve to reach an ideal. Some examples of principle-level goals are: be physically fit, be thrifty, and be productive. This level is still quite abstract; a person does not just become physically fit or thrifty or productive, one has to exhibit such qualities by doing specific activities or *programs* [Schank & Abelson 1977]. Some example of *program-level goals* are: 1) running three times a week to become physically fit; 2) spending money within a budget to become thrifty; and 3) minimizing the amount of time spent browsing social media websites to become productive. To perform a program-level goal, a person does *sequences* of specific actions. For example, the *sequence-level goals* to complete the goal of running three times a week may consist of putting on shoes, going outside, running a specified route, *etc.*

In the rest of this chapter, we are talking about "program-level goals" when we refer to "goals". Program-level goals are more specific than principle- or system-concept level goals, so they are more actionable or more ready to be acted upon. We found that people use personal informatics tools to help them set and complete program-level goals. For example, P4 used SparkPeople because she wanted to become physically fit (principle-level goal), but the value of the tool was in helping her track her progress in accomplishing her program-level goals: running three times per week and eating within a specified amount of calories.

Knowing one's goals had an effect on the number of kinds of data the participants collected. For example, P9 had problems sleeping because of her leg cramps. She wanted to address the problem to improve her sleep (principle-level goal), but she did not know what caused her leg cramps. She tracked what she ate and her physical activity to see if these were causing the leg cramps, so she could make program-level goals, such as "avoid X kind of food" or "don't do physical activity X hours before sleeping."

Once participants identified their program-level goals, they changed their data collection habits. For example, when P3 was diagnosed with diabetes, she did not know the appropriate program-level goals to manage her diabetes, such as what specific foods to avoid, how active she could be, *etc*. To figure out her goals, she collected multiple kinds of data: what she ate, what physical activity she did, as well as her blood sugar level. She is a "brittle diabetic" (her blood sugar fluctuates to dangerous levels quickly), so figuring out the effects of food and physical activity was critical, but difficult to do. She did this for two years until she understood her blood sugar fluctuations better and she was able to set appropriate food and physical activity goals. When this happened, she stopped collecting the other pieces of data because she already knew their effects. She still tracks her blood sugar level, but she just takes mental notes of the meal, physical activity, and sleep quality prior to her blood sugar level measurement.

5.3.4 Discrepancies

Once people know their goal, they compare their current status with their goal [Carver & Scheier 2001]. We also observed this in our interviews. Participants checked their current status then compared it with their goal: Is there a difference between my current status and my goal? How big is the difference? And what should I do to reduce the difference? For example, P4 wanted to become more physically active, so she set a goal of exercising every other day or about three times a week. She looked at her weekly physical activity using SparkPeople. She checked whether she reached her three-times-a-week goal and how much her current status differed from the goal. When she found a difference, she modified her schedule to compensate for her missed physical activity. Also, how participants addressed discrepancies changed over time. At the beginning, P4 was very strict at meeting her goals, so she immediately addressed missing her goal by exercising the same day. A year after her physical activity tracking she became less strict about meeting her goal. She allowed herself to miss days, and instead of exercising immediately, she postponed physical activity until the end of the week when she had more time.

Another example is P11 who compared her daily food consumption with a range of calories, a goal that she had set in the DailyPlate tool. Every day she checked whether she was within the range of her allotted daily consumption. When her consumption was below her goal, she increased her consumption for that day. If she was within range, she made sure that she did not go over. Both P4 and P11 found that comparing their current status with their goal helped them make immediate decisions to address any differences. If they were meeting their goal, they could focus on maintaining it.

A problem with this question is that it is largely dependent on knowing what the program-level goal is. If the goal is undefined, the person cannot act on fixing their problem. This is what happened with P9. She knew her principle-level goal: fix her leg cramps when she goes to sleep. Unfortunately, she did not understand the causes of her leg cramps well enough to set appropriate program-level goals, such as avoiding certain foods or certain physical activity.

5.3.5 Context

Participants also wondered what other things were happening at or near the same time as their current information-seeking context. They were curious about how other events may explain what was happening to them *in the present*. For example, P3 kept in mind other events at or near the time she checked her blood sugar level (*e.g.*, what she ate, what physical activity she did), so she could act on problems appropriately. P6 noted his current mood and stress level along with his blood sugar level. He thought that his blood sugar level might explain how he was feeling.

How participants answered this question was dependent on their access to additional data. Some people depended on other devices. For example, P6 used Fitbit and Zeo to automatically record his physical activity and sleep quality. He used the data from these devices to figure out the relationship of his physical activity and sleep with his blood sugar level. Some people used written notes (on paper or a web site) to remind themselves of other events that happened at a particular time. P8 used the annotation feature in the SleepTracker software to record her mood, stress level, and caffeine intake, which may be related to her sleep quality. P5 kept a journal of her activities to remind her of what she did when she spent her money. Sometimes, people just depended on their memory to remind them of what happened. For example, P4 diligently recorded her data at the start of her self-tracking, but after a while she just used her memory. She explained, "I just depend on my memory…I didn't want to become, like, OCD (obsessive-compulsive) about it." However, one problem with dependence on memory is that one's memory of events can be unreliable and degrades over time.

5.3.6 Factors

Unlike the previous question, which asks what influences a person's current status, this question asks what influences behavior over a long period of time. Factors collected over time help to identify and monitor trends. For example, P4 was curious how her physical activity and nutrition affected her overall health over a long period of time.

Participants were interested in how other factors may be affecting their behavior. For example, it is not sufficient to say that one wants to lose weight; it is important to know how one's physical activity level and food consumption affect one's weight. By knowing the factors, people can act on those factors to change their behavior. This is especially important when other things could cause the behavior. For example, P2 was interested in losing weight. To help her accomplish this goal, she tracked several types of information in addition to her weight: exercises she did, what she ate, total calories, and water drank. She used the CalorieTracker Android app to help her compute the calories of her food and DailyPlate to store all the data online. She used the DailyPlate graphs and charts to see the trends in her weight and how they were affected by other factors. When her weight went up, she reduced her food intake and increased her physical activity. She also made sure that her weight went down at a “healthy rate of decline”, so that she lost weight in a healthy way. P2 also wrote in a journal to record her goals and how she felt about her progress. She said, “I look for things that I have done well. Places where I might have made a misstep, either I’ve done too much exercise in one day or I’ve done too little. Or maybe I didn’t meet all of my exchanges or maybe I met all of my exchanges, calorie-wise.”

One problem that participants experienced in answering this question is that a tool did not exist that could help them explore their data holistically. Instead, they had to look at their data one at a time. Even when data was stored in the same tool, they had to look at different graphs separately (*e.g.*, Daytum). Using different tools for different types of data exacerbated this problem. For example, P6 used Fitbit for physical activity and Zeo for sleep and there was not an easy way to look at these data together. P7 used Fitbit for both sleep and physical activity tracking, so she was able to explore both her sleep and physical activity data together. However, she also collected other types of data using Daytum and your.flowingdata, which she could not easily review along with her Fitbit data.

With some difficulty and inconveniences, some participants managed to explore their data together using paper graphs (P9 and P6) or by painstakingly reviewing logs of their data (P2 and P8). However, participants experienced other setbacks: exploring multiple types of data was confusing and understanding the influences of the factors on their behavior was difficult.

5.4 Phases

We noticed that participants asked some questions more often than others at different times. We analyzed our data further by looking at when participants asked certain questions. We identified two distinct phases when participants asked different sets of questions: Maintenance and Discovery. We also found that participants did not remain in one phase; instead they transitioned between the two. We discuss the properties of each phase and the transitions between the phases in the next sections.

5.4.1 Maintenance Phase

The Maintenance phase is marked with participants mostly asking *Status* and *Discrepancy* questions. In this phase, participants used their collected data to maintain awareness of their status relative to a goal and to maintain their behavior. When in the Maintenance phase, participants can be characterized in the following way: 1) they already knew the goal they were trying to meet and 2) they have identified how different factors affected their behavior. We describe each of these characteristics below.

Participants in the Maintenance phase have already identified their program-level goals. In this phase, they self-track to determine whether their current actions are in line with their goals. P13 wanted to be more productive (principle-level goal), and had already determined his program-level goal: limit his visits to social media websites to 20 minutes a day. While his StayFocusd Chrome browser extension stored his total web site visit times over a week and a month, he did not look at those numbers; he just needed the tool to alert him when he went above his goal. P1 used Mint to keep track of her expenditures to make sure that she is meeting several budgets that she had already set for various categories of expenditures (program-level goals). When she showed us her Mint account, she had set budgets for 14 categories!

Also, participants in the Maintenance phase already knew the relationships between their behavior and factors that affect their behavior. They collected information about their behavior; they did not collect other types of data that might affect their behavior because they were not useful anymore. For example, P13 just tracked the minutes that he spent on Facebook, Twitter, and other social media sites, because he already knew how browsing such web sites affected his productivity. He did not track other factors that might affect his productivity (*e.g.*, sleep quality, interruptions). P1 did not use the exploratory tools within Mint to see how much she had spent on different categories and what she purchased. Instead, she primarily used the main screen where her budget was prominently displayed to check whether she was within her monthly budget.

During the Maintenance phase, participants only tracked one or a few types of data. They have already defined their goal and were collecting just enough information that would allow them to tell whether they were meeting their goal. For example, P1 and P5 only reflected on their expenses and P13, on his productivity.

5.4.2 Discovery Phase

The Discovery phase is marked with participants mostly asking *History*, *Goals*, *Context*, and *Factors* questions. When in the Discovery phase, participants can be characterized in the following way: 1) they did not know the goal they were trying to meet and/or 2) they have not identified the factors that influenced their behavior. We describe each of these characteristics below.

Participants in the Discovery phase were still trying to figure out what their program-level goals were. When P3 was newly diagnosed with diabetes, she knew that she had to manage her blood sugar level (principle-level goal), but she did not know specifically what kinds of foods to avoid or how much physical activity she could perform (program-level goals). P8 tracked the quality of her sleep so that she feels better rested (principle-level goal). She explored her sleep data to "spot trends for which I can take corrective action." She wanted to figure out the specific program-level goals that would improve her sleep quality, such as eating dinner earlier or refraining from coffee or alcohol. She also added that she was "trying to take a long-term view", so that the solution is "not a quick-fix approach."

Also, participants in the Discovery phase did not know how different factors affected their behavior. Because of this lack of knowledge, participants collected different types of data, so they could figure out the correlations between them. P3 tracked food consumption and physical activity along with her blood glucose levels because she wanted to figure out how her eating and exercise habits affected the fluctuations in her blood glucose level. P9 had leg cramps while sleeping. She had several hypotheses about what caused her leg cramps. She talked to her doctor who said the leg cramps might be due to an electrolyte imbalance, so she tracked the types of food she ate. She also used FitBit to see if her amount of physical activity had an effect on the occurrence of her leg cramps.

5.4.3 Transitions Between Phases

We found in our interviews that people did not stay in one phase; instead, they transitioned between the two phases. Several participants who were in the Maintenance phase at the time of the interviews were in the Discovery phase earlier in their self-tracking regimen. P6 initially tracked his blood sugar level, his food consumption, and mood until he found that "it turns out one of the things I do to manage stress is eat something, because blood sugar feels good. So if things are unsettled or high pressure, eating something feels good." P6 described his transition to gaining control of his diabetes, "In the initial phase, three and a half years ago, over about six months, I learned to control my blood sugar down to a level from 300 to about 180. Then I escaped there and measurement became less interesting because there was no progress to be made; it was steady state stuff."

P3 had a similar experience in dealing with her diabetes. She said, "When I first became diabetic, I needed to keep track of everything. At this point in my life, I've had diabetes for about 15 years, and I no longer write anything down." Now, she just wears a continuous blood glucose monitoring device to alert her whether her blood glucose is too high or too low. Her reason for transitioning was two-fold: 1) tracking all the information "would be onerous" and 2) "it wasn't helping me anymore. I was remembering. Not the exact numbers, but I was remembering trends."

P4 tracked her physical activity and food consumption diligently at the beginning, but became more lax later and did not track her food consumption. She said, "I feel like I have a handle on it. I have accomplished the goals of creating a healthy lifestyle for myself. As long as I stay like this I'm good. It's more maintenance." She still kept track of her physical activity, but for her food tracking, she just "keeps a mental note of it and just overall have become more self aware of what I eat and stuff."

Sometimes people have difficulty transitioning to the Maintenance phase because they could not find an actionable goal. P9 described that she still did not know what caused the leg cramps when she sleeps. She said, "They're not completely gone, but they're not as bad as they were. But I still don't know exactly what's caused them." She added that she still recorded the recurrence of the leg cramps, “It may always be sort of a mystery, and so I still have data for every night I’ve had leg cramps.”

All the participants who were in the Maintenance phase at the time of the study described anecdotes when they might go back to the Discovery phase. For example, while looking at her budget, P1 saw that she made a purchase of $24 for a gift and she asked herself, “What was that?” She said since she did not remember, she explored her data to find an explanation. Since Mint provided enough detail about her purchases, she easily found that the gifts were bought at a local mall, which reminded her that she recently purchased a gift for a friend there. Sometimes the explanatory data was not immediately available, so the participant had to restart data collection of influencing factors. For example, P7 who had recurrent insomnia tracked her sleep using FitBit. Patterns of insomnia or weird dreams would appear intermittently and she would again note factors that may have caused the problem.

5.5 Features

We have identified the questions that people asked and the phases in which people asked these different questions. Now, we discuss the features that should be supported in building personal informatics tools and how Ubicomp technologies can help. We also describe opportunities for Ubicomp to explore.

5.5.1 Supporting the Maintenance Phase

Supporting the Maintenance Phase is not as difficult as the Discovery phase because many personal informatics tools already support collecting the user’s current status. Additionally, if a Ubicomp technology can sense simple things about a user’s behavior, it is not difficult to display the information back to the user. However, there are some opportunities to better support the Maintenance phase.

5.5.1.1 Alert the user when they are not meeting their goal

During the Maintenance phase, people are not as interested in the details of their data. They have fixed their problem or already know how to fix their problem. When the user has fixed their problem, a constant reminder that they are performing well could become bothersome. Instead, tools should allow users to have control of when they want to look at their data. If the user already knows how to fix their problem, but has not fixed it, feedback about the progress towards goals has been shown to have a positive effect on self-efficacy and achievement [Schunk & Swartz 1993].

If the user is not meeting their goal, it is important that the user is alerted. Ubicomp technologies can help here in identifying whether the user is meeting their goal or not. Because alerts can sometimes be unwelcome, Ubicomp technologies, such as just-in-time feedback demonstrated by the Context-Aware Experience Sampling Tool [Intille *et al.* 2003], can help determine the opportune time to alert the user of discrepancies.

5.5.1.2 Assist the user when they don't meet their goal

When the user does not meet their goal, the personal informatics tool can be proactive in assisting the user in resolving the problem. One idea is to analyze the user's history to create suggestions for resolution. For example, an automated analysis can reveal the causes of the problem. The tool can say "when you drink coffee at 6pm, you have a hard time sleeping, so avoid drinking coffee at 6pm". Automated analysis can also remind users of what they did before to resolve the problem. For example, "last time when you weren't being active you were sitting on the couch watching TV. During the other times you were active, you decided to walk your dog around the neighborhood."

5.5.2 Supporting the Discovery Phase

There are many opportunities for support in the Discovery phase because 1) there are many questions that are asked during this phase; 2) some questions require data collected over a long time; and 3) some questions can be answered using multiple types of data.

5.5.2.1 Collect data anytime, anywhere, and often

Ubicomp technologies can help people collect more data about themselves. One of the entry barriers to personal informatics is the burden associated with collecting data everyday over a long period of time [Li *et al.* 2010]. Automated data capture as exemplified by many Ubicomp technologies (*e.g.*, [Abowd & Mynatt 2000; Gemmell *et* *al.* 2006]) can reduce this burden by automating the data collection and storing large amounts of data about the user.

There is a caveat about user involvement in reflection that is important. In the Discovery phase, user involvement is critical. People want to discover the relationships between data. Automation can diminish users' engagement with their data. This does not mean that automation should not be supported. It just means that automation should be balanced with ways to keep users engaged with their data. One way to do this is to force users to interact with their data daily, either by sending reports or alerts. On the other hand, user involvement in the Maintenance phase is not as critical. Users are just trying to maintain their behavior. Telling people that they are doing well can become annoying. Instead, the Ubicomp tool should be there to notify the user if anything unusual happens.

5.5.2.2 Support different kinds of collection tools

Most personal informatics tools only support collection of one or a few types of data. However, many participants wanted to collect multiple types of data during the Discovery phase. One thing to do is to wait for an "ultimate" data collection tool that can collect any kind of the data that a user wants to collect. However, this might just be a pipe dream or could be too far off into the future. More realistically, users should be allowed to use different kinds of collection tools, and then a system or a service can help users integrate data from the different collection tools. There is a proliferation of APIs available, and we can take advantage of this. Recently, Fitbit and Zeo partnered with RunKeeper to share data with each other. This is a good development because people can now use different tools to collect data. However, this is still incomplete because there is a plethora of tools that are not interoperable. Interoperability of devices has been part of Ubicomp since Weiser started the field [Weiser 1991], so the expertise exists in Ubicomp to help develop and establish standards for interoperation between self-tracking devices and systems.

5.5.2.3 Data should be presented together

This is a corollary of the last feature. One of the many complaints that people had while answering their questions is that they had to go to different applications/web sites to answer their questions. They wished that they could explore their data in a single interface. Existing personal informatics tools and Ubicomp tools currently do not support this. If they do, they do so in a limited fashion, only supporting a few tools. Again, Ubicomp technologies can help here. There has been plenty of research in Ubicomp on how to integrate data together [Freeman & Gelernter 1996; Gemmell *et al.* 2006]. The technology is already available to help people collect and see their data from multiple sources at once.

5.5.2.4 Reduce the upfront cost of data collection

The relevance paradox is a problem that occurs when people do not collect data that they do not find important, but when they realize the data is important, they do not have the data they need [Andrews 1984]. This is also relevant to personal informatics. Often people do not decide to self-track because the data is not important to them. However, when the data becomes important (*e.g.*, they get sick or they want to develop new habits) they do not have the necessary data to start reflecting immediately. Thus, they have to invest plenty of upfront cost to bootstrap their data collection. One solution is to support lifelong data collection of multiple types of data, just in case, the data becomes relevant for self-reflection. There is already a lot of effort in Ubicomp research to support lifelong data collection [Gemmell *et al.* 2006; Hodges *et al.* 2006]. Once the user needs the data, Ubicomp tools can provide the necessary data for the user to figure out what their goal should be or what factors are influencing their behavior.

5.5.3 Supporting Transitions between Phases

Since people transition between the two phases, personal informatics tools should not be designed for just one phase, but should be flexible to support both. This is important because it prevents a potential problem with any personal informatics tool: people may stop using the tool because their information needs are not appropriately supported.

5.5.3.1 Identify which phase the user is in

Personal informatics tools should identify what phase the user is in and change its reflection features appropriately. Without this support, people might find the tool useless because of too little information during the Discovery phase, or people may be burdened with too much information during the Maintenance phase. It is an interesting Ubicomp research challenge to automatically determine what phase the user is in, based on sensed data.

5.5.3.2 Help users transition from Discovery to Maintenance quickly

The Discovery phase is data intensive and can be burdensome to users. Personal informatics tools should help users who are in the Discovery phase to identify program-level goals and how different factors affect their behavior, so users can transition quickly to the Maintenance phase. This would be interesting future work to explore how Ubicomp technologies help users understand their data.

5.5.3.3 Continuous data collection throughout the phases

The amount of data that users need decreases when users transition from the Discovery phase to the Maintenance phase. However, this does not mean that tools should collect less data during the Maintenance phase. Instead, only the amount of data presented to the user should decrease. We suggest tools should continue collecting as much data in the Maintenance phase as during the Discovery phase. This ensures that if a user who is in the Maintenance has to transition to the Discovery phase because of a new problem, the user can immediately reflect on her data.

5.6 Discussion

This chapter explores the different questions that people ask about their data and why they ask these questions. We identified six types of questions: *Status*, *History*, *Goals*, *Discrepancies*, *Context*, and *Factors*. We discuss how people answered these questions using existing tools and the problems that they encountered. Identifying these questions is important because they require different answers and different kinds of data, which have implications on how tools should support them. Ubicomp technologies play a big role in addressing these needs because what data is collected and how data is collected affect how people reflect on their data.

We also discovered that these questions are not asked at the same time. We identified two distinct phases in which people ask certain questions more often than others: Discovery and Maintenance. The distinction between the phases is important because it highlights the need for personal informatics tools to support different information needs, and to be better tailored to users' current needs, instead of providing them all the tools to answer all six questions at once (when they do not need all of them). Additionally, the phases are not static; people's information needs change. They transition from Discovery to Maintenance, and vice versa. Again, Ubicomp can play a big role here supporting the different information demands of the two phases and the transitions between them.

Though we did not conduct a controlled study to observe how the questions differ between the phases because it is out of the scope of this research, the identification of the questions and the phases is an important first step towards the development of future controlled studies. For example, we could create visualizations for each of the questions then observe whether people use certain visualizations more often than others based on what phase they are in. We expect that people in the Discovery phase will heavily use visualizations that answer *History*, *Goals*, *Context*, and *Factors* questions, while people who are in the Maintenance phase will use visualizations that answer *Status* and *Discrepancy* questions.

5.7 Conclusions

Current personal informatics tools are not designed with a sufficient understanding of users' self-reflection needs. This study explored what kinds of questions people ask about their behavior. In this way, the study makes a general contribution to personal informatics systems. Specific to the thesis, this study suggests when and how contextual information could be important in answering people's questions about their behavior. Additionally, this study suggests that people do not need to see contextual information all the time, but it is important during the Discovery phase. This study is important because designers and developers can better tailor their personal informatics systems to the needs of users. I identified six kinds of questions that people ask in varying frequency between two phases. I presented features that should be supported by personal informatics tools to help people reflect better on their data and discussed ways that technology can provide the necessary support. In the following chapters, I describe the specific visualization features that should be supported to help people understand their data when they are exploring and reflecting on their data.

Chapter 6
Visualization Features to Help Associate Behavior with Contextual Information

In the previous chapters, I showed that there is value in supporting reflection on contextual information for physical activity. My subsequent research showed that people want to be able to reflect on multiple types of data together and that this is especially important during the *Discovery* phase of reflection. In the following chapters, I focus on the specific features necessary to better support reflection on multiple types of data together. As a first step towards this goal, I conducted a study to determine the specific visualization features that people need to explore multiple types of data together. In the study, I sketched prototypes of different kinds of visualizations. I presented the visualizations to users and asked them questions about their thoughts about the different visualizations.

In the following sections, I describe the sketches of different types of visualizations to support the two phases of reflection: *Discovery* and *Maintenance*. I validated the designs with participants from the study described in the previous chapter.

6.1 Sketches

I sketched five different types of visualizations (Figure 2, Rows 1-5): timeline, single-value displays, progress bars, pie charts, and information art. These visualizations differ in how much data and the level of detail they can show.

Timelines. Timelines are used to display time-based data, showing multiple data points over time. With these graphs, the x-axis unit is time and the y-axis unit is the type of data that the user had recorded (e.g., step counts, blood sugar level). In the sketches (Figure 2, Row 1), the timelines have blue lines; the area underneath the lines is shaded with light blue.

Single-value displays. These types of displays show a value at a particular point in time (e.g., a person's current temperature or heart rate) or an aggregate value (e.g., today's step counts or hours worked). Because these displays are compact, they are often used to give user's real-time feedback about their current status. In the sketches (Figure 2, Row 2), the single-value displays have a simple square display with space for a few numbers. These sketches are representative of what may be seen on pedometers or simple blood glucose meters.

Progress bars. These types of visualizations are similar to the single-value displays, but they show single data points relative to goal value. These visualizations show the user's progress towards the goal (e.g., how much they have done, as well, as how far they have to go to reach the goal). In the sketches (Figure 2, Row 3), the progress bars are simple gray bars representing the overall goal value with an overlapping blue bar representing the current progress towards the goal.

Pie charts. These types of visualizations show multiple data points. Unlike the timeline visualizations, the data points are not organized by time, but by categories. The circle represents a whole (or 100%), each data point represents a part of the whole (or a percentage). In the sketches (Figure 2, Row 4), the pie chart is represented with a simple round circle with a few slices, which represent the categories. The category that the user is interested in is highlighted with an orange color.

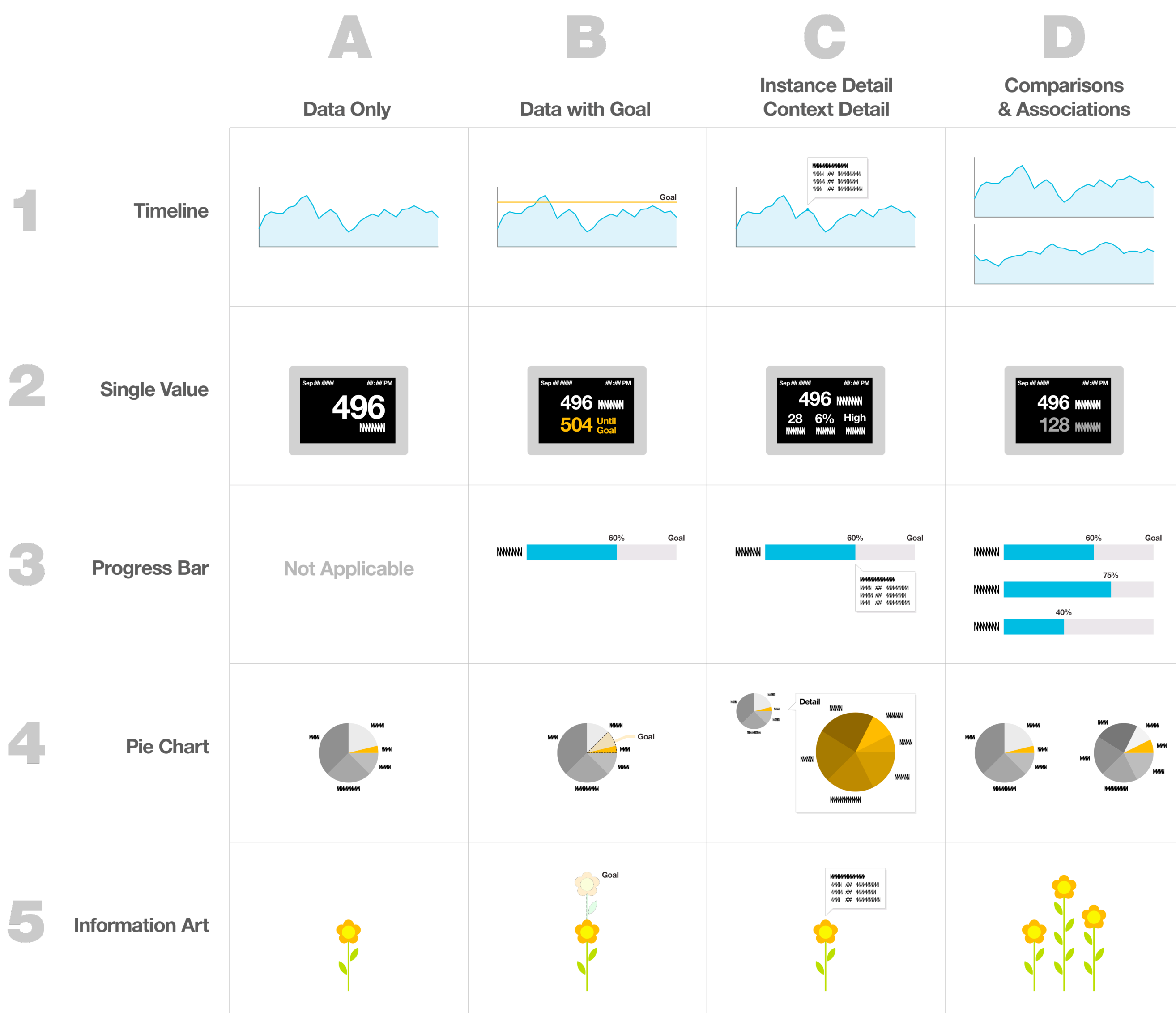

Figure 8. Sketches of designs to support reflection. The rows 1-5 are different types of visualizations. The columns A-D are permutations of the visualization types.

Information art displays. Information art displays are aesthetically pleasing, abstract displays that show data points in pictorial form [Holmquist & Skog 2003, Consolvo *et al.* 2008, Miller & Stasko 2002]. In the sketches (Figure 2, Row 5), the information art display is represented with a yellow flower reminiscent of the flower display in the UbiFit project [Consolvo *et al.* 2008] and Fitbit device.

6.2 Sketch Permutations

I sketched different permutations of the visualization types by adding and customizing the properties of the visualizations. The properties include goal information (Figure 8, Column B), multi-faceted reflection using instance/context detail (Figure 8, Column C), and features for comparing and associating different types of data (Figure 8, Column D).

6.2.1 Goal Information

- For the timeline sketch, the goal information took the form of a horizontal line on the timeline. For example, if the timeline represented blood glucose level, the goal line might represent the maximum level for which blood sugar level is dangerously high.
- For the single-value display, the goal information was represented as another value adjacent to the current status value. In this case, the value was the amount needed to reach the goal. For example, if the display showed the user's current step counts, the goal value is the number of steps needed to reach the user's goal.
- No modification was needed for progress bar visualization because goal information is an inherent part of progress bars.
- For the pie chart display, the goal information was represented as a pie slice delineated by dashed lines.

6.2.2 Instance/Context Detail

Instance/context detail refers to additional data about a piece of single data point. For example, a display about step counts with instance/context detail will show the person's total step counts along with speed information, heart rate, and location information.

In four types of visualizations (timeline, progress bar, pie chart and information art), instance/context detail is implemented as a popup that would appear above a data point where the user's mouse is hovering. The popup shows details about the data point, such as the value of the data point and associated context. For example, if the timeline shows the user's step counts, the popup might show the user's step counts for a particular range of time including what she was doing, where she was, and whom she was with.

In the single-value visualization, instance/context detail is implemented as additional numerical value on the display. For example, if the single value display is showing step count information, the display might include extra values for mileage, ambient temperature, heart rate, *etc.*

6.2.3 Comparisons and Associations

Support for comparison and association allows users to compare their data with another set of data at another point in time or from another category. In the sketches, this feature was supported by duplicating the visualizations to allow users to compare between them. For example, a timeline might show a person's weight over time stacked on top of a person's timeline of step counts.

6.2.4 Summary Notes

For the timeline visualization, I added a sketch of a timeline with a textbox where users can write summary notes. I added this, so that users can have a place to store their thoughts after reflecting on their timelines.

6.3 Method

All the participants (except for P1) from the study described in the previous chapter returned for this interview. During the interview, I described two scenarios to the participants, showing the different design sketches (described above) that they could use for reflection. We asked users various questions about the designs. This interview was also videotaped.

6.3.1 Scenarios

The two scenarios were based on typical situations for the Discovery and Maintenance phases. In the Discovery scenario, participants were asked to imagine that they did not know the goal or standard they were trying to meet and they did not know the factors that were affecting their behavior. For this scenario, the set of displays shown to participants was the Timeline sketches (1A-1D in Figure 8). The reason for this is that the Timeline sketches were more suitable to answer the kinds of questions that were more important during the Discovery phase: *History*, *Goals*, *Context*, and *Factors*. For example, timelines (Sketch 1A in Figure 8) can provide the necessary data about the past to answer questions about *History*. The timeline with the goal line (Sketch 1B in Figure 8) can be used to answer *Goal* types of questions. Questions about *Context* and *Factors* can be answered by showing other kinds of information about a particular instance (Sketch 1C in Figure 8) and by having multiple visualizations together that can be compared (Sketch 1D in Figure 8). After showing the initial set and asking them if the solution is sufficient, participants were asked to select features from the whole grid that they thought would be useful.

In the Maintenance scenario, participants were asked to imagine that they already knew their goals and the factors that affect their behavior. For this scenario, I first showed the set of Single Value sketches (2A-2D in Figure 8). The reason for this is that the Single Value displays provide the necessary data to answer the kinds of questions that were more important during the Maintenance phase: *Status* and *Discrepancy*. Unlike the timeline visualizations, the single value displays help users answer Status and Discrepancy questions without overwhelming users with too much data. I also showed users the Progress Bar and Information Art sketches, because they are similar to the Single Value sketches that they display a reduced amount of data.

6.4 Discovery Phase Scenario Results

Participants generally agreed that the timeline views were appropriate for the Discovery phase scenario. The following are the reasons that participants provided:

6.4.1 Looking Back in Time

Participants appreciated the ability to look back in time using the timeline visualizations. Reflecting on the past is useful for reviewing behavioral data, for establishing a baseline, and for finding trends. P2 said it would be good for "weekend review" to see a timeline of her exercise and diet for the week. P4 explained that looking back in time allowed her to establish a baseline of her physical activity and allowed her to compare her physical activity between weeks. P9 said that being able to see trends in one's data could be helpful in addressing any correlating with other data points. In her example, if her mood started going "south", she could correlate her mood with the weather. If she only had one data point for either mood or the weather, she would not know be able to make that correlation.

6.4.2 Seeing Details to Reason What Happened

Participants liked the ability to see more detail about a particular point in time using the timeline visualization with instance/context detail (Sketch 1C in Figure 8). This feature is useful for seeing details of what happened around that the same time as a particular data point. P7 described this sketch as the "rollover one" because detail information appears by rolling over on a data point. She said, "I like the rollover one, so that you can just see details." P11 further elaborated on the benefit of seeing details. She said, "You can just go on one specific day and then all at once you see your progress, your fitness time, your weight on that day." Another benefit of this feature is that users can start finding reasons why something happened. P4 described an instance when this feature would be helpful, "When looking at exercise, there are couple of times where I really didn't meet my goal, so it will be really nice to be able to say 'why didn't I meet my goal then?'."

Instead of showing single data points of different kinds of data on the popup, P9 suggested showing sparklines [Tufte 2006]. She said, "If on that hover [popup] I had a sparkline graph of the weather, so I could see just very quickly the trend of the weather in addition to the weather that day...I could compare that way."

6.4.3 Comparison of Different Kinds of Data

Participants liked the Comparisons & Associations version of the timeline visualizations (Sketch 1D in Figure 8) because it gave them the ability to compare multiple kinds of data together in one interface. The following are some of the descriptions by participants on how they would use this feature:

- P6 liked this feature because it matched his interest in the relationship between his data. This interest in finding relationships between multiple types of data is common with many users of personal informatics tools as described in Chapter 4). When shown the timeline sketches, he said, "The most interesting things here is the ability to compare two different time frames...because I'm really interested in the relationship between data." He wished there was an application to find relationships between his Zeo (sleep quality tracker) and CPAP machine (sleep apnea tracker). He said, "It's hard to find useful tools to overlay the two [kinds of data] just to see the relationships...If somebody post somewhere online an app that allows you to merge these two data streams to see interesting patterns, I probably could study [the two data streams] a little bit more."
- P2 would use this feature to *find balance* between her diet and physical activity to achieve the right amount of daily calories, which was crucial to her illness. She said, "Because I got sick, I need to track [my diet]. Then as I introduced exercise back into my life, obviously, that takes a toll on total calories, so I needed to see how much I was exercising." By having both types of information, she can find the imbalances. She added, "I just needed the [exercise] time and the calories burned to total that into what I had as an output, so I can see how many calories I needed to add per day."
- P4 described that she tried to find a *cause-and-effect relationship* between her physical activity and food consumption when she first started self-tracking. She said, "It would be interesting for me to see if days I'd exercise more if I naturally eat more too." She added that seeing the cause-and-effect relationship would help her become "more aware of your tendencies to act one way or another."

Some participants offered suggestions on how to improve this sketch. P7 asked for more control of the visualization. She said that the user should "be able to pick" what kinds of data to visualize and should be able to put the visualizations "where you want it to stack". P9 suggested that the visualizations should also overlap and not just stack on top of each other. She explained her suggestion, "I don't know if that would be helpful or not, but it would at least be an interesting view." 

6.4.4 Goal

Participants liked the visualization sketch with the goal line (Sketch 1B in Figure 8). P5 said, "I like having the goal line...I always like being able to see what my base should be and if I am above or below." She added that she has been using this feature in Mint; she likes that she can track her finances daily and check if she was meeting the two budgets that she had set for herself. P11 liked that the goal line makes it easy to see whether the she is meeting her goals; she said, "I like the timeline with the goal...because you can just simply look at it."

P9 suggested that the visualization should highlight and allow commenting on two kinds of spaces on the graph with respect to the goal line: 1) the negative space between the data line and the goal line, which represents the difference between what she did and her goal; and 2) the area above the goal line and under the data line, which represents what she did that exceeded her goals. She explained, "I'm making observations about [my] data...I'm kind of wanting to fill in an annotation about a range of days that are above or below [my] goal."

6.4.5 Writing Summaries

Participants liked the sketch where they can write summaries and notes about their visualizations. Some participants already did this by supplementing their personal informatics tools with a journal or with a note-taking application. For example, P2 wrote in a journal about her mood associated with her exercise and diet. She did this because "the numbers told me what I did, but it didn't tell me how I did [my exercise and diet], or what I was feeling about it. Or if there is an odd day, going back on my journal would tell me why that day was odd.” P9 said she currently uses an application to take notes about her nutrition.

P11 liked this feature, but she pointed out a problem. She said, “To be able to take notes, I do like that, but I don’t think I would use that very much...I just probably won’t remember.” Reminding users to reflect on their visualizations and showing the note-taking fields prominently could resolve this.

P9 provided a suggestion regarding the granularity of the data on which a note can be applied. The sketch that I showed participants had a note-taking field that applies to a complete visualization. P9 suggested that notes should also be applied to individual data points. This would be similar to the Timeline+Detail sketch, but with a note-taking field on the popup.

6.4.6 Progress Bar

I also showed participants the progress bar sketches (Figure 8, Row 3) in the Discovery phase scenario. Some participants liked this sketch because it allowed “see[ing] things at a glance” (P7). However, P7 added that the usefulness of this sketch is dependent on what type and how much data she wants to reflect on. She said, “I guess it depends. Like, if it’s weight loss, you would want a graph, more of a standard timeline or something. But maybe for a daily thing too or a short-term goal, I like the [progress bar].”

On the other hand, some participants still preferred the timeline over the progress bar for the Discovery phase scenario. P11 said, “I just prefer the graph because it’s easier. It seems easier to look at and it’s more about comparison against other days.” She explained, “watching what you eat isn’t just about one day; it’s like a daily thing, you have to compare between days.”

6.5 Maintenance Phase Scenario Results

Participants said the Single Value and Progress Bar sketches are useful for the Maintenance phase scenarios because the sketches made it easier to be aware of one’s current status immediately. P2 said, “A tool like this where I can just quickly see [my current data], like if it was an iPhone or an Android app, would be pretty sweet." I showed P4 the Single Value with Goal sketch (Sketch 2B in Figure 8) and she said, "I think this is a little bit more useful because they have this on SparkPeople...It will give you a weekly progress, but I think you could also set it up to say you have met your goal this week."

P11 noted that the Single Value sketches are more helpful with goal information, such as, the Single Value with Goal sketch and all of the Progress Bar sketches (Sketch 2B and Row 3 in Figure 8). She saw a Single Value sketch and she said, "DailyPlate does that with calories. Like they have something like that with the [current status] and goal. I like that, but it's best when it's in conjunction with the [Progress Bar sketches]." She added that while she liked the Progress Bar sketches, she preferred that they show the actual numerical value instead of percentage values.

P9 explained why the Single Value and Progress Bar sketches were appropriate for the Maintenance phase, "[This type of visualizations] is about compliance and the other one [the timeline visualizations] is about understanding relationships. They're very different in my mind, but what I see here is all very helpful for compliance." This sentiment is consistent with the kinds of questions that are more frequently asked in each of the phases.

P9 suggested that having the previous day's status along with the current day's status would be helpful. She explained by giving an example with mood information, "You know, if it's like my mood is 8, now, I know what my mood is because I just said it, but it would be interesting to see the other [day]'s display."

6.5.1 Timeline is still useful

While participants noted that the Single Value and Progress Bar sketches were useful, some participants felt that the ability to see more detail with timelines was still useful. They would not look at the timeline all the time, but it would be nice for the timeline to be available, in cases, when they need to explore their data in detail. P2 said, "I think I would miss the timeline." She wanted "an option that [the data] is all stored somewhere and I could go to a timeline." But she added that the timeline does not need to be the primary visualization, "I don't need to see it like in front of me."

Another example was P4 who used a heart rate monitor. The device is an example of the Single Value sketches because it allowed her to see how many minutes she has exercised and how many calories she was burning in real time. However, she also tracked her exercise minutes and calories in SparkPeople. She reasoned, "I use [the device] in conjunction with tracking it and being able to see the past as well." She added, "It wouldn't be an awful thing if I stop using SparkPeople...[but] I just like being able to look back and see if I've done well for the past 2 weeks."

6.5.2 Dependent on Type of Data

Participants added that what visualization is shown in real time during the Maintenance phase is dependent on the kind of data that they are collecting. For example, P3 is diabetic and she said that the Single Value sketches would not be helpful in managing her diabetes. She said that she needed to see a timeline (albeit with a shorter time range: 3 hours) to see whether she is within range of healthy blood glucose levels and whether her blood glucose level is trending up or down. Another example is P7 who said that the Information Art sketches with the flower visualization "would be nice." However, she added that the appropriateness of the flower visualizations depends on the type of data, "I guess it depends what simple flowers would [represent]."

6.5.3 Value of the Flower Visualizations

We expected that the flower visualizations were suitable for the Maintenance phase because Information Art visualizations were designed for peripheral awareness information, which are quickly accessed throughout the day and can be helpful or useful even if it is not absolutely critical to the person's current task [Miller & Stasko 2002]. Indeed, many participants said the flower visualizations in the Information Art sketches were useful for the Maintenance phase. P9 found the flower visualization useful and motivating. She said, "It's a great way to very quickly tell where I am and it's also a motivator...like on days that I play racquetball, my flower is as all as it gets...I feel like

I've completed something." However, she added that, "If it will be the only data I could ever see it would not be as useful."

Some participants did not like the flower visualizations because they wanted to use it beyond its intended purpose. For example, some participants wanted to see numerical values which are often left out of Information Art visualizations for glanceability. P11 said, "I definitely like the concrete stuff better when it comes to calories and everything. Just easier with a concrete picture in front of you with numbers than with just looking at a picture without numbers." P4 said that the flower visualizations were not for her because "I'm a number's person...for me, [the flower visualization] would not be useful because there's no number." This problem could easily be resolved by adding numerical values along with the flower visualizations.

Another reason was that some participants felt that the cuteness of the flower visualizations were not appropriate for them. P11 said, "I don't think that will be as helpful for me. It would be something cute, but I don't think that would be for me." P5 said, "It's cute, but I feel that...it is more suited to for my 12-year-old sister. When you are 12 and you see a flower, it's kind of cool, but at 21 you are kind of like 'okay, it's a flower'." However, she added that the flower visualization might be good for teaching kids. The choice of flowers may have been appropriate for the participants of the study, but this could be resolved by finding more appropriate images or by asking the users about their preferences.

6.5.4 Differences between Maintenance and Discovery Phases

Participants described various reasons why the sketches were appropriate for the Maintenance phase.

Timeline is not needed anymore. P13 said, "Since I know my goal now, I don't need [the visualization of] the time I spend." He reasoned that since he had already determined to limit the amount of time he spends in social media sites to 20 minutes, he just needs the personal informatics tool he is using to make sure that he does not go beyond that limit.

He said, "I just need to know where I am within the limits. I just need to be within the limits." He uses the StayFocusd Chrome extension to alert him when he reaches the limit.

Insights from the historical data did not outweigh the burden of collecting data. P3 said, "I was keeping a log and then...I just decided that wasn't that helpful anymore...It wasn't giving me information that I needed." She explained, "I was already seeing trends. I already kind of knew what my trends were that the log was telling me. Probably, it would have been okay to keep [logging], but it's quite a burden to do that."

Details are not important anymore. P4 said, "I felt that all this micromanaging, like [tracking] the extra 20 calories, doesn't matter. I felt I had an overall good idea and I felt I have been able to successfully change my eating habits." She already started looking at the big picture of her health; she said, "Like over a week, one day might be awful, but then if I keep the rest of the 5 pretty good, overall, it would work out."

P8 said, "My ultimate goal is to have a downward trend and cut weight and if that is happening then I feel okay. I'm doing the right thing, so I don't need to pay attention as I would if it was going back up." However, she added that she would need to keep watch of her data to check if she needs to take action.

6.6 Summary

In this chapter, I presented sketches of different visualizations to support reflection in the Discovery and Maintenance phases. I validated the sketches by asking participants about the usefulness of the different sketches in two scenarios (one for the Discovery phase and the other for the Maintenance phase). I described the results of the interviews where I found which visualization features worked and did not work for each of the phase of reflection.

This work gives us a better idea of the specific visualization features that need to be supported to help people within the Discovery phase. As we saw in the last two chapters, the Discovery phase is when people need the ability to reflect on multiple kinds of personal data. This is relevant to the thesis because it informs us of the visualization features that will support people in their exploration of contextual and behavioral information that could lead to better awareness of factors that affect behavior. The lessons from this study would help guide the design of an application that helps people in the Discovery phase.

In the next chapter, I describe the development of a personal informatics dashboard that enables people to reflect on multiple types of personal data in one interface. How do we build a system that has all the necessary features that users need? How do we make it easy to build? And does it work?

Chapter 7
Visualization Integration

The previous chapters showed the value of associating contextual information with physical activity. Additionally, this work demonstrated that this value is not unique to physical activity; self-trackers want the ability to associate contextual information with other types of behavioral information. Furthermore, I found that the association of multiple types of information together is especially useful during the Discovery phase of self-tracking. In the last chapter, I explored sketches of different visualization features to support reflection multiple kinds of data. This chapter describes my implementation of a personal informatics dashboard, which supports the viewing of multiple types of data in a single interface. I discuss the technical problems of developing a personal informatics dashboard, and then I introduce the one solution that I developed called visualization integration. I present my implementation of a personal informatics dashboard using the visualization integration approach called *Innertube*. Finally, I describe the interviews I conducted with participants to validate the usability of the dashboard.

7.1 Why a Personal Informatics Dashboard?

As we saw in the previous chapters, people want to see their data together (Chapter 4) and seeing multiple kinds of data is most useful during the Discovery phase (Chapter 5). A personal informatics dashboard will allow users to view their fragmented data together in one interface. Having the ability to view one's data together has several benefits:

- Users do not have to visit several web sites to view their data, which saves the user time.
- Users can more easily make associations between different kinds of data. For example, a user who collects sleep data with Zeo and physical activity data with Nike+iPod can see how his sleep is affected by his physical activity.

Currently, people's self-tracking data are usually fragmented between different tools. There are several reasons for this: 1) people use different tools for different purposes (*e.g.*, Zeo for sleep, Nike+iPod for physical activity, MoodJam for mood); 2) many self-tracking tools do not share their data with others, so users have to visit multiple web sites or use multiple applications to view their data together; and 3) it is difficult to build a personal informatics dashboard.

According to the previous chapters and, especially, Chapter 6, a personal informatics dashboard should have the following features:

- Allow comparison of data of the same type between two different time ranges.
- Allow comparison between different kinds of data occurring at the same time ranges.
- Allow recording of notes on specific data points and/or ranges of data points.
- Be flexible to support different kinds of data from multiple sources.

There are other ways that people's data could be shown for self-reflection besides a personal informatics dashboard that visualizes the data into one interface. One way is to let users share visualizations with others. ManyEyes is a public web site where people can create and share interactive visualizations to discuss with others [Viegas *et al.* 2007]. While ManyEyes is not strictly for personal informatics, the approach of sharing visualizations can be applied for self-reflection where users discuss their personal data with others. Examples of sharing visualizations of personal data are the personal informatics tools, Mycrocosm [Assogba & Donath 2009] and Grafitter [Li et al. 2009]. While my dissertation focuses on supporting people reflecting alone on their data, sharing of visualizations can be built as a feature of personal informatics dashboards and further explored in future work.

In the next sections, I discuss the problems in developing a personal informatics dashboard that supports the above features. I then propose a solution to these problems and I describe my implementation and validation of the proposed solution.

7.1.1 Building a Personal Informatics Dashboard

One way to create a personal informatics dashboard is to create an all-in-one device that tracks, stores, and visualizes multiple kinds of data. However, such a device currently does not exist. There are so many kinds of data that a user might want to collect that it is currently infeasible for a single device to support all of them. Additionally, such a device will need to allow customization of components, because the combination of types of data that a user might want to collect might not be the same as another user.

While an all-in-one device is currently infeasible to support the tracking, storage, and visualization of different kinds of personal data, there are other ways that systems have supported this need. Below, I provide an overview of the different approaches that current systems have taken. To assist in the description of the different approaches, I introduce the following terminologies: *platforms* and *data sources*. Platforms are systems that provide services to integrate data together by providing ways to enter data, storage, and visualizations. Data sources are the different applications, devices, and web sites that collect data. The different approaches can be classified by two properties. The first property is how the data sources supported by the platform collect data. The data source can collect data *automatically* or *manually*. The second property is whether data from the data sources are *pushed into* or *pulled by* the platform. When data is pushed into the platform, the data source is responsible for sending data to the platform. On the other hand, when data is pulled from the platform, the platform is responsible for downloading data from the data source.

Automatic Collection and Push Platform. This type of platform allows multiple data sources to push data into the platform. These platforms provide an API for the devices/applications to connect and send data, which the platform stores. A consequence of this type of system is that the different devices have to follow the API that the platform provides. An example of this type of platform is Pachube (http://pachube.com). Different type of devices can connect and send data to Pachube. Pachube, in turn, stores the data that the devices send. While Pachube does not provide visualizations to users, it provides an API to retrieve the data to be visualized.

Manual Collection and Push Platform. There are also platforms that allow people to manually input data in one place. These systems also provide storage for user data, but instead of providing devices with an API to send data, these systems provide an interface (a web site or an application) for users to manually input data. Some examples of this type of system are Quantter, Daytum, and The Carrot. All of these systems provide an interface on a web site for users to enter data about themselves. Some interfaces comprise of a simple text field where users have to enter data using a specified format (*e.g.*, "Item : Amount" for Daytum, "# activity : number unit" for Quantter), while some interfaces provide a complete form with different fields depending on the type of data that is being entered (*e.g.*, The Carrot). A consequence of this type of system is that the user has to follow the data input format specified by the system or has to use the interface provided by the system.

Automatic/Manual Collection and Pull Platform. Instead of providing an interface for users to enter data or an API for devices to store data, there are platforms that download data from multiple data sources, such as, devices (*e.g.*, Fitbit and Withings) or web sites (*e.g.*, Google Calendar, Twitter). This type of platform is agnostic to whether the data is automatically or manually collected, because, typically, platforms of this type do not provide the mechanism for collecting data. This type of platform needs to know the different APIs of the different sources to download data. Subsequently, this type of system needs to know the format of the data in order to visualize the data. Examples of this type of systems are Poyozo and Grafitter. Poyozo automatically downloads data from Twitter, Facebook, Last.fm, Foursquare, and other data sources. Grafitter automatically downloads data from Twitter, Delicious, and Blogger. Both Poyozo and Grafitter provide interfaces to visualize personal data.

7.2 Data Integration

The different approaches I presented above are similar in that they are all *data integration* approaches. Regardless of how the data source collects data (manually or automatically) or how the platform gets the data from the data sources (push or pull), they all involve getting the data into a central place, so that visualizations can be generated. Some examples of personal informatics dashboards that take this approach are: Google Health (http://google.com/health/), Microsoft HealthVault, RunKeeper (http://runkeeper.com/), GravityEight (http://gravityeight.com/), Fitbit (http://fitbit.com/), and The Locker Project (http://thelockerproject.org/). However, the data integration approach presents several problems for personal informatics dashboards.

7.2.1 Accessing Data

These personal informatics dashboards have to know the different data APIs for each of the data source that they integrate, because these download data from multiple sources. This is a problem because there are at least 400 self-tracking tools in existence today. There is also the problem of not having access to an API. Not all personal informatics tools expose their data to external systems via an API. Another aspect of this problem is that these systems have to partner with other data sources to share data. This is a slow process that requires that each company to agree to share their data with others. Cooperating data sources are effectively releasing control of the data they collected. Once the personal informatics dashboard obtains the data, the cooperating data source has no control on how the personal informatics dashboard uses the data. The personal informatics may visualize the information for the time being, but may use the data for other purposes, such as advertising, automation, generating recommendations, *etc.*

7.2.2 Parsing Data

The second problem is that after downloading data from the different sources, personal informatics dashboards have to parse the different formats. One way to make parsing data easier is to have a standard data format. Creating a standard format that supports multiple kinds of data is challenging because it is difficult to predict the types of data people will want to use. As a result, a standard format will need to be flexible in order to support future kinds of data. Additionally, another issue is the adoption of a standard format. There has not been a big push within the personal informatics community to agree upon a standard format. There have been attempts like OMHE and Grafitter, but none of these formats have gained widespread adoption.

Since there is no standard format for the different kinds of data people might collect about themselves, these personal informatics dashboards have to implement parsers for each format. This is a significant problem between different types of behavioral data, such as step counts, types of food consumed, movements during sleep, money spent, *etc*. However, this also remains a problem for sources that contain the same types of behavioral data. For example, there are several personal informatics tools that collect step counts (*e.g.*, Fitbit, Nike+iPod), but each of these tools has a different way of formatting their data.

One notable example of an application that integrates data from a number of sources is Mint. This site can collect and integrate information from multiple banks and credit cards. However, Mint has the benefit that they only have to deal with spending data and there is a standard for that, which banks and credit cards have already agreed upon. Unfortunately, such a standard does not exist yet for the multiple types of data that different self-tracking tools can utilize.

7.2.3 Generating Visualizations

If the personal informatics dashboard is responsible for generating the visualizations, then the generation of the visualizations is centralized. This centralization leads to several problems.

First, the personal informatics dashboard that generates the visualizations must know how to visualize all the different types of data that they are integrating. Additionally, when a new type of data is integrated into the system, the personal informatics dashboard might not know how to generate the appropriate visualization for the new data, thus, there will be a lag between when the data is collected and when the data can be effectively visualized.

Second, the personal informatics dashboard has to recreate visualizations for each data that it integrates. This duplicates the work that different tools have already done. For example, Zeo produces visualizations for their data. Scanadu, another application, downloads data from Zeo and, because it cannot easily access the visualizations from Zeo must build visualizations to display the Zeo data.

Third, even if a personal informatics dashboard has the resources to recreate the visualizations for each data source, the dashboard is not effectively leveraging the expertise of the cooperating systems that act as data sources. These cooperating systems that collected the data may have greater expertise regarding the data; they know the nuances of the data and they may also know how to more appropriately visualize the data. Unfortunately, the personal informatics dashboard has limited ways of leveraging this expertise because the cooperating systems are treated only as sources of data. For example, Zeo has deep expertise in sleep tracking because they created a device that tracks sleep and visualizations of sleep data. A personal informatics dashboard that uses Zeo as a data source does not take advantage of the visualizations that Zeo has created.

Finally, the cooperating data sources risk having their data devalued, because the personal informatics dashboard may not know how to appropriately display the data to users. This could be problematic if the participating system is competing with other systems that collect similar types of data. A personal informatics dashboard may inadvertently favor one device over another because they are not appropriately displaying the data. For example, the BodyMedia SenseWear device and the Fitbit both collect physical activity information. A personal informatics dashboard may only generate visualizations of step counts for data that are coming from both devices. However, the BodyMedia SenseWear device collects other types of data that are lost from just visualizing step counts.

7.3 Visualization Integration

Now, the question is how do we build a personal informatics dashboard but without the disadvantages of the data integration approach? The approach I propose is called *visualization integration*. That is, instead of a central system/application integrating data, the central system/application will integrate visualizations. The personal informatics dashboard that I am building will integrate visualizations together in an interface without having to download raw behavioral data from any different personal informatics tools.

7.3.1 How Does It Work?

The usual approach to integrating visualizations in a personal informatics dashboard has been for a central application/server to 1) download raw data from multiple remote sources, 2) parse the raw data, and 3) generate visualizations of the raw data. The visualization integration approach relieves the central application/server of the responsibility for the three steps. Instead, the central application/server is responsible for the communication between remote visualizations. The approach consists of the following components:

- Widgets are windows/panels that display visualizations. With this method, the widgets can be remote web pages that are hosted separately from the central application/server.
- A dashboard displays the multiple widgets together in one interface. This is the central application/server. The dashboard coordinates the communication between the widgets. Widgets receive messages from the dashboard as to what kind of visualizations to display (e.g., display the visualization of steps for a particular date, display the visualization of locations for the week). Widgets can also send messages to the dashboard (e.g., the type of data currently displayed, the date currently displayed).
- A communication protocol enables the communication between the widgets and the dashboard.

7.3.2 Benefits

In this section, I discuss the benefits of a personal informatics dashboard that uses the visualization integration approach. I will discuss these benefits from the perspective of the dashboard, the individual personal informatics tools, and the user experience.

7.3.2.1 The Dashboard

With visualization integration, the personal informatics dashboard does not download data from cooperating data sources. This avoids the three problems that personal informatics dashboards encounter from accessing data, parsing data, and generating visualizations. In effect, the visualization integration returns these tasks back to the widgets, which has several benefits, as I will discuss in the following section.

Freed from the other responsibilities, the dashboard is now only responsible for integrating and managing the different widgets. The dashboard does this by providing a mechanism for different widgets to communicate with each other. I will show later that this is sufficient to support many of the features that people need to explore multiple kinds of data.

7.3.2.2 Individual Personal Informatics Tools

With the visualization integration approach, individual personal informatics tools are not just mere sources of data. These individual tools must now provide visualizations that can communicate with the dashboard in addition to collecting data. This may seem like adding extra burden on the designers and developers of personal informatics tools, but this configuration has several advantages.

Flexibility and Ease of Development

Visualization integration leverages the fact that most personal informatics tools already create visualizations of data that they collect. Developers and designers of these tools have the privilege to access their data and the expertise to process the data. Visualization integration gives developers the freedom to generate the appropriate visualizations for the data. With some modifications and by using the communication protocol that the dashboard provides, personal informatics tools can transform their visualizations into widgets that can be added into a personal informatics dashboard.

Additionally, the widget for these personal informatics tools can immediately interact with other widgets. This frees up developers of personal informatics tools to focus on what they visualize on the widget instead of focusing on how to integrate with other widgets.

Control of Data

Some personal informatics tools do not provide open data access APIs for other tools to easily access their data. Some reasons for this include security and concerns about losing control of their data to competitors. Because of these concerns, these closed tools prevent users from reflecting on multiple types of data. The visualization integration approach allows visualizations from these personal informatics tools to be integrated without having to provide access to their data to other tools.

Most personal informatics tools create visualizations of their data using Flash and Javascript visualization libraries. These libraries access data from the personal informatics tool via a data access API (designated by a URL). But because of the Same Domain Policy enforced by browsers, the raw data is only accessible to visualizations that are within the same domain name. However, accessing the URL outside of the browser can easily circumvent this restriction. For example, there are unofficial Fitibit APIs programmed in Python[1][2], Ruby[3], and Perl[4] that access data from Fitbit in this manner.

Personal informatics tools that create widgets have options in how they generate visualizations, so that they do not expose their data.

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[1] https://github.com/jplattel/FitBit.py

[2] https://github.com/wadey/python-fitbit

[3] https://github.com/danmayer/ruby-fitbit

[4] https://github.com/ericblue/Perl-FitBit-API

- They can generate images of the visualizations on the server. The problem with using images for visualizations is that images are not interactive.

- The data shown in visualizations could be a subset of the raw data. For example, an application that collects the user's step counts per minute can choose to visualize the data in 10-minute increments. They can further abstract the raw data by creating a visualization of when the user is active or not (where active is measured by whether the number of steps in a 10-minute increment exceeds a particular threshold).

7.3.2.3 Users

The data integration approach is limited by what data sources the dashboard can integrate (that is, data sources it can access, data that it can process and visualize). However, the visualization integration approach can integrate any widget as long as that widget follows the communication protocol of the dashboard. This leads to the following benefits to users:

- *More choices*. The amount of choices that users can integrate into the dashboard is only limited by adoption of the protocol.

- *Flexibility*. Corollary to having more choices, users can choose any combination of widgets that they want to integrate.

7.3.3 Limitations

The visualization integration approach has several limitations, which I describe below. However, these problems can be mitigated, easier to overcome than the problems of data integration, or also a problem that exists with data integration.

7.3.3.1 Graphical Consistency

In order to maximize the utility of the visualizations, it is important to ensure graphical consistency between the different types of widgets. This can be improved by having an interface guideline for developers. This can also be resolved by recommending a particular visualization API. However, a personal informatics dashboard cannot enforce the usage of a particular visualization API. Hopefully, an interface design guideline and the emergence of effective and well-designed visualizations would set standards for developers.

7.3.3.2 Dependence on Developer Participation

A personal informatics dashboard that uses the visualization integration approach is dependent on external developers creating widgets for the dashboard. The personal informatics dashboard will not be as valuable to users without the participation of external developers. However, participation is also a problem with the data integration approach. With the data integration approach, external systems must agree that they are willing to expose their raw data to the personal informatics dashboard. As I discussed earlier, participating in a data integration ecosystem has its difficulties and I believe these problems are more difficult to overcome than participating in a visualization integration ecosystem.

7.3.3.3 Lack of Automatic Correlational Analysis

A personal informatics dashboard that uses visualization integration approach cannot do automatic correlational analysis of data between separate widgets. However, even if you can integrate data together in one place, doing automatic correlational analysis of one's data would still be difficult, because 1) data is sparse; 2) the user would need to collect data over a long period of time; 3) algorithms to do correlational analysis would need to be robust and insightful (I think this is another research project).

7.3.3.4 Support for Data Sources With No Visualizations

The visualization integration approach assumes that the personal informatics tool wants or has the expertise to create visualizations. However, there are some personal informatics tools that only collect data and do not provide visualizations to users. In this case, the dashboard will have to integrate data from these data sources. Thankfully, the visualization integration approach does not preclude data integration. Personal informatics tools can create widgets that provide data instead of visualizations, and then the personal informatics dashboard can provide visualizations for the data or pass the data to other widgets that can visualize the data. Thus, a personal informatics dashboard can support three types of widgets:

- Widgets that show visualizations.
- Widgets that provide data.
- Widgets that can receive data from the personal informatics dashboard and create visualizations.

7.3.3.5 Limited Support for Linking and Brushing

Visualization integration has limited support for *linking and brushing*. Keim [2002] defined linking and brushing as a visualization technique in which "interactive changes made in one visualization are automatically reflected in the other visualizations." Visualization integration can support linking and brushing for data if reflecting interactive changes made in one visualization to the other visualizations only requires data that is shared between widgets. For example, the implementation of a personal informatics dashboard that I will describe later supports sharing of time information (points of time and ranges of time) between widgets. Therefore, it can support linking and brushing where the interactive change only needs time information to be reflected on other visualizations. On the other hand, if an interactive change requires information that cannot be passed between the widgets (*e.g.*, the current implementation does not support passing of other information besides time information), then visualization integration cannot support linking and brushing for those types of information. One problem in circumventing this problem is that the availability of information to share between widgets depends on the willingness of the individual widgets to share their data with other widgets. However, this is also a problem with data integration. The other problem is the amount of time that is needed to transfer data between widgets. If linking and brushing requires a huge set of data, passing the data between all the widgets may be slow. This may be difficult to circumvent because passing information between the widgets happens during the point of interaction.

The limited support for linking and brushing is a sacrifice that visualization integration makes to facilitate reflection on multiple types of data in a personal informatics dashboard. On the other hand, data integration sacrifices the flexibility to integrate multiple types of data sources together in one place for the sake of visualization capabilities. As I discussed, integration of multiple pieces of data is currently difficult with data integration, so visualization integration is an approach that sacrifices some support for visualization techniques in order to easily support reflection on more types of data together. However, as data integration problems are resolved (*e.g.*, new techniques are developed, new standards are created, and new agreements and partnerships are forged between companies, making it easier to integrate multiple data sources), data integration may become a better choice for personal informatics dashboards than visualization integration.

7.4 Innertube

In this section, I will describe *Innertube*, my implementation of a personal informatics dashboard that uses the visualization integration approach. Innertube has three primary components, the Innertube Dashboard, Innertube Widgets, and the Innertube Widgets API, which I will describe in detail in the following sections.

Innertube is implemented using standard web technologies: Javascript, HTML, and CSS. I also use many Javascript libraries, such as: easyXDM (cross-domain messaging), jQuery (DOM manipulation), Backbone.js (Model-View-Controller framework), Underscore.js (utility functions), and Date.js (improved date manipulation).

7.4.1 Dashboard

The *Innertube Dashboard* is the user interface in which users can view their widgets (Figure 9). It has the following features:

- The dashboard can show several widgets at once.
- Widgets are displayed as a stack and users can reorder them.
- Each instance of widget on the dashboard is called an *exploration*. An exploration has information about the widget, the range of data selected, the date selected, and the height of the viewing window.

The Innertube Dashboard allows the following interactions between widgets:

- Comparison of different types of data
- Comparison of the same type of data between different times.
- Comparison of the same time range between different types of data.
- Selection of different granularities (day, week, month, year) to view.
- A time range selected in one widget is propagated to other widgets.

7.4.2 Widgets

Innertube Widgets show visualizations of personal data, such as number of steps, calories consumed, money spent, or sleep quality. I implemented six widgets, which are used in the evaluation study of Innertube (described later).

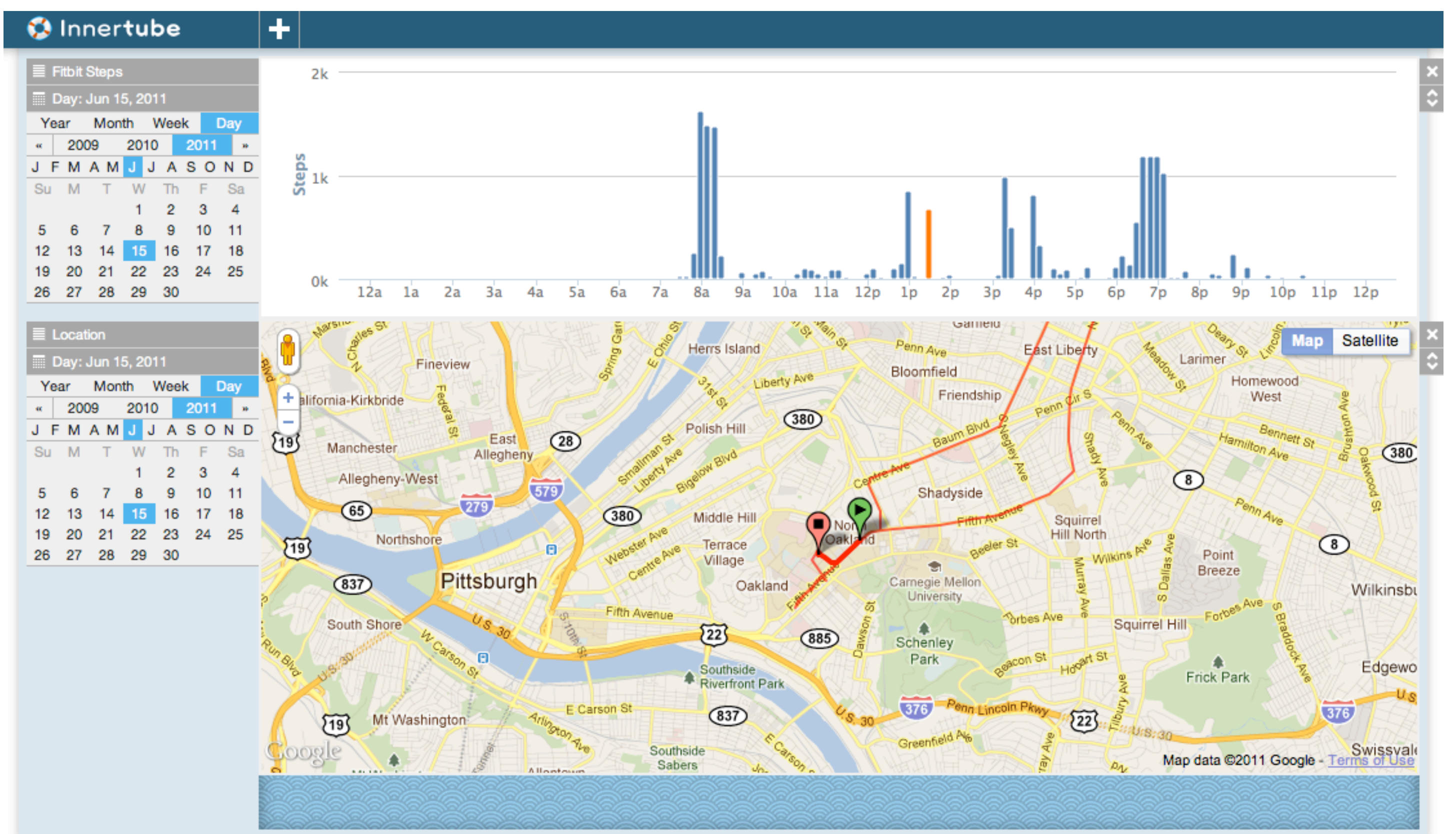

Figure 9. The Innertube Dashboard with two widgets: the Fitbit Steps widget and the Location widget. The user has selected the date June 15, 2011 and the time range between 1:25 PM and 1:30 PM.

7.4.2.1 Fitbit Steps

The Fitbit Steps widget shows the user's step counts collected using the Fitbit device. The visualization shows step counts for a day in 10-minute increments. The 10-minute increments are selectable. The visualization is implemented using the Highcharts Javascript visualization library.

7.4.2.2 Location

The Location widget shows the user's GPS locations collected using the QStarz GPS device. The visualization shows every minute of the user's GPS locations for a whole day. When the user selects a time range on the dashboard, the corresponding GPS locations are highlighted on the widget. The visualization is implemented using the Google Maps Javascript library.

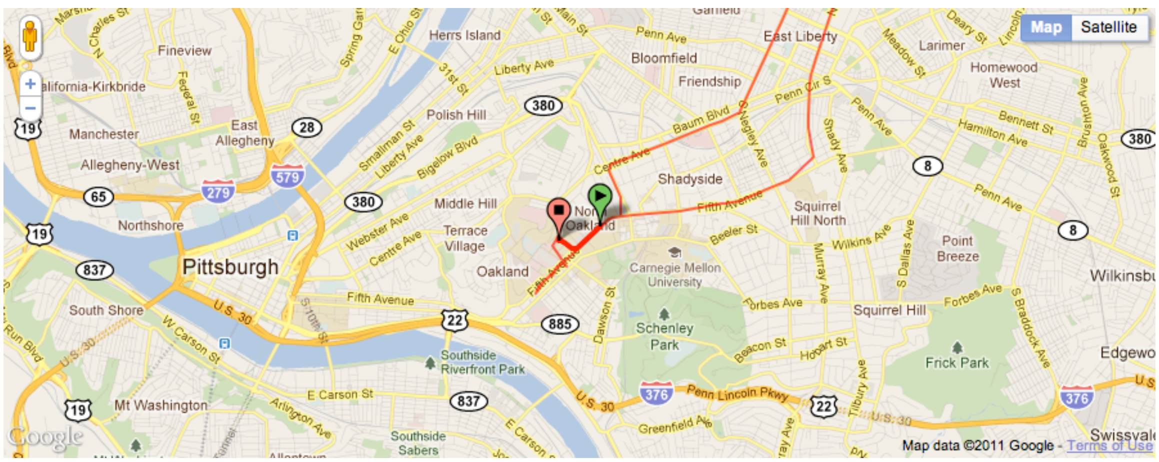

Figure 11. Location widget.

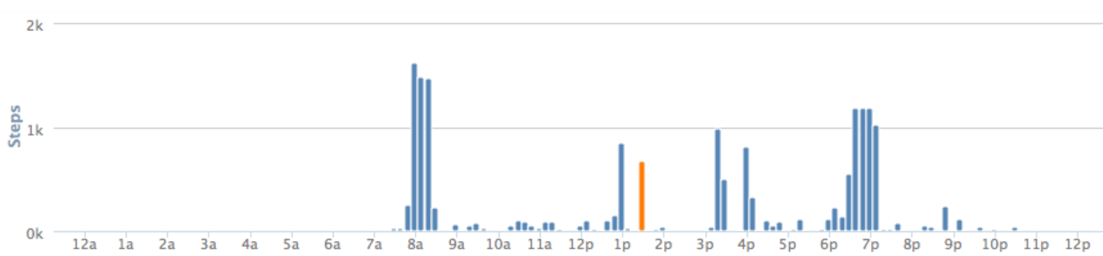

Figure 10. Fitbit steps widget.

7.4.2.3 Weather

The Weather widget shows the weather in a particular city (identified by a zip code). The visualization shows the weather (temperature, humidity, and an image representing current conditions) for every hour of the day. The user can select any hour of the day.

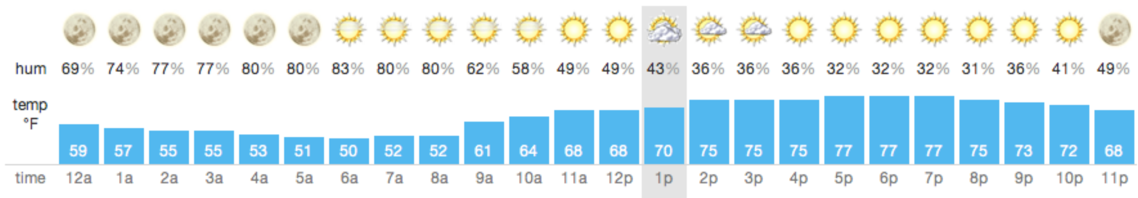

Figure 12. Weather widget.

7.4.2.4 Energy Level

The Energy Level widget shows the user's reported daily energy level for the whole week. Energy level is split into three factors: amount of sleep (number of hours), level of busyness (5-point Likert scale), and level of energy (5-point Likert scale). The user can select any day on the visualization.

Date	Sun Jun 12	Mon Jun 13	Tue Jun 14	Wed Jun 15	Thu Jun 16	Fri Jun 17	Sat Jun 18
Sleep		7.5 hours	7 hours	6.5 hours	6 hours	7 hours	7.5 hours
Busyness		3 out of 5	5 out of 5	2 out of 5	3 out of 5	3 out of 5	2 out of 5
Energy		4 out of 5	3 out of 5	3 out of 5	2 out of 5	4 out of 5	5 out of 5

Figure 13. Energy Level widget.

7.4.2.5 People

The People widget shows the people who were active with the user and who were suppportive of the user's pursuit to be more active. The user can select any day on the visualization.

Date	Sun Jun 12	Mon Jun 13	Tue Jun 14	Wed Jun 15	Thu Jun 16	Fri Jun 17	Sat Jun 18
Supportive People		husband		husband	husband	husband	husband
Active People		husband		husband	husband	husband	husband

Figure 14. People widget.

7.4.2.6 Notes

The Notes widget shows the daily notes that the user wrote. There are two kinds of notes that users can write: mood notes and general notes. The user can select any day on the visualization.

Date	Sun Jun 12	Mon Jun 13	Tue Jun 14	Wed Jun 15	Thu Jun 16	Fri Jun 17	Sat Jun 18
Mood	Rested, happy	Tired	A bit tired, a bit grumpy	Tired, cranky, sad			
Notes		30 mile ride!	I forgot to attach pedometer until I left for work. I spent the morning cleaning so that was some				

Figure 15. Notes widget.

7.4.3 Widgets API

The Widgets API is what makes the interaction between the widgets and the dashboard possible. There are two components that communicate with each other: the Widget RPC (remote procedure call) and the Dashboard RPC. The Widget RPC allows widgets to send messages to the Dashboard, while the Dashboard RPC allows the dashboard to send messages to the widgets. The communication happens using cross-domain messaging enabled by the Javascript library, easyXDM.

Widgets can call the following procedures to the Dashboard:

- Reload the widget.
- Get and set the height of the widget.
- Get and set the date and range of time that the widget is showing.

- Get and set the highlighted date and range of time.

The Dashboard can call the following procedures to each widget:

- Set the date and range of time that the widget is showing.
- Set the date and range of time that the widget should highlight.

7.5 Evaluation

I conducted a study of Innertube. In order to get the multiple types of data that participants would reflect on using Innertube, I had participants use two devices, a Fitbit pedometer and a QStarz GPS monitor, for a week. Participants completed a questionnaire at the end of each day. I also collected weather information every hour.

The Fitbit pedometer is a small device that easily clips on the person's belt, pocket, shirt, or bra. The Fitbit pedometer has a small display that shows users their step count, their mileage, calories burned, and a flower visualization of their progress. The Fitbit pedometer automatically synchronizes that data it collects to the Fitbit web site when the user is near the base station. For this study, I downloaded data from the Fitbit web site, so the user's step counts can be visualized in Innertube.

The QStarz GPS monitor is another small device that users can carry in their pocket or in a backpack. The device continuously records the user's location throughout the day. For the purpose of this study, I calibrated the device to record the user's location every hour. The QStarz GPS monitor does not have a display; instead, the tracked GPS locations have to be uploaded to a computer and visualized using QStarz software. For this study, I exported data from the QStarz software and processed it, so that the user's location can be visualized in Innertube.

Participants completed a paper form at the end of each day. Some participants preferred to fill out an online form, so they were given that option. Both forms had the following fields:

- Mood (free-form text)

- Amount of sleep (number of hours)
- How busy was your day? (1: not busy, 5: very busy)
- Energy level (1: very low, 5: very high)
- List people who were supportive today.
- List people that you were active with.
- Notes

A web application polled the Yahoo! Weather API every hour during the duration of the study to collect weather information (*e.g.*, temperature, humidity, and weather conditions). The web application stored the data in a database. The web application also generated the weather widget for Innertube.

I recruited 15 participants (P1-P15, 4 males and 11 females) aged 20 to 59 with various backgrounds from around the city proper using Craigslist. The participants were selected from a batch of 56 people who completed the study pre-questionnaire. The criteria for selection was that they had some experience tracking personal information. Participants received $30 for their participation in the study.

I met twice with each of the participants. The meetings were one week apart. In the first meeting, participants answered questions about their physical activity, the factors that they think affects their physical activity, and their experience tracking personal information. After completing the questionnaire, I introduced participants to the devices that they will carry and wear and the form that they will complete each day for a week.

In the second meeting, participants returned the devices and the form that they completed each day. Again, participants answered a questionnaire about their physical activity, the factors that they think affects their physical activity, and their experience tracking personal information. While answering the questionnaire, I prepared the participant's data that will be visualized in Innertube. After completing the questionnaire, participants explored the multiple types of data they collected using Innertube. While they were doing this, I had participants think-aloud, that is, describe to me what they were looking for, whether they found what they were looking for, and what problems they encountered.

This part of the study was audiotaped. After the think-aloud, participants completed a questionnaire about their thoughts about Innertube.

7.6 Results

7.6.1 Usefulness

Most participants agreed that Innertube was useful (10 agreed and 3 strongly agreed). Eight participants cited how useful it was to have the ability to reflect on multiple kinds of data together. P9's description was representative; she said, "It was useful in the sense that it gave me concrete contexts, in space and time, by which I could measure and evaluate my own physical activity. Interacting with that data gave me the opportunity to hypothesize about what factors influenced my own physical activity, and what specifically motivated me or discouraged me from exercising."

The other five participants who found Innertube useful cited the following reasons. P1, P3, and P4 said it was useful to have the ability to review their steps over a long period of time. P5 and P11 said that it was useful because the interface showed their steps in detail.

Two participants were neutral (P8 and P15). P8 expected that the interface automatically analyzed the data. She said, "For an interface like that, I would expect it to do more of the analysis for me." Automated analysis of data is not the goal of Innertube, so this feature is future work. P15 did not find Innertube useful; she was "not sure under what conditions looking at all this information would be useful to me." She explained, "My routine is pretty set, so what I saw wasn't surprising in any way."

7.6.2 Ease of Use

Almost all participants agreed that Innertube was easy to use (10 agree and 4 strongly agree). The one participant who was neutral (P4) wrote, "Had trouble at first in figuring out the system, but got it figured out shortly."

Some participants described problems that they encountered while using Innertube:

- P3 was confused by which calendar controlled a widget. She wrote, "Sometimes, I expected something to change that didn't (such as a weekly view of the weather."

- It was not immediately obvious to P7 that the widgets were linked together. She wrote, "I did not realize that the variables were all connected (such as clicking on weather at a particular time and my location would show up)."

- P8 did not understand how to add widgets to the dashboard. She wrote, "I kept opening up blank widgets by accident."

7.6.3 Satisfaction

Most participants were satisfied with Innertube (8 agree and 2 strongly agree).

Three participants were neutral and two participants disagreed. The following are the problems that they described:

- The GPS device that P4 used was defective, which resulted in many inaccuracies. The visualizations of her locations were "all over the place." This problem is not due to Innertube and can be fixed by using a GPS device that is not defective. P4 also noted that she wanted to see visualizations of her total step counts per day. The next version of the Fitbit steps widget could incorporate this.

- P7 preferred "to see miles rather than steps." She explained, "I do not have a good sense of how steps translate to distance." This problem could be fixed with the next version of the Fitbit steps widget.

- P8 and P15 did not find Innertube useful, which is consistent with their responses in the Usefulness section.

7.7 Conclusion

This study presents a new approach called visualization integration that makes it easier for developers to build personal informatics dashboards. To prove the feasibility of this new approach, I implemented a working system called Innertube. I also deployed

Innertube in a field study to evaluate its usefulness and ease of use. This work is important to the thesis because supporting reflection on multiple kinds of data is currently difficult to support with data integration, the usual approach of implementing personal informatics dashboards. The difficulty of building dashboards limits the number of types of data that users can reflect on. With the visualization integration approach, personal informatics dashboards are easier to build and can more easily support different types of data. The visualization integration approach makes more visualizations available for users to reflect on and creates a foundation to further explore the role of contextual information in personal informatics systems.

Chapter 8
Conclusions

In this chapter, I discuss the contributions of this research. Briefly, this dissertation has demonstrated the following:

- It demonstrated the value of reflecting on contextual information in the physical activity domain.
- It described the stages of personal informatics activity that tools need to support, as well as, identified the problems experienced by users in each of the stages.
- It identified the kinds of questions that users ask about their personal data and how the importance of these questions change depending on what phase of reflection the user is in.
- It evaluated different visualization features to support reflection on multiple kinds of data together.
- It proposed a solution called visualization integration that makes it easier to build a personal informatics dashboard (an interface that allowed reflection on multiple kinds of data) compared to the usual approach of data integration. It demonstrated the solution by implementing a personal informatics dashboard.

This final chapter recapitulates the contributions made by the studies and systems presented in the dissertation.

8.1 Chapter Summaries

Each of the chapters of this dissertation discussed a study or a set of studies, which explored a particular aspect of how personal informatics systems could improve awareness of factors that affect behavior. In this section, I summarize the contributions of each chapter. By doing this, I hope to convey the progression of my research. My research started with tackling a specific domain (physical activity) without regard specific knowledge of the considerations of supporting personal informatics tools. As my research progressed, it expanded the domains in which personal informatics is used, while focusing on the different aspects of supporting the activity of personal informatics.

8.1.1 Ch. 3: Using Context to Reveal Factors that Affect Physical Activity

The contribution of this aspect of my research is that I showed how contextual information could help users become aware of factors that affect behavior. In this case, I focused the exploration in the domain of physical activity. The exploration consisted of conducting field studies, which informed the development of two prototype systems. I evaluated the prototype systems in field studies to explore how users would use the tools and how the tools would affect users' awareness of factors that affect their behavior.

The field studies of the prototype systems revealed that how collection of data is supported (manual vs. automation) has an effect on the users' awareness of factors that affect their behavior. When data was collected manually, collecting contextual information led to higher awareness of factors compared to not collecting contextual information. On the other hand, when data was automatically collected, there was no difference in awareness of factors whether contextual information was collected or not. While manual data collection was beneficial for awareness, users found it too burdensome that they were less likely to continue using the tools. While automated data collection did not make a difference in awareness of factors, users were more willing to continue using the tools over a long period of time resulting in more data, which may contain more insightful data for the user.

One of the reasons that manual data collection was successful in making users more aware of factors that affected their behavior is that the users were more engaged with their data. In this case, users were forced to think about the factors that affected their physical activity, since they had to write down what they were doing, where they were, and whom they were with, in addition to their physical activity level.

Users of the IMPACT 2.0 system (semi-automated data collection) were less engaged with their data compared with users of the IMPACT 1.0 system (manual data collection). These users were not forced to think about the factors that affected their behavior because they did not have to record their physical activity nor the contextual information related to their physical activity. The IMPACT 2.0 system had an opportunity to engage the users by forcing them to reflect on their data (either daily or weekly), but this was not part of the design of the system.

This study suggests that there is a tradeoff between manual and automated data collection in the amount of data that can be collected and how much awareness the user gains from using the system. Clearly, there is benefit from the ability of automated data collection to collect more data than manual data collection. Such systems can overcome the lack of engagement by encouraging users to reflect on their data more often (daily or weekly).

8.1.2 Ch. 4: Stage-based Model of Personal Informatics Systems

Jumping from my research on the value of contextual information on awareness of physical activity, I wanted to explore the problems that users experience with tools for personal informatics in general. From my research with IMPACT, users had to collect and reflect on different kinds of data about their physical activity. Each type of information had to be collected by different kinds of tools and these pieces of data had to be visualized. While I limited the kinds of data collected in the IMPACT prototypes, other kinds of data might have been relevant and could have been added (*e.g.*, calendars of activities, mood, weather). These other types of data would also need to be collected and visualized. I thought that regardless of the kind of data for personal informatics, there must be similarities in how personal informatics systems must be supported.

Another impetus for exploring tools for personal informatics in general is that there is no comprehensive list of problems that people experience when they use tools for personal informatics. If developers and designers are going to effectively make tools for personal informatics, they need to be aware of the problems.

This research resulted in several contributions. First, it introduced a stage-based model that describes the different kinds of activities in personal informatics that systems must support. The activities are represented as stages to emphasize the progression and dependency between the activities. The five stages are *Preparation*, *Collection*, *Integration*, *Reflection*, and *Action*. Second, the research described the problems that people experience in each of the stages. Having such a list of problems helps developers and designers avoid the common problems that users encounter when using tools for personal informatics. Lastly, this research described four properties of the stages to take into consideration when developing tools for personal informatics. The properties are:

- *1) Problems from earlier stages affect the later stages*; and *2) The stages are iterative*. These properties are important because they emphasize that developing a personal informatics system requires a holistic consideration of the features of the stages.
- *3) Each stage can be manual or automated.* This property is important because it highlights It also highlights the considerations that the IMPACT prototypes encountered with how to support collection (manually or automatically).
- 4) *Uni- or multi-faceted support*. While most personal informatics systems collected one kind of information, many users in the study expressed the need to reflect on multiple types of data together. As in my research with the IMPACT systems, which focused on contextual information with physical activity information, personal informatics users for other types of data (*e.g.*, nutrition, diabetes, finance, productivity, *etc.*) also wanted to be able to associate multiple kinds of data together.

8.1.3 Ch. 5: Phases of Reflection

In the study presented in Chapter 5, I chose to focus on the *Reflection* stage in the stage-based model of personal informatics systems. The reason for this was I wanted to explore what kinds of questions people asked about their data and how they used existing tools for personal informatics to answer their questions. As implied by the model of personal informatics systems, the stages are inter-related. While I focused on the Reflection stage, how people reflected on their data (what kinds of questions people wanted to answer and how they explored their data) is also affected by the other stages. Therefore, the results of this study also inform how the other stages should be supported.

The first contribution of this study is the identification of six kinds of questions that people wanted to answer when they are reflecting on their data. The six kinds of questions are: *Status*, *History*, *Goals*, *Discrepancies*, *Context*, and *Factors*. Identifying the kinds of questions has implications on the type of visualizations users need and the effort needed to collect the necessary data to answer the questions. The kinds of questions differed in following ways:

- They differed by the amount of data that are visualized (*e.g.*, *History* questions are answered by exploring visualizations with more data points compared to *Status* questions). Consequently, the amount of data has an effect on amount of effort is needed during the Collection stage (*e.g.*, *History* questions require collecting data over a longer period of time compared to *Status* questions).
- They differed by the need to visualize multiple types of data (*e.g.*, *Factors* questions are answered by having data visualized along with contextual data). Consequently, this affects the number of kinds of data that the user collects (*e.g.*, *Factors* questions require collecting contextual data).

The second contribution of this work is that it identified two phases of reflection where the importance of the different kinds of questions is different. This is important because it suggests that tools for personal informatics need to provide different kinds of support depending on which phase the user is in. For example, the kinds of questions that are important during the Discovery phase (*i.e.*, *History*, *Goals*, *Context*, and *Factors*) means users need more support during this phase to collect multiple kinds of data over a long period of time.

8.1.4 Ch. 6: Visualization Features

In Chapter 6, I described a study that focused on creating preliminary designs of features to support exploration of data in the Reflection phase. The contribution of this study is that it helped me determine the features that need to be supported in applications that help users through the Reflection phases. But more importantly, the lessons from the sketches for the Discovery phase guided the design of the personal informatics dashboard that I developed to help users reflect on multiple kinds of data in one interface.

8.1.5 Ch. 7: Personal Informatics Dashboard

In Chapter 7, I discussed an implementation of a personal informatics dashboard, which allows users to reflect on multiple types of data together in one interface. I presented the difficulty of implementing such a system because most systems approach the problem by integrating data together (*data integration*). I proposed a different solution called *visualization integration*. I described my implementation of a personal informatics dashboard that use the visualization integration approach called *Innertube*.

The first contribution of this work is that it proposes a different approach to creating a personal informatics dashboard. I describe in detail the disadvantages of the solution that most systems employ: *data integration*. I, then, proposed a solution that circumvents the problem of data integration. My proposed solution called *visualization integration* makes it easier to build a personal informatics dashboard by eliminating the need to download data from multiple sources without diminishing the ability to explore visualizations of multiple kinds of data in one interface.

The second contribution of this work is that I implemented a personal informatics dashboard using the visualization integration approach. My implementation is composed of a personal informatics dashboard web site, a collection of widgets, and a library for developers to build more widgets.

8.2 Contributions to HCI

This dissertation approached the problem of supporting personal informatics from the perspective of human-computer interaction. It focused on the goal of better understanding oneself by collecting personal data and reflecting on the data. This task is time consuming, but can be alleviated by using computing technology, such as mobile devices, sensors, and visualizations. By using HCI methods in my studies and the development of the prototypes, the dissertation identified the problems that users experience with personal informatics tools, especially, when the user needs multiple kinds of data at the same time. These studies also led to models, guidelines, and lessons that can help designers and developers build personal informatics tools that are easy to use and insightful.

8.2.1 Users

This dissertation identified the difficulties users encounter when they need multiple kinds of data to better understand their own behavior. The studies I conducted with the IMPACT prototypes showed the difficulties users encounter in the domain of physical activity. While manually collecting data with IMPACT 1.0 helped people become more aware of factors that affect their physical activity, users did not enjoy the experience because the task was burdensome. IMPACT 2.0 reduced the burden of data collection by providing a mobile device, but users awareness of factors that affected their behavior was not better than if they did not collect contextual information. In Chapter 4, the dissertation further elaborated on the problems that people experience when using tools for personal informatics beyond the domain of physical activity. The primary problem with personal informatics is that it is task intensive, so tools must provide plenty of support. Additionally (as I found in the Phases of Reflection study), the kinds of questions people want to answer change, which has repercussions on the kinds of support that people need from their tools.

The dissertation proposed some solutions to help users reflect on multiple types of data. I created two prototypes of IMPACT that supported self-tracking of physical activity and contextual information in different ways. IMPACT 1.0 users manually collected data, while IMPACT 2.0 users used a mobile device that partially automated data collection. I did not follow a particular framework to guide the creation of the two prototypes. In retrospect, the development of the two prototypes could have avoided some problems if I had known what kinds of support users needed from personal informatics tools. I addressed this problem with the study that produced the stage-based model of personal informatics systems. The model delineated the kinds of support that users need from their personal informatics tools. The study also described the problems that users experience from current tools that they use. With this model, personal informatics tools may directly address the problems that users experience.

The Phases of Reflection study delineated the kinds of questions that users wanted to answer about their personal data. The study also defined two phases when the kinds of questions that users wanted to answer change importance. This study is helpful to users because this framework says that users' reflection needs are not monolithic. Instead, this framework emphasizes that users have various kinds of questions, which require different amounts of data and kinds of visualizations. Additionally, users' reflection needs do not remain static; instead, they fluctuate between phases. With this framework, visualizations in personal informatics tools may directly help users answer their questions about their personal data.

The Visualization Features and Personal Informatics Dashboard chapters describe my effort to build a user interface that will help users reflect on multiple types of personal data. The Visualization Features chapter explored the specific visualization features that might help users reflect. The Personal Informatics Dashboard describes the application I created called Innertube that implements the lessons from the Visualization Features and my previous studies. Additionally, the implementation of Innertube uses the visualization integration approach, which makes it easier for users to integrate more types of data.

8.2.2 Developers

This dissertation identified the difficulties of building personal informatics tools that support collection and reflection on multiple kinds of data. The dissertation's exploration into the design and technical problems of personal informatics systems is critical in improving the development of these systems.

In my development of the IMPACT prototypes and their subsequent deployments, I experienced first hand the problems of building personal informatics systems, albeit in the domain of physical activity. From the studies, I discovered the tradeoffs regarding ease of use and users' awareness of factors that affect physical activity between manually and automatically collected data. Additionally, the development of the prototypes did not follow a particular framework. Therefore, I missed problems that could have been caught earlier.

In Chapter 4, I discussed the stage-based model of personal informatics systems, which described the different aspects of personal informatics systems that developers have to support. With this model, designers and developers have a framework to evaluate the features of existing systems and to determine the features that they need to build into their tools.

In Chapter 5, I identified the kinds of questions that people ask when they are reflecting on their data and I identified that different kinds of questions are more important at different Phases of Reflection. The lessons from this study could help designers and developers tailor their personal informatics tools based on the changing information needs of users.

In Chapter 6, I created different sketches of visualizations, which I validated with users. The lessons from this study show designers and developers some features that are necessary to appropriately support each of the Phases of Reflection.

In Chapter 7, I described the difficulties of implementing a personal informatics dashboard when using the common approach of data integration. I proposed a new approach called visualization integration, which makes it easier to build a personal informatics dashboard that is flexible to use and extensible by developers. This new approach eliminates the need for developers to go through the whole process of download data from multiple sources, parsing the data, and visualizing the data together. Instead, each developer can focus on building individual visualizations for each data source and type, *e.g.*, Fitbit can focus on providing visualizations of steps, Zeo on visualizing sleep. With the visualization integration approach, their visualizations can immediately interact with the other visualizations that other developers have created. I implemented a personal informatics dashboard called Innertube that employs the approach that I proposed. The system also took lessons from the Visualization features study. By building Innertube, I showed that visualization integration is a viable approach to building a personal informatics dashboard. Also, by having an implemented system, current developers of personal informatics systems can take advantage of the technology.

8.3 Future Work

There are several ways to continue the work presented in this dissertation. First, longer field studies of personal informatics could be prepared. The field studies I conducted were long and time-consuming to deploy; they lasted from three weeks to two months with 30-40 participants using the prototypes daily. However, running longer studies with personal informatics systems will become easier as more systems become available. Also, deployments can include more participants as personal informatics systems become more robust and more affordable. Running longer field studies ranging from half a year to a full year with more participants would give these studies more statistical power to detect differences in the effects of different personal informatics interventions. Longer field studies could also better detect changes in behavioral domains where changes do not occur quickly (*e.g.*, weight loss, smoking cessation, improving sleep patterns).

Second, research could be conducted on other behavior domains. My field studies focused on physical activity because there are many tools that collect physical activity information. However, more and more kinds of data about different behaviors could be collected easily, such as blood glucose level, medication intake, sleep patterns, *etc*. The proliferation of advanced monitoring tools and personal informatics systems creates an opportunity to explore a wide variety of behaviors that may benefit from adding contextual information. Additionally, physical activity is not the only behavior where awareness of factors is beneficial. There are many kinds of factors that affect different behaviors, and awareness of these factors could help people address problems. For example, people experiencing problems with their sleep patterns may benefit from being aware of their caffeine intake, physical activity, and stress levels. People with diabetes may benefit from awareness of food intake, mood information, and physical activity.

Lastly, research could be conducted to explore how awareness of factors could result in changes in behavior. In this dissertation, I focused on the issues of personal informatics systems during the Collection, Integration, and Reflection stages (from the model of personal informatics systems) because problems in these earlier stages can result in problems during the Action stage (the final stage in the model of personal informatics systems). This dissertation provides some suggestions on how to improve support during these earlier stages. With some of this foundational work and future improvements in personal informatics systems' capability to collect and visualize different types of information, there will be more opportunities to focus on the Action stage of the model of personal informatics. With stronger statistical power from longer field studies and more participants, research on the Action stage could explore whether awareness of factors could result in changes in behavior.

8.4 Closing Remarks

This dissertation is in response to a growing trend in computing technology whereby more data about people are being collected. The over-arching goal of this dissertation is to create computing technology that help people use the data collected about them to better understand their own behavior, their habits, and, ultimately, themselves. In particular, this dissertation explored how computing technology can help people better reflect on the multitude of personal data that represented them. People are inherently multi-faceted with many interests, responsibilities, and characteristics. Understanding oneself requires that one looks at all these facets. However, most personal informatics systems tend to focus on one facet of a person. I showed that there is value in reflecting on multiple types of personal data. However, collecting and reflecting on multiple kinds of data is difficult because using personal informatics systems even on one type of data is difficult. I also showed when reflecting on multiple kinds of data is useful and what visualization features need to be supported to help people reflect. Finally, I described a barrier to implementing personal informatics dashboards. I proposed a solution to these problems and I implemented a working prototype to demonstrate that the solution is feasible. The research area of personal informatics is wide and growing. I hope that this dissertation will provide a link from its foundation of behavioral research and technical research in life-logging, ubiquitous computing, and visualizations towards a world where computers can help people better understand themselves.

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