The Anatomy of Context-aware Mobile Patient Monitoring

Completed Research Paper

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Abstract

Context-aware mobile patient monitoring provides new opportunities to deliver medical care. Despite an exploding number of mobile patient monitoring applications, we lack a holistic and comprehensive taxonomy of context dimensions in mobile patient monitoring and thus fail to fully understand context-aware behavior. In a design science approach we build conceptual models for both context and context-awareness in mobile patient monitoring. We instantiate and evaluate the suggested artifacts in a field study. Our primary contributions are conceptual models for context dimensions in mobile patient monitoring and insights into the context-aware behavior of these applications. This study reveals the importance of various stakeholders (e.g., care provider and relatives) and disease-specific insights from medical research contributing to the value creation in context-aware mobile patient monitoring. We further illustrate that current solutions offer only restricted set of context-aware features, not taking full advantage of sensor-enabled mobile devices to collect continuous contextual health information.

Keywords: Context, context-aware, mobile health, patient monitoring, mobile computing, electronic health, healthcare, design science research
Introduction

To date, information used for personal health care is mainly captured via self-report surveys and infrequent doctor consultations. The widespread adoption and availability of mobile devices provides new opportunities for the integration of mobile health into existing electronic health services (Kay et al. 2011). Sensor-enabled mobile devices can potentially collect in situ continuous contextual information that can dramatically change the way health is assessed as well as how care and treatment are delivered (Lane et al. 2011). This potential is even higher in rural settings and other places where health services are hardly affordable and often hard to access (Luz et al. 2012). Context-aware mobile patient monitoring applications may also benefit medical researchers, allowing them to reach more participants for their studies in order to collect data for research effort success. Embedded sensors in mobile devices can typically provide rich contextual information while ensuring data collection efficiency and accuracy. The tremendous potential of mobile patient monitoring has lead to an exploding number of applications in public app stores. Companies such as Apple Inc. have recognized and provide dedicated development kits (e.g., HealthKit and ResearchKit) to foster innovation around their mobile platform.

Having said this, context and context-awareness are considered to have key roles in mobile patient monitoring. Surprisingly, however, we have not found consensus of what we actually mean when we use context and context-awareness in this specific domain. Current literature mostly focuses on single medical use cases. Scholars thereby derive specific context dimensions that may apply to specific diseases, but do not generalize their insights into a comprehensive taxonomy of relevant context dimensions for mobile patient monitoring. A taxonomy can provide a generic classification of concepts in mobile patient monitoring, which will then guide the design of specific mobile applications. From a technology perspective, several researchers attempted to provide development frameworks helping software developers to implement context-aware features in mobile patient monitoring applications. While such frameworks are valuable to create innovative applications based on reusable components, they target the implementation phase rather than the actual conceptualization of a mobile patient monitoring application. Current literature provides no holistic and comprehensive taxonomy of what context means in mobile patient monitoring and fails to fully understand context-aware behavior in mobile applications.

In this paper, we seek to close this gap in research and addresses the following research questions: (1) What are the relevant context dimensions in mobile patient monitoring? (2) How do mobile patient monitoring applications adapt to these context dimensions?

Using a design science research methodology (Peffers et al. 2007), we develop conceptual models for both context and context-awareness in mobile patient monitoring. Since context-aware mobile patient monitoring is a novel approach, its design can be seen as a search process. Design science allows for an iterative build-and-evaluate process in order to produce a set of artifacts that supports the identified problem. Building on existing literature, we start by reviewing generic definitions of context and context-awareness and analyze existing mobile patient monitoring applications. From this literature review, we identify the candidate context dimensions relevant for mobile patient monitoring as well as a classification of context-aware features. We discuss and refine our conceptual models based on a field study, in which we closely collaborate with senior physicians to develop a mobile application to monitor patients with age-related macular degeneration. Patients suffering from this eye condition are typically older than 50 years and are not familiar with mobile technology. Designing a mobile application that addresses macular degeneration is therefore particularly challenging. The field study demonstrates how the presented conceptual models help guide the design of a context-aware mobile patient monitoring application called Alleye. Our contributions are conceptual models that formalize the relevant context dimensions and insights into context-aware features of mobile patient monitoring applications.

We proceed as follows. In the next section, we review the related work, identify the research gap and formalize the research opportunity. We then describe the research methodology. Next, we present our conceptual models illustrating the context dimensions and context-aware features in mobile patient monitoring. Based on a real-world case, we then demonstrate how the presented artifacts can be used to identify and define aspects of context in a mobile patient monitoring application. Finally, we summarize our paper’s contributions, describe the limitations of our research, and provide an outlook for future research.
Related Work

Context and Context-awareness in Mobile Computing Environments

Context and context-aware systems are seen as a specific field of ubiquitous computing (Baldauf et al. 2007) and are often associated with mobile computing. The Merriam-Webster dictionary defines context as “the interrelated conditions in which something exists or occurs” (Merriam-Webster 2004). Various researchers provide a more precise definition of context in relation to computing environments. Schilit et al. (1994) describe three different context categories: (1) computing context (e.g., network connectivity, communication costs, and communication bandwidth, and nearby resources such as printers, displays, and workstations), (2) user context (e.g., the user's profile, current social situation, location, and people nearby), and (3) physical context (e.g., lighting, noise levels, traffic conditions, and temperature). Building on this study, Chen and Kotz (2005) propose to add a fourth category, time context (e.g., time of day, week, month, and season). While nowadays there is no unified definition of context for computing environments, the definition provided by Dey and Abowd (1999) has become widely accepted. They associate context to an entity and define it as “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.”

