Design of the Feedback Engine for a Diabetes Self-care Smartphone App

Completed Research Paper

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Abstract

Chronic disease management is a serious problem, both for patients with such a disease and for the healthcare delivery system. Technology, in particular smartphones, could be a key part of the solution because it is available when needed to help patients with daily monitoring and care of their chronic conditions. We are designing and developing a smartphone app to support patients with advanced type 2 diabetes. This paper reports the design of the feedback engine for our app. We created a feedback model based on (1) Bandura's Social Cognitive Theory and Goal Setting Theory, which are often used as a basis for behavioral health interventions, (2) advice from medical experts, and (3) preferences of patients collected via focus groups. We report the dimensions of our feedback model and the rationale for each, as well as how those dimensions are operationalized in the feedback engine.

Keywords

Diabetes, Type 2, Chronic disease, Self-Care, Smartphone, App Design, Feedback Engine, Social Cognitive Theory, Goal Setting Theory, Self-regulation

Introduction

As chronic disease management becomes a more prevalent problem, the U.S. healthcare delivery system is struggling. Patients with chronic diseases such as diabetes can see their primary care physician for 15 minutes or so, only a few times a year, yet their condition requires daily attention. Thus, those with chronic conditions are essentially responsible for their own disease management, as much as, or more than, their physicians. So, how well are they doing? With the rising prevalence of type 2 diabetes and heart disease, and associated contributing factors such as obesity and physical inactivity, statistics indicate they are not doing well.

Technology, such as smartphones, could be a key part of the solution. While your doctor is only occasionally available, your mobile phone is usually in your pocket. If it is a smartphone with significant computing and storage capacity, it could function as a personal health assistant that is always there to help you manage your health (Brown et al. 2013). It could monitor your health status, perhaps in real time, and provide personalized guidance for managing chronic conditions (Patrick et al. 2008).

Diabetes, the chronic condition that is our focus, affects 8.3 percent of the U.S. population. Overall estimated diabetes healthcare costs increased 41% from $174 billion in 2007 to $245 in 2012 (American Diabetes Association 2013). Daily patient self-care, in collaboration with physician advice and regular clinic appointments, is the standard treatment for diabetes, unless complications arise requiring surgery. Diabetes self-care management is complex, requiring activities such as blood glucose monitoring, managing fats, fiber and sweets in daily diet, and exercise. For patients with diabetic foot ulcers, a common complication of diabetes, they must also clean and care for their wounds, assess their wound condition, and recognize the presence of any new wounds. These wounds can exist for many months and require diligent care over this time to heal.

Our research, to design, develop, and test a smartphone-based app for patient-centered care of advanced diabetes, focuses on two key challenges: automatically analyzing wound healing progress of patients with diabetic foot ulcers, and using technology to motivate these patients to take better care of their diabetes. We focus on the latter challenge in this paper, and present the design of our feedback engine.

Background

Smartphone diabetes-related applications

Some smartphone apps for supporting chronic disease management are now available. For example, physical activity-tracking apps use a smartphone's accelerometer and its GPS tracking features to collect data automatically. Similarly, a smartphone's Bluetooth feature can gather data from nearby Bluetooth-enabled devices such as scales and glucometers (Smith et al. 2007). The phone's camera can collect images for analysis or scan barcodes at supermarkets to provide automatic entry of nutrition values for daily diet entries. These features are important because users of apps generally prefer automated data entry over manual input.

For example, Preuveneers and Berbers (2008) propose a mobile phone system for assisting diabetes patients. By monitoring user location and current activity, recalling past activity, logged blood glucose levels can be combined with contextual data to assist the patient with daily drug dosage and maintain stable glucose levels. Yoshihiro et al. (2006) propose a software system which allows diabetes patients to record their activities such as meals eaten, exercises, insulin and medicine intake to keep their blood glucose levels stable. Patients can then upload these activities to their doctor for advice. Villarreal et al. (2009) also propose a framework for patients to self-monitor.

Several commercial systems exist for diabetes patients to tele-monitor themselves. The iPhone App store includes several free applications (Blackstock 2010). Glucose Buddy, Diabetes Log, Log for life, Bant and DiabetesGrapher are applications that assist the patient with the manual entry and storage of patient data such as glucose levels, carbohydrate consumption, insulin dosages and activities. The Diabetes meal planner Lite and Glucose Mate Free help patients plan their meals by looking up and calculating the Glycemic load of food that patient eat.

Non-iPhone commercial applications include Sidiary (www.sidiary.org, 2014), which includes a log book application that runs either on a PDA or smart phone. In Sidiary, diabetes patients use external meters to measure blood pressure, insulin and glucose levels, and then this data is uploaded and synchronized to a smart phone or PDA. Welldoc also has an application that allows patients to self-monitor themselves and receive valuable instant feedback on ideal glucose ranges and physicians' instructions (Mobihealthnews 2009). Other commercial smartphone diabetes systems include My Diabetes Guide (Silk 2009).

While some of these apps have a large user base, most are still at a prototype stage, even if they are already available. For example, at the time of writing, of 222 diabetes apps available from the Apple's App Store, only eight supported a core set of six diabetes management tasks (setting measurement units, logging blood glucose, logging carbohydrate intake, logging insulin doses, displaying data graphically, and exporting data) (Garcia et al. 2011). Of the 162 diabetes apps available from Google's Play Store, only six supported these tasks. Clearly, there is much more to do to deliver apps that truly meet the needs of those who want to, and need to, better manage their health, including their chronic diseases.

Behavior change mechanisms in smartphone apps

A variety of behavior change and feedback mechanisms have been proposed in smartphone apps targeted at various health conditions. For example, Hebden et al. (2012) propose smartphone apps for nutrition and physical activity. Self-regulation was fostered in an app by enabling users to enter physical activities performed or vegetables consumed daily from which daily or weekly summaries were generated as feedback to the user. User entries were compared with public health guidelines, to enable users to self-reflect. Apps provided motivational tips as a source of positive encouragement that would assist young adults in creating more positive beliefs around their ability to change their behavior, e.g., “You can split up your exercise target into as little as 15-minute bursts”. These tips were also tailored to users’ self-reported behavior.

Burns et al. (2011) propose a context-aware mobile application for mitigating depression. By gathering the readings of various mobile phone sensors and mining the data, their app predicted the moods of users with the goal of identifying users requiring assistance. Participants received tailored feedback and interventions based on mood scores generated by the app. The app also provided reminders of scheduled therapeutic activities.

Only recently have apps for supporting chronic diseases started to include feedback to users that is explicitly designed to promote behavioral change. Our diabetes support app is explicitly designed to promote behavioral change because its feedback engine is based on a model of feedback grounded in health-related behavioral change.

Method

Our overall methodological approach is design science (Gregor and Hevner 2013; Hevner et al. 2004; Peffers et al. 2007). Our goal is to create an IT artifact, specifically a smartphone app, that is usable and useful to patients as they self-manage their type 2 diabetes. In this paper we focus on the design and development of the feedback engine in the app, which is one of the core challenges in designing an app that motivates its users to improve their health. Within our overall design science approach, we used a combination of methods to design the feedback our app presents to users.

First, to ensure that our app is patient-centric (Brown et al. 2013), we conducted focus groups of patients with advanced diabetes. During the spring of 2012, we conducted two focus groups at University of Massachusetts Medical School (UMMS) to better understand patients' needs and to assess initial design alternatives. The overall purpose was to investigate how patients with advanced diabetes and diabetic foot ulcers perceive smartphone technologies as a platform to support diabetes self-management. Patients who had type 2 diabetes and had been treated at the UMass Memorial Wound Clinic at least once in the past year due to diabetic foot ulcers were contacted by phone and were invited to participate in the study. We recruited all patients who agreed to participate and were available to come to one of our focus groups. In total we had 6 subjects (4 for the first focus group and 2 for the second one).

The primary finding that affected the design of our feedback engine was that everyone wanted positive and encouraging feedback. The preference for positive re-enforcement (rewards) rather than negative (punishment) is consistent with the long history of research on the relationship between feedback and performance, e.g., (Kluger and DeNisi 1996), as well as recent literature on attempts to change health behaviors via smartphones, e.g., (Dennison et al. 2013). It was clear that any negative feedback would likely lead to non-use of the app. Since our app’s target demographic was senior citizens (over 55), they wanted a user interface with large buttons, bold lettering, and simple graphs.

Any form of social networking functionality was rejected by most of the patients. Only one patient who was an active Internet user showed interest in sharing information through a social network. This result may be related to the concerns of some subjects about privacy protection. Some were unwilling to reveal any information even to their spouses.

Second, to ensure our app is behaviorally and medically sound (Strong et al. 2012), we worked with domain experts and drew on exiting theories related to health behaviors. In terms of domain experts, our research team includes an expert in behavioral medicine who specializes in behavioral changes related to managing obesity and diabetes and a physician whose specialty is diabetes care. While we want to ensure that our app is medically sound, in compliance with FDA regulations, our app does not provide medical advice. In terms of health-related behavioral theories, we primarily draw on Social Cognitive Theory (Bandura 1986) because its concepts of goal-setting, self-monitoring, and behavioral contracting are widely used in studying health behavioral interventions (Glanz and Bishop 2010).

Functionality and Architecture of the Sugar App

Before presenting the design and implementation of our feedback engine, we provide a brief overview of the functionality and architecture of our app, which we call Sugar, so that readers have a context for understanding the design of the feedback engine.

The functionality of the Sugar App includes blood glucose management, weight management, physical activity management, and diabetic foot ulcer image analysis. For each of these, the app collects data (via Bluetooth enabled devices for glucose and weight), analyzes and displays that data, and provides feedback to the user. It also synchronizes with Microsoft HealthVault for external cloud storage of data. Figure 1 shows this functionality in the context of the basic architecture of the app.

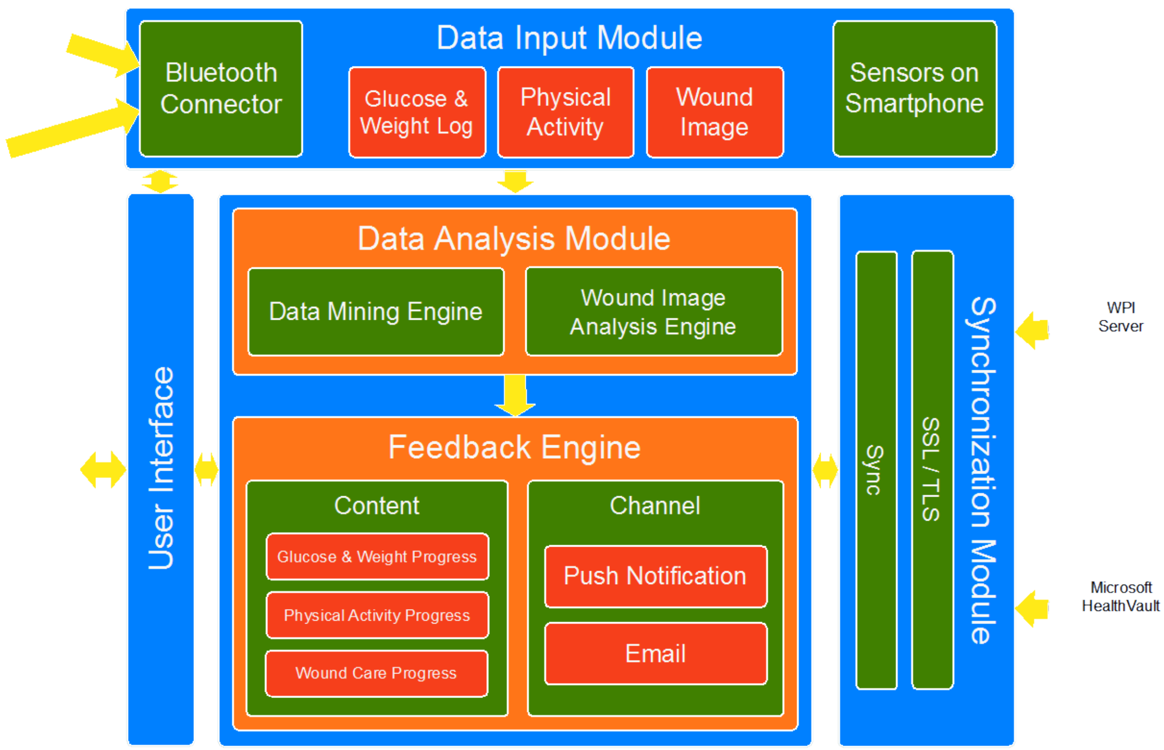

Figure 1. The Architecture of the Sugar App

The app consists of five main modules: User Interface, Data Input Module, Data Analysis Module, Feedback Engine, and Synchronization Module. The **User Interface Module** handles the smartphone's display. The **Data Input Module** retrieves glucose and weight data wirelessly from a Bluetooth-enabled glucometer and a weight scale (to avoid user typing). Alternatively, these values can be manually input through appropriate screens. Physical activity data are also manually input. The data input module also collects wound photos taken with the smartphone's camera. The **Data Analysis Module** continuously mines the collected patient data and wound images, analyzes the trends and generates a score for wound healing by analyzing the wound images. The **Feedback Engine**, which is the focus of this paper, generates feedback based on the knowledge it learns from existing data and the rules programmed into the engine. The **Synchronization Module** copies the data in Sugar app to the Microsoft HealthVault and maintains consistency between the data in the cloud and the data in the app's local storage.

Conceptual Design of Sugar's Feedback Engine

The conceptual design of Sugar's feedback engine is based on a feedback model we developed from the behavioral health literature in conjunction with our behavioral health domain expert and principles of good user interface design. The feedback engine is a "push" design, i.e., given pre-set user parameters, the feedback engine automatically provides the feedback. In addition, at any time through the User Interface module, users can request a trend line of their measures (i.e., a "pull" design option).

Due to strict FDA regulations, the Sugar app does not give any medical advice such as interpreting the patient's data in a clinical sense, diagnosing the patient's condition based on interpretations of entered data or recommending medications. Instead, the feedback takes the form of statistical reports on the frequency of data entry and trend analysis of entered data values. Comparisons are also made between the user's measurements and goals they set.

Our feedback model captures four aspects or dimensions of feedback: (1) feedback domain, (2) feedback purpose, (3) feedback goal type and (4) feedback frequency. In addition, to these aspects or dimensions of feedback, we must also avoid overloading the user with too much feedback. Thus, we have developed rules for prioritizing feedback.

Tables 1 and 2 present our feedback model for one feedback domain, i.e., feedback about glucose levels. The rows in these tables capture the feedback purpose and the columns capture feedback frequency. The cells explain the feedback provided with an example. Table 1 covers one feedback purpose, which has a column for "after value entry". The other three purposes are in Table 2 because the "after value entry" is not applicable for these purposes. Each of the aspects of the conceptual design of our feedback engine is discussed below.

		Glucose (G) **Goal 1:** # of measurements **Goal 2:** Stay within pre-set range		
Purpose	**Display Method**	**After Value Entry**	**In Daily Report**	**In Weekly Report**
Promote **self monitoring** by <u>acknowledging</u> use.	Check for a valid entry.	Emergency message if value in danger zone otherwise acknowledgement message.	Acknowledge entry.	Acknowledge entry.
	Examples:	"New glucose entry recorded. Good job!"	"Thank you for monitoring your glucose yesterday!"	"Thank you for monitoring your glucose last week!"

Table 1. Feedback Design – Acknowledging Data Entry

Feedback Domain

Our app provides feedback on glucose levels, weight, physical activity level, and wound healing. For each of these domains, the feedback engine provides feedback for different purposes and goal types, and at different frequencies.

Feedback Purpose

Consistent with social cognitive theory (Bandura 1986; Glanz and Bishop 2010), the app provides feedback that acknowledges a user's input, promotes regular self-monitoring, promotes goal setting, and promotes behavioral contracting. We explain each purpose starting from the purpose of simply acknowledging a user's input to promote basic self-monitoring to a purpose that promotes behavioral contracting.

At the most basic level, simply **acknowledging**, in a positive way, the receipt of a measure from users encourages them to continue their self monitoring so they have data to give to Sugar, and can receive a "Good Job!" message (see Figure 2a). See Table 1 for examples of feedback to acknowledge inputs.

While simply acknowledging inputs promotes basic self-monitoring, a stronger way to encourage **self-monitoring** is to track and report how often (the frequency of) a user's input for each measure. The feedback provided tells users how long it has been since they last entered such a measure. Examples of feedback to promote this form of self-monitoring are shown in the top of Table 2.

		Glucose (G) **Goal 1:** # of measurements **Goal 2:** Stay within pre-set range	
Purpose	**Display Method**	**In Daily Report**	**In Weekly Report**
Promote regular **self monitoring** by monitoring frequency of use.	Check time elapsed since last entry. Follow reminder rules for length of no use.	Acknowledge # of times measured.	Acknowledge # of days measured.
	Examples:	"You measured your glucose n times (OR "time") yesterday. Well done!" or "You did not measure your glucose yesterday. Try to measure regularly today."	"You measured your glucose everyday last week. Good job!"
Promote **goal setting.**	Compare most recent value to previously recorded value(s) or their aggregates.	Compare # of times measured today vs yesterday.	Present glucose ranges recorded.
	Examples:	"You measured your glucose more often yesterday compared to the day before yesterday. Well done!"	"Your glucose changed between x and y this week. Knowing the appropriate range for you is important."
Promote formalized **behavioral contracting.**	Compare most recent value to a goal.	Acknowledge if Goal 1 or 2 met, # of times within range.	# days Goal 1 met and % Goal 2 met.
	Examples:	"Yesterday you met your measurement goal." or "Your glucose was x% in range."	"You met your measurement goal everyday last week!" or "Your glucose was y% in range last week."

Table 2. Feedback Design – Promoting Healthy Behaviors

The feedback engine promotes **goal setting** by monitoring progress. Specifically, the feedback engine compares the value(s) entered to previous values of the same type, e.g., values from last week. As users start to learn their values, they start to set and/or refine goals for those values (Bandura 1986; Locke and Latham 1990). Examples of feedback to promote goal setting are shown in the middle of Table 2.

Finally, the strongest from of feedback promotes **behavioral contracting** by comparing the values entered to the goals set by users. Because choosing a goal is a separate conceptual and cognitive process than committing to that goal (Locke and Latham 1990), we have designed feedback to encourage the commitment process of behavioral contracting. "A behavioral contract is a means of scheduling the exchange of positive reinforcements among two or more persons" (Stuart 1971). In our case, the contracting occurs between the user and the app, i.e., users commit to making progress toward their goals by engaging with the app. Examples of this type of feedback are shown in the bottom of Table 2.

Goal Type and Goal-Setting

Through its feedback, Sugar is making users aware of how well their current behavior adheres to goals they have previously set for themselves. Thus, understanding the types of goals users can set and how they set them (sample screens) is important to understanding the feedback the Sugar app provides. Sugar app users can set two main types of goals: Measurement frequency goals and measurement value goals.

1) **Measurement frequency goals.** During app setup, users decide how many times each day and how many days each week they will measure each data domain. For instance, app users may decide to measure their glucose readings twice a day or weigh themselves daily. As users utilize the app, it captures their frequency of measurement of each data domain and provides feedback on how well they adhere to their pre-set measurement frequency goals. Consistent with theories around self-monitoring and goal-setting (Bandura 1986; Carver and Scheier 1998; Glanz and Bishop 2010), users are more likely to adhere to their usage frequency goals because they set those goals themselves. The actual choices made will vary for different app users.
2) **Measurement value goals.** Sugar app users can also pre-set what measured values they would like to achieve. For instance, a patient can decide what ranges of blood glucose readings they will strive to stay within or how much walking (physical activity) they will strive to perform each day or week. As users utilize the Sugar app over time, the actual measurement values entered into the app are compared with their pre-set goals for each measure, and feedback is provided. Consistent with theories around behavior contracting (Bandura 1986; Glanz and Bishop 2010; Stuart 1971), users are more likely to achieve their value goals because they set those goals themselves.

Feedback driven by a purpose specified in health behavior change theories and by goals set by users themselves provides a powerful theoretical grounding for our feedback model and the design of our feedback engine.

Feedback Frequency

Our feedback design also considers the appropriate frequency for each feedback message. Frequency is important because giving feedback to users too frequently causes fatigue, resulting in users eventually ignoring the feedback messages. On the other hand, if feedback is not frequent enough, opportunities are missed to effect behavioral change. The feedback engine generates user feedback at three frequencies: immediate, daily and weekly, as explained below.

1) **Immediate feedback** is given to Sugar app users after they enter new data (glucose, weight readings, physical activity, or wound images). First, any entry of data into the Sugar app is acknowledged to encourage the user to keep using the app (see Figure 2a). Second, the feedback engine checks that the values entered are valid. Success or failure of entering valid data is indicated and the entered data is displayed to the user for immediate review and confirmation. Finally, while care was taken not to provide actual medical advice, in some cases, entered readings can indicate imminent danger to the Sugar app user if they do not receive urgent care. For instance, extremely high glucose readings may lead to a diabetic coma (ketoacidosis) if not addressed urgently. If the Sugar app receives glucose readings above an upper bound, which is pre-determined for the patient by their doctor, the Sugar app provides feedback to the patient suggesting that they call their doctor or healthcare provider (see Figure 2b).
2) **Daily feedback** is given to Sugar app users at the same time every day (see example in Figure 3b). The time at which the user receives their daily report is customizable so that each user can choose whatever time they are most likely to be able to reflect on the feedback. Daily feedback summarizes

the user's activities, physiological measurements and usage of the Sugar app over the previous 24 hours. Daily reports include an acknowledgement (Thank you) for any data the user entered in the past 24 hours (promoting app usage for self-monitoring). Daily reports also include feedback on (i) how many times the patient measured their data in the past 24 hours (promotes self-monitoring frequency), (ii) a comparison of how the measurement frequency of the past day compares with other 24-hour periods and to long-term history data for trend analysis (promotes goal setting), and (iii) how the actual values entered compare with daily goals users set for each measure (promotes behavioral contracting). Tables 1 and 2 in the "Daily Report" column provide examples of daily feedback for glucose readings. Figure 3b shows an example daily report.

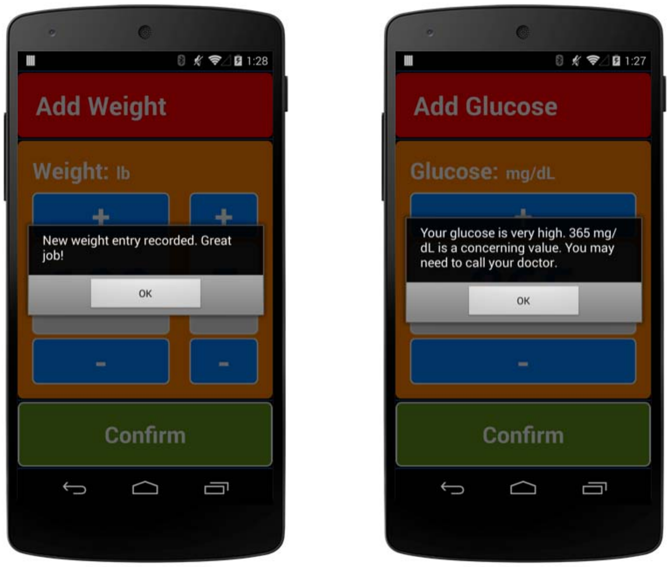

Figure 2. Examples of (a) Acknowledging (left) and (b) Warning (right)

3) **Weekly feedback** is given to Sugar app users on the same day and time every week. Like daily feedback, the day and time that weekly feedback is provided is customizable so that each user can choose whatever day and time they are most likely to be able to reflect on the feedback. Weekly feedback summarizes the user's activities, physiological measurements and usage of the Sugar app over the past week. Weekly reports include an acknowledgement (Thank you) for any data the user entered in the past week (promoting app usage for self-monitoring). Weekly reports also include feedback on (i) how many times the patient measured their data in the past week (promotes self-monitoring frequency), (ii) a comparison of how the measurement frequency of the past week compares with other weeks (promotes goal setting) and (iii) how the actual values entered compare with weekly goals the users set for each measure (promotes behavioral contracting). Tables 1 and 2 in the "Weekly Report" column provide examples of weekly feedback for glucose readings. Figure 4 shows an early design of the weekly report.

Feedback Priority

Goals set by users are used to form rules in the feedback engine. These rules are checked whenever users enter new data (to generate immediate feedback) and on days/times chosen by them (daily and weekly feedback). Feedback is generated for every rule condition that is met. In some cases, too many rule conditions are met at the same time. In such cases, displaying all feedback messages corresponding to each rule would result in too many messages being displayed (see Figure 4 for an example of too many messages). The screen clutter would overwhelm the user and potentially lead to them ignoring some messages or, in the worst case, decreasing their use of the Sugar app.

To avoid an overload of messages, we prioritize messages and display a single screen of only the most important messages when too many rule conditions are met. We prioritize the importance of feedback types in the following order: behavioral contracting > goal setting > self-monitoring > acknowledging monitoring frequency > acknowledging use. For example, if too many rules are triggered, a message about how a user's current weight compares with their weekly goal (behavioral contracting) will be displayed while a message thanking the user for measuring their weight (promoting app usage for self-monitoring) may be suppressed.

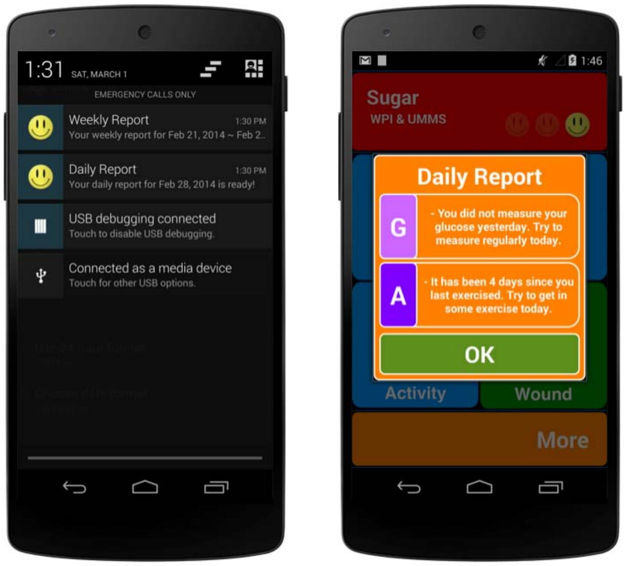

Figure 3. Android (a) notification drawer (left) and (b) daily report (right)

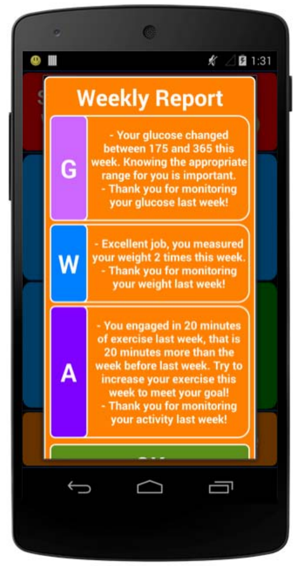

Figure 4: An example of overwhelming feedback (too many messages)

Technical Implementation of Sugar's Feedback Engine

The Sugar app is implemented using Google's Android SDK which supports the Android operating system version 2.2 and above. The feedback engine is implemented using Java code within the Android framework. The pseudocode for the feedback engine is presented in Figure 5.

Input: History data loaded from database ***d***.

Output: A feedback report ***R***.

Algorithm:

    for each data category c **in** [glucose, weight, activity]

        load data from database d for category c to dataset d_c

        create an empty report R_c for category c

        for each feedback type t **in** [behavior_contracting, goal_promoting, self_monitoring, acknowledging]

            for each feedback rule r_t of type t

                check rule r_t in d_c

                if r_t returns **true**

                    generate feedback message m with the message template for rule r_t

                    add message m to report R_c

        sort the messages in R_c by priority descending

        add the first 3 messages in R_c to final report R

    return R

Figure 5: Feedback Engine Pseudocode

Conclusion

The design and implementation of the Sugar's feedback engine is a design science contribution because it demonstrates how social cognitive theory about individual behavioral change can be used to create a model that forms the foundation for a smartphone app feedback engine. The feedback engine operationalizes Social Cognitive Theory and Goal Setting Theory in the context of self-management of a chronic disease. Behavioral theory and medical expertise, however, must be complemented by user-centered requirements, in our case, from focus groups.

While our model of feedback and its implementation as Sugar's feedback engine, is a contribution in itself, we have not completed the design science process (Peffers et al. 2007). The Sugar app is designed and implemented and is being used by various members of the research team. While we have been working with patients and domain experts as we design and implement the app, formal usability and usefulness testing is still important. Our next steps, usability and acceptance testing, will provide additional information for refining our feedback engine design. We will be conducting usability evaluations starting this spring. Then, we will be testing acceptance, use, and usefulness of the app as patients with advanced diabetes are given the app and Bluetooth devices for use in their home over several weeks.

In addition to empirical testing, we are continuing to build our feedback model in several ways. First, we are continuing to review the rich literature on goal setting, e.g., (Locke and Latham 1990) and feedback and control of behavior, e.g., (Carver and Scheier 1998). Second, we are assessing the theory and recommendation from this literature in light of results from studies of how to change the behaviors of those with diabetes so as to improve their health, e.g., (Mulcahy et al. 2003) to determine which theories and recommendations from the general literature are most applicable in the diabetes self-care context. Finally, as we conduct our empirical tests and review the diabetes behavior literature, we are refining how our feedback model should best be captured in the Sugar app.

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