Various papers provide a categorization of context types, which then helps designers to identify the most important aspects of context that will be useful in their applications (Dey and Abowd 1999). Schilit et al. (1994) distinguish three different aspects of context, i.e., where you are, who you are with, and what resources are nearby. Ryan et al. (1998), on the other hand, distinguish between the context types location, environment, identity, and time. Similarly, Dey and Abowd (1999) suggests using location, identity, activity, and time to characterize context. Compared to Ryan et al. (1998), they use the notion of activity instead of environment. While environment is seen as a synonym of context, activity denotes what is occurring in a situation. According to Dey and Abowd (1999), these context types look at the who, where, when, and what. An application designer must then determine why the situation is occurring. The determination of the why allows the designer to encode some action in an application, which then enables an application to afford context-awareness.

Context-aware, on the other hand, is sometimes used as synonym for other terms such as adaptive (Brown et al. 1997), responsive (Elrod et al. 1993), context-sensitive (Rekimoto et al. 1998), or reactive (Cooperstock et al. 1995). Schilit et al. (1994) simply describe context-aware applications as applications that are informed about context and adapt themselves to context. Ryan et al. (1998) are more precise and name specific examples of context information. They define context-aware as description of a computer’s ability “to sense and act upon information about its environment, such as location, time, temperature or user identity.” Chen and Kotz (2005) give two definitions of context-aware computing. A mobile application can either adapt its behavior to the discovered context (i.e., active context-awareness) or it can make the context available to the interested user (i.e., passive context-awareness). Dey and Abowd (1999) distinguish two definition categories for context-awareness, namely using context and adapting to context. Using context is generally described as the ability of computing devices to detect and sense, interpret and response to aspects of a user’s local environment and the computing devices themselves (Hull et al. 1997; Pascoe et al. 1998). Adapting to context has been defined as context-aware applications that dynamically change or adapt their behavior based on the context of the application and that of the user (Abowd et al. 1998; Brown et al. 1997). Applications must therefore modify their behavior in order to be considered as context-aware. For instance, an application that simply displays a patient’s location does not modify its behavior and would therefore not be considered to be context-aware. Dey and Abowd (1999) address this issue and combine the two categories of using context and adapting to context. They state that a system is context-aware “if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user’s task.”

Classification of Context-aware Applications

To further define the field of context-awareness, some scholars have suggested categorizing context-aware applications. In a two-by-two matrix, Schilit et al. (1994) distinguish two dimensions: whether the effected task is receiving information or executing a command, and whether the task is effected manually.
or automatically. They suggest the four following application classes: (1) Proximate selection: Applications that emphasize their locus and the selection of nearby located objects. The user interface automatically adapts to the current locus and the located objects (e.g., computer input and output devices, people in the same room, non-physical objects, and places). (2) Automatic contextual reconfiguration by adding new components, removing existing components, or altering the relationships of existing components due to context changes. Components typically include servers and their connections, software modules and hardware elements. (3) Contextual information and commands exploit the fact that people do certain things when they are in specific places such as in the library, the kitchen, or the living room. Different results occur based on the context in which they are issued. (4) Context-triggered actions are simple if-then rules that specify how context-aware systems should adapt. This class is similar to the contextual information and commands class, but the actions are invoked automatically according to previously defined rules.

Dey and Abown (1999) propose a different classification according to the features of context-aware applications. Compared to Schilit et al. (1994), Dey and Abown do not distinguish services and information, arguing that in most cases these concepts are difficult to distinguish, since it depends on specific scenarios whether data is used as information or as service. (1) Presentation of information and services to a user combines Schilit et al.’s proximate selection and contextual information and commands and adds the notion of presenting context (as a form of information) to the user. (2) Automatic execution of a service corresponds to Schilit et al.’s context-triggered actions. (3) Tagging of context to information for later retrieval describes the ability to associate digital data with the user’s context, a class which is not found in Schilit et al.’s classification.

**Context in Mobile Patient Monitoring**

A sub-discipline of mobile health, patient monitoring has been defined as “using technology to manage, monitor, and treat a patient’s illness from a distance” (Kay et al. 2011). Patient monitoring leverages modern mobile devices such as personal digital assistants (PDAs), smartphones, and tablet computers. The latest generation of these devices embed powerful sensors providing access to context information (Lane et al. 2010) about location (via GPS, WiFi access point and cellular tower location, and digital compass), orientation (via three-axis gyroscope), movement (via accelerometer), presence of nearby objects (via proximity sensor), and lighting (via ambient light sensor).

Studies about context-aware mobile patient monitoring applications mostly focus on specific medical use cases (e.g., medicine-taking, cardiac, and diabetes). For instance, Årsand et al. (2010) describe their lessons learnt when designing a mobile health application to assist patients with diabetes. Their study provides new insights to make mobile diabetes diaries more aware of their environment. The authors conclude, that to improve usability and convenience, future systems should have a stronger focus on context-awareness. Kumar et al. (2008) discuss the use of mobile devices for remote cardiac patient monitoring and argue that context-aware systems result in a better usability, which is essential for the use in a home-monitoring scenario. The mobile device should thereby adapt itself to the user and not vice versa. Liu et al. (2011) analyze 200 mobile applications in Apple Inc.’s App Store to provide an overview of the status and trends of iOS mobile health applications. They conclude that users disproportionately favored context-aware mobile applications that enhance both usability and utility of mobile applications. These insights are supported by Baldauf et al. (2007), who find that context-aware systems combined with mobile devices are of high value and could significantly improve usability. In another study, Wolf et al. (2013) measure the performance of four mobile applications that evaluate photographs of skin lesions. When the picture is evaluated, the mobile application provides the user with feedback about the likelihood of malignancy. The authors conclude that reliance of mobile applications is highly variable. For instance, measured sensitivity ranges from 6.8% to 98.1%. Through the increasing availability and openness of embedded sensors in mobile devices, these test results will eventually be more accurate in the future. The U.S. Food and Drug Administration (FDA) addresses quality and reliability issues by regulating the development of mobile medical applications (Barton 2012). The provided guidance document focuses mostly on mobile applications that present risks for patients if they do not work as intended. Mobile applications of which intended use is similar to that of an existing medical device (e.g., by using sensors) have been recommended for regulatory oversight in the U.S.
Technology-oriented approaches suggest mobile health frameworks targeting mobile application developers (e.g., Broens et al. 2007; Laakko et al. 2008; Paganelli and Giuli 2007). Paganelli and Giuli (2007) provide an ontology-based context model and a related application framework that focuses on alarm notification in chronic patient care. In a similar approach, Broens et al. (2007) suggest an application framework for supporting the development of context-aware mobile health applications. The framework seeks to facilitate the use of contextual information (i.e., context acquisition, context provisioning, and context reasoning) for user-tailored applications.

Research Opportunity

Nowadays, a rich set of examples exists that demonstrates the use of context-aware mobile patient monitoring applications in specific medical use cases. However, existing studies often do not clearly state what is meant by context and context-awareness. Scholars investigating single medical use cases only describe specific aspects of context in mobile patient monitoring. While such approaches are valuable to illustrate an emerging technology’s potential, it is oftentimes hard to imagine how the insights of a medical use case can be used when designing a mobile patient monitoring application in another context. Focusing on a technology perspective, several researchers have attempted to provide a context-aware framework to help software developers to implement mobile applications for patient monitoring. While such frameworks are valuable to ensure software component reusability, they target the project’s implementation phase rather than the actual design and conceptualization of a mobile patient monitoring application. We currently lack a holistic and comprehensive taxonomy of what context is in mobile patient monitoring and therefore do not fully understand context-aware behavior in mobile applications. Medical use cases in mobile patient monitoring will remain very specific, and a taxonomy cannot cover all these specificities. Designers must then adapt the taxonomy to meet their requirements, using only the concepts that are relevant in their specific context. Under such circumstances, a taxonomy can be seen as a valuable instrument to guide mobile patient monitoring application design. In this paper, we target the development of such a taxonomy and seek to answer the following research questions: (1) What are the relevant context dimensions in mobile patient monitoring? (2) How do mobile patient monitoring applications adapt to these context dimensions?

Methodology

The research we present here follows the design science research methodology, which is described as a build-and-evaluate process with the goal of producing a set of artifacts (Hevner et al. 2004). Our paper seeks to conceptualize artifacts that support the design of context-aware mobile patient monitoring applications. These artifacts were developed in a search process (Hevner et al. 2004) involving an iterative evaluation and refinement of the suggested conceptual models, based on systematic literature reviews and insights from extensive fieldwork.

As part of our research, we conducted a field study. One of the authors collaborated with two senior physicians and an epidemiologist to conceptualize and develop a context-aware mobile patient monitoring application targeting patients with age-related macular degeneration (AMD). The developed mobile application covers all three categories of context-aware features outlined by Dey and Abowd (1999): presentation of information and services to a user, automatic execution of a service, and tagging of context to information for later retrieval (see also the Related Work section). Owing to its comprehensive coverage of context dimensions and context-aware features, we argue that this case is particularly well suited for the purpose of our study.

Our research process follows the design science research methodology (DSRM) proposed by Peffers et al. (2007) (see Figure 1 for an overview). It is triggered by the (I) problem identification and motivation. Inspired by practical experiences from the field, we have come to realize that current literature provides little guidance on how to conceptualize and design a context-aware mobile patient monitoring application. The identified research opportunities motivate our study.

For this paper, we defined two concrete (II) objectives of a solution for the identified research gap. First, we seek to provide a holistic and comprehensive description of context dimensions in mobile patient monitoring, thereby creating domain-specific context models. Second, we seek to identify context-aware features in order to understand how mobile patient monitoring applications adapt to context. During the
(III) design and development stage, we inferred the requirements for our artifacts by drawing on theoretical foundations from the literature on context and context-aware computing (Dey and Abowd 1999; Schilit et al. 1994) as well as from the literature on context-aware mobile patient monitoring. For our objective 1, we use generic definitions from previous studies as a starting point to provide domain-specific definitions of context dimensions in mobile patient monitoring. To address objective 2, we first analyze the capabilities of seven context-aware mobile applications presented in current literature. Our field study allowed us to instantiate the initial conceptual models within a real-world case. The (IV) demonstration stage served as a review process. Through the close collaboration with senior physicians and a senior epidemiologist, we received constant feedback on our artifacts’ design. The collected data allowed us to evaluate and refine the initial conceptual models on context and context-aware features in mobile patient monitoring. Finally, we (VI) communicate the resulting artifacts of our research study in this paper, and we intend to do additional workshops with practitioners.

![Figure 1. Design Science Research Methodology (following Peffers et al. (2007))](image)

**Context and Context-awareness in Mobile Patient Monitoring**

**Context Dimensions in Mobile Patient Monitoring**

In their definition of context, Dey and Abowd (1999) focus on entities to characterize context, namely user, person, application, place, and object. By analyzing existing literature, we find similar entities in mobile patient monitoring. However, the entities proposed by Dey and Abowd are too limited to provide a precise description of context in mobile patient monitoring. We need a refinement of these entities to capture a comprehensive and holistic description of the relevant context dimensions. Since mobile applications in patient monitoring typically target patients as end-users, we use the following domain-specific terminology: patient (entity user) and mobile application (entity application). Various studies identify specific persons who contribute to context in mobile patient monitoring, namely relatives (Paganelli and Giuli 2007), care provider (Lee et al. 2006, 2007), and the patient community (Swan 2009; Triantafyllidis et al. 2013). From our field study, we gained additional insights and found evidence for disease-related information (i.e., medical knowledge bases), mostly resulting from medical research, as context in mobile patient monitoring. The widespread adoption of modern mobile devices allows medical researchers to target specific patient groups for clinical trials. Embedded sensors in mobile devices can provide rich contextual information while ensuring efficient and accurate data collection for research effort success. We assume that this discipline therefore largely benefits from the widespread adoption of context-aware mobile patient monitoring. Medical researchers can then transfer the findings from their research to clinical practice, either by developing further context-aware algorithms that consider the latest disease-specific research findings, or by communicating context information to the patient community, care providers, or patients. This addresses an important issue in medical research, given that nowadays only a fraction of research products is translated into practice (Pronovost et al. 2008; Tabak et al. 2012).
Table 1 summarizes the context dimensions in mobile patient monitoring. Given the adapted dimensions, we suggest a refinement of Dey and Abowd’s (1999) definition of context. Our definition is specific to the domain of mobile patient monitoring: Context is any information that can be used to characterize the situation of a specific dimension in mobile patient monitoring. Dimensions are relatives, care providers, patient communities, medical knowledge bases, computing environments, or places that are considered relevant to the interaction between a patient and a mobile application, including the patient and mobile application themselves.

<table>
<thead>
<tr>
<th>Entity (Dey and Abowd 1999)</th>
<th>Dimension</th>
<th>Description</th>
<th>References</th>
<th>Covered by field study</th>
</tr>
</thead>
<tbody>
<tr>
<td>User</td>
<td>Patient</td>
<td>Defined by various patient-related characteristics such as demographic data (e.g., age, sex, place of birth, and education level), patient consent for clinical studies, and medical history (e.g., diagnoses, examinations, medication, and risk factors)</td>
<td>For instance Årsand et al. 2010; Banos et al. 2014; He et al. 2014</td>
<td>Yes</td>
</tr>
<tr>
<td>Person</td>
<td>Relatives</td>
<td>Describes the relevant characteristics of a patient’s relatives such as availability, communication channels, and family medical history (e.g., diabetes, cancer, and cardiovascular diseases)</td>
<td>For instance Paganelli and Giuliani 2007</td>
<td>Yes</td>
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<tr>
<td>Care provider</td>
<td></td>
<td>Describes the care provider (e.g., treating physician, general practitioner, nurses, etc.) and their characteristics such as experience, medical specialty, availability, location, etc.</td>
<td>For instance Lee et al. 2006, 2007</td>
<td>Yes</td>
</tr>
<tr>
<td>Patient community</td>
<td>Social sharing and providing various disease-related information that inform and educate the community</td>
<td>For instance Swan 2009; Triantafyllidis et al. 2013</td>
<td>No, but potentially relevant</td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>Mobile application</td>
<td>Comprises device-related attributes such as sensing data (e.g., location and orientation of device), network connectivity, communication bandwidth, and functionalities (e.g., availability of front-end camera)</td>
<td>For instance Broens et al. 2007; Wac et al. 2009</td>
<td>Yes</td>
</tr>
<tr>
<td>Object</td>
<td>Medical knowledge bases</td>
<td>Describe relevant disease-related findings from medical research that eventually influence the treatment process for patients (or patient subgroups, i.e., personalized medicine), transfer research findings to practice (e.g., to care providers and patient communities)</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Computing environment</td>
<td></td>
<td>Surrounding objects supporting and influencing the interaction between the mobile application and the patient (e.g., server and physical objects embedded with sensors and network connectivity)</td>
<td>For instance Pawar et al. 2008</td>
<td>Yes</td>
</tr>
<tr>
<td>Place</td>
<td>Place</td>
<td>Characteristics of a physical place impacting the patient’s health condition (e.g., humidity, air quality, noise levels, and temperature)</td>
<td>For instance Chu et al. 2006; Mitchell et al. 2011</td>
<td>No</td>
</tr>
</tbody>
</table>
The context dimensions described in Table 1 are in direct relationship to each other. Compared to the entities identified by Dey and Abowd (1999), we distinguish, for instance, several persons (e.g., relatives, care provider, and patient community) that influence patient monitoring activities. To better understand the interactions among the context dimensions, we provide a conceptual model that illustrates the context dimensions and their relationships (see Figure 2).

![Figure 2. Domain-specific Context Dimensions in Mobile Patient Monitoring](image)

**Context-awareness in Mobile Patient Monitoring**

To better understand the context-aware behavior of current mobile patient monitoring solutions, we analyzed seven publications that present specific mobile applications (see Table 2). We base our analysis on Dey and Abowd (1999), using their suggested categories (i.e., activity, identity, location, and time) to identify aspects of context describing the context dimension patient. Furthermore, we classify the context-aware features of the mobile applications (see also Related Work section). For selecting the publications for our analysis, we looked into the academic literature databases of the Association of Information Systems (AIS) and Google Scholar. We used different combinations of the terms context, context-aware, mobile, application, patient, and monitoring to search the databases. We also analyzed two publications (Liu et al. 2011; Martínez-Pérez et al. 2013) that provide overviews of mobile health applications.

The analyzed mobile applications cover all the different context categories and context-aware features, illustrating the variety among the selected solutions. Interestingly, each mobile application uses a method to identify (I) the patient in order to provide personalized feedback or to tailor medical treatment. Only three of the mobile applications use sensor technology to analyze a patient’s activity (A). Thus, data collection often relies on manual input from the patient. By looking into the context-aware features, it is somewhat surprising that only two of the analyzed mobile applications explicitly mention a service that is automatically executed (E), while presentation of information and services to users (P) and tagging of context to information (T) were more frequent features. For instance, the eCAALYX solution, a mobile application for remote monitoring of elderly persons with chronic diseases (Boulos et al. 2011), informs clinicians when monitored health information exceed a certain threshold. However, all the analyzed mobile applications presented the patient with some information and feedback about the monitored data.
From Table 2, we synthesized that the context categories and the classification of context-aware features proposed by Dey and Abowd (1999) fit the domain of mobile patient monitoring. We then continued our analysis by looking into specific sensor technology (Lane et al. 2011) built into modern mobile devices. These sensors can provide in situ continuous contextual information on various aspects of mobile patient monitoring. Using the context categories activity, identity, location, and time, Table 3 suggests how these context categories relate to specific sensors. We thereby refine the categories activity and location, since we can differentiate different subcategories by analyzing current sensor technology. Especially for the category activity, various sensors (gyroscope, accelerometer, touch screen, and ambient light) allow one to differ specific context information used in mobile patient monitoring. Since our context categories relate directly to specific sensor technology, designers can then identify the hardware requirements for a mobile application.
Table 3. Context Categories and Related Sensor Technology

<table>
<thead>
<tr>
<th>Context category</th>
<th>Subcategory</th>
<th>Sensor technology</th>
<th>GPS</th>
<th>Proximity sensor</th>
<th>Gyro</th>
<th>Accelerometer</th>
<th>Ambient light</th>
<th>Camera</th>
<th>Touch screen</th>
<th>Microphone</th>
<th>Touch ID</th>
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<tr>
<td>Activity</td>
<td>Physical condition</td>
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<td>Gesture</td>
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<td>Identity</td>
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<td></td>
<td>Position and nearby objects</td>
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<td>Lighting</td>
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<td>Time</td>
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</table>

Figure 3 summarizes the relationships between the concepts context dimension, context category, and the classification of context-aware features. The identified context categories and subcategories from Table 3 allow us to describe each context dimension. At the same time, context categories enable specific context-aware features in mobile patient monitoring, often by using specific sensor technology (see Table 4). A context dimension might also serve as a data source for another context dimension (see the context dimensions and their relationships in Figure 2). The next section demonstrates how the provided conceptual models can be used to conceptualize a context-aware mobile patient monitoring solution.

Alleye: A Context-aware Mobile Patient Monitoring Application

In collaboration with two senior physicians of a Swiss cantonal hospital and a senior epidemiologist we conceptualized, developed and evaluated Alleye, a mobile application that seeks to monitor and tailoring the treatment process for patients with AMD. Current treatment regimens in AMD are sub-optimal, since they bear the risk of under-treating patients who require more intensive treatment. AMD is a form of sight...
loss caused by damage to the retina. The result is a shadowlike void in the center of a patient’s visual field. To date, 160 million people across the world suffer from AMD.

In the early phase of this project, it became clear that we heavily rely on context information to ensure reliable and valid testing of the retina. From a clinical perspective, the real-time validation of an eye test is crucial, since patients could easily falsify a test. Context information for validation was acquired via the mobile device’s embedded sensors. The server-side analysis of the collected data can then assign a patient to a specific patient cluster. This allows to provide a patient with personalized feedback on his or her course of illness, in order to later on tailor the treatment process in the hospital, i.e., personalized medicine.

**Mobile Application Design**

The mobile application provides a simple menu structure composed of patient data (identification and basic test parameters), instructions, eye test, and feedback on the performed tests (see the sample views in Figure 4). At the outset of the first test, every patient was provided with a unique patient identification. This identifier allowed the responsible physician in the hospital to match the patient’s data of the mobile application with the patient’s electronic health record in the hospital. At the same time, the involved medical researchers could use the identifier to recognize and group all the tests of a patient without the need to know his or her personal data.

The eye test is based on a computerized version of a vernier hyperacuity alignment task. Vernier acuity is the ability to detect a misalignment among lines or dots and is more accurate than visual acuity. The eye test seeks to localize damage to the retina. Before the test starts, the mobile application measures and approves the optimal distance between the patient’s eye and the screen (takes approximately five seconds). The optimal distance between eyes and device is between 30 cm and 40 cm, and the test is performed monocular, i.e., only the treated eye is open. Patients might try to change the mobile device’s position, searching for a preferred retinal locus, and thereby falsifying the test. This behavior can typically be observed by measuring the mobile device’s rotation via sensors. After performing a test, patients get an overview of the development of their test results and the frequency of testing.

The shared interface with the treating physician will allow for gaining remote access to medical care in urgent cases. Treating physicians in the hospital can then access real-time data of longitudinal treatment performance. They may receive alerts if eye test values exceed a critical threshold or can contact a patient in case of unexpected test results. The collected datasets might also be used in an anonymized format for research purposes.

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**Figure 4. Views of Alleye: Instruction, Eye Test, Distance Measurement, and Feedback**

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User data input was initially stored on the mobile device and then wirelessly transmitted to an external server. If a wireless connection was not available, the application stored the data locally until transfer to the server was possible. As soon as the datasets were successfully submitted to the server, the concerned datasets were tagged in the local database as being submitted. This prevented the mobile application from sending the same datasets twice. Data submission happened automatically and unobtrusively for the user in background tasks, so that these activities would not distract patients from undergoing the eye test. Transmitted data included a patient identifier, a detailed log of user interactions, and test results. Data was transmitted over secure sockets layer using the security protocol Transport Layer Security (TLS). No clinical information or patient names were transferred. Server-side algorithms will then allow a personalized optimization of the eye test both in terms of treatment intensity and thresholds for critical test values.

Since the patients were not familiar with the use of mobile devices, we observed in our clinical study that they relied on their relatives for support (e.g., how to charge the mobile device’s battery). On the other hand, patients were somehow proud to be part of such a clinical study and showed the prototype mobile application to their relatives. The relatives then also started to try the mobile application and to perform the eye test themselves.

**Context Dimensions and Context-awareness in Alleye**

To design and conceptualize our mobile application, we used the previously presented conceptual models to structure and define the aspects of context that will be useful in our application. Through the extensive fieldwork we could then refine our initial conceptual models. The following table summarizes context dimensions, context categories, and context-aware features of Alleye. Based on the concepts of Dey and Abowd (1999), we distinguish the following context-aware features: P = presentation of information and services to a user, E = automatic execution of a service, and T = tagging of context to information for later retrieval.

To conceptualize Alleye, we used the context dimensions patient, care provider, relatives, mobile application, medical knowledge bases, and computing environments. Relatives had an interesting role in our field study: they influenced the context in which eye test was performed by supporting the patient, a phenomenon that was not visible in the collected data. It was only through interviews with patients that we could find the influence of this context dimension. This provides evidence that, as modeled in our artifact, context dimensions inform each other. Compared to the previously analyzed mobile applications (see Table 2), we relied heavily on context-aware features that automatically execute a service (E). Data collected from a patient’s activity should be tagged for later retrieval (T). For instance, in our clinical study, we provided the patient not only with his or her latest test results but also place these test results in context by comparing them to previous test results. In future scenarios, these test results can also be related to other medical data (e.g., date of injections at the hospital). In our field study, we mainly used the presentation of information (P) to inform the patient about warnings, when he or she did not correctly perform the eye test.

| Table 4. Context Dimension, Context Category, and Context-aware Features of Alleye |
|-----------------------------|-----------------|----------------|----------------|
| Dimension | Category | Description | Context-aware feature | Sensor technology |
| Patient | Identity | Unique identification code provided by the hospital to anonymously match the data on mobile device with the patient’s health record | Display patient information (e.g., name and birthday) | Presentation of test performance | Results tagged with time-stamps |

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<table>
<thead>
<tr>
<th>Patient</th>
<th>Activity: Physical condition</th>
<th>Verify that the eye test is performed monocularly (nontreated eye closed)</th>
<th>Provide a warning when both eyes are open</th>
<th>Front-end camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient</td>
<td>Activity: Gesture</td>
<td>Measuring patients uncertainty by logging his or her behavior while performing the eye test (e.g., number of corrections)</td>
<td>Tag the data with time-stamps for later analysis</td>
<td>Touch screen</td>
</tr>
<tr>
<td>Care provider</td>
<td>Activity</td>
<td>Initial instructions influencing how and when eye test is performed; feedback during follow-up visits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relatives</td>
<td>Activity</td>
<td>Providing support in the usage of the mobile device</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile application</td>
<td>Location: Position and nearby objects</td>
<td>Measure distance between treated eye and mobile device, calculated via optical method</td>
<td>Present a warning when the distance is outside the specified range</td>
<td>Tag the data with time-stamps for later analysis</td>
</tr>
<tr>
<td>Mobile application</td>
<td>Location: Position and nearby objects</td>
<td>Control rotation of mobile device to limit visual axis</td>
<td>Present warning when the rotation is outside the specified range</td>
<td>Tag the data with time-stamps for later analysis</td>
</tr>
<tr>
<td>Mobile application</td>
<td>Time</td>
<td>Every user interaction was tagged with time-stamps</td>
<td>Tag the data with time-stamps for later analysis</td>
<td></td>
</tr>
<tr>
<td>Mobile application</td>
<td>Activity</td>
<td>Availability of network connection</td>
<td>Transfer of test results</td>
<td>Network connection</td>
</tr>
<tr>
<td>Medical knowledge bases</td>
<td>Activity</td>
<td>Assign patient to patient cluster based on test results in order to individualize eye test and treatment process</td>
<td>Personalize the eye test based on patient cluster</td>
<td></td>
</tr>
<tr>
<td>Computing environment</td>
<td>Activity</td>
<td>Availability of server-side services</td>
<td>Transfer of test results</td>
<td>Network connection</td>
</tr>
</tbody>
</table>

**Evaluation**

*Mobile application development:* In technical reviews of the mobile application, we eliminated the technical errors and ensured that the mobile application functions correctly. To do so, we conducted meetings every second week to evaluate the current prototype in the project team. Each meeting has lead to new requirements and guided the development of the next prototype version. Data collected during meetings and the evaluation of prototypes informed the design of our conceptual models and allowed us to refine the artifacts. Overall, 42 prototypes were created. After a project duration of 18 months, we engaged in a more naturalistic evaluation and tested our concepts in a clinical study, receiving insights from physicians and patients to further refine the conceptual models.

*Clinical study:* In our research process, we not only instantiated our conceptual models in a mobile application, but also evaluated this instantiation within a clinical study. Through this study, we could finally evaluate the usability of Alleye with potential end-users, which provided us with further insights
for the development of our conceptual models. For the clinical study, every patient was provided with a fifth-generation Apple iPod touch with the pre-installed mobile application. The participants provided written informed consent, and the clinical study was approved by the ethics committee. All patients attending an ophthalmological consultation at the Retina Centre of the Swiss cantonal hospital between June and October 2014 were evaluated for inclusion in this study. Patients were excluded if they were unable to use the mobile patient monitoring application, i.e., owing to cognitive or visual problems.

The research assistant configured two specific settings for each patient. First, she randomly assigned a navigation option for the patient. Two navigation options were available: A patient would perform the eye test either by interacting via buttons or via touch gestures. The second setting was the contrast: the eye test’s background was either white or black. These settings allowed researchers to assess whether navigation option and contrast would influence test results and usability. The second view in Figure 4 illustrates the navigation option with up and down buttons and a black background. The research assistant instructed patients in the proper use of the device and assisted patients when completing the test for the first time. During the clinical study, the test should be executed three times per week, between two routine clinical visits (approximately one month). After data cleaning, 240 eye test measurements of 17 patients were available for the analysis. Patients had a mean age of 78.1 years. The proportion of women was 53%.

Concerned patients are typically older than 50 years and not familiar with modern touch-based mobile devices. It was therefore particularly challenging to design a mobile application that was easy to use and that would also deliver reliable and valid test results for the treating physician. After two months, patients returned to the clinic to give oral feedback on user-friendliness, to answer pre-defined questions of interest, and to fill out the System Usability Scale (SUS). The SUS, originally developed by John Brooke (1996), is a valid and reliable tool for measuring usability. It consists of 10 items with response options each on a Likert scale (ranging from 1 = strongly agree to 5 = strongly disagree). Recent research shows that the SUS provides a global measure of system satisfaction as well as additional subscales for usability and learnability (Lewis and Sauro 2009). Because the patients who took part in our clinical study were native German speakers, we used the German translation of the SUS released in a crowdsourcing project by Wolfgang Reinhardt (Reinhardt 2012). For the German translation, usability experts submitted proposals that were consolidated and then translated back into English by native speakers, to ensure the translated items had the intended meaning. Based on the 500 tools that have been investigated as reference, a SUS score higher than 68 is considered to be above average (Lewis and Sauro 2009; Sauro 2011).

![Figure 5. Boxplot of the SUS score: percentile ranking from 0 to 100](image)

The score may not be seen as percentages; it should be considered in terms of percentile ranking. SUS scores among the 17 patients included in our clinical study ranged between 28 and 100. The average SUS score was 77, with a single outlier, and 76.5% of all patients had an above-average score (see Figure 5). Interestingly, 13% of the participants use a smartphone daily, while 60% never used one. All patients that use their smartphone weekly or daily strongly agreed that the mobile application is easy to use. It is therefore critical to facilitate ease-of-use for patients who have never used a smartphone. Even though the mobile application was very minimalistic, patients rarely asked for more information (13%). Of the patients, 86% agreed or strongly agreed that they were satisfied with the application. Overall, patients agreed or strongly agreed that application was efficient (94%) and effective (86%) to use. None of the patients disagreed that the mobile application would improve his medical care.
Conclusion and Future Work

Modern mobile devices have substantial potential in patient monitoring and will enable new avenues for delivering care. Sensor-enabled mobile devices allow one to continuously collect contextual information that, when a patient’s privacy is respected, benefit the patient’s health and facilitates the care providers’ work. At the same time, context-aware mobile patient monitoring applications enable medical researchers to reach more participants for their studies and to collect a vast amount of data, which will increase the success of their research. Despite this potential, we currently lack a comprehensive understanding of what is meant by context and context-awareness in mobile patient monitoring.

Our paper made two primary contributions. First, building on generic definitions and prior work about context in computing environments, we provide a conceptual model for context dimensions in mobile patient monitoring. Thereby, we directly answered our first research question: What are the relevant context dimensions in mobile patient monitoring? Our model on context dimensions revealed the importance of various stakeholders (e.g., relatives, care providers) and disease-specific insights from medical researchers contributing to the value creation in context-aware mobile patient monitoring. Our second contribution are insights into the use of context-aware features in mobile patient monitoring, allowing us to identify and define context aspects and providing an answer to the question: How do mobile patient monitoring applications adapt to these context dimensions? The analysis of mobile patient monitoring applications presented in current literature shows that context-aware features are up to now mostly restricted to the presentation of information and services to a user and the tagging of context to information for later retrieval. Our field study reveals the execution of automated services as a very relevant domain for monitoring specific diseases and for contributing to personalized medicine. The second result comes with a limitation, since we did not search for context-aware mobile patient monitoring applications in public app stores that might not be present in scientific literature databases. It remains to be seen whether these applications provide more advanced context-aware features.

This study is a first attempt to formalize the concepts of context and context-awareness in mobile patient monitoring, seeking to provide scholars and practitioners with a consensus about the vocabulary needed to describe these concepts when designing mobile applications. The provided artifacts extend existing theoretical conceptualizations of context-aware applications to account for the specificities of mobile patient monitoring. A taxonomy that seeks to provide a holistic and comprehensive description of context in mobile patient monitoring comes with certain limitations. Context describes the entire situation relevant to a specific application and its users. A taxonomy can only enumerate the set of dimensions and aspects that may potentially be relevant for a context-aware mobile patient monitoring application. Hence, it needs to be adapted to specific medical use cases in order to identify the relevant context dimensions and context-aware features. For instance, in one case, observing the patient’s place might be the most important aspect, while in another medical use case, this feature might be completely obsolete. In our field study we demonstrate that a taxonomy can provide valuable guidance in the design of a context-aware mobile patient monitoring application. Our empirical insights are mostly related to one project that resulted in a successful clinical study. Further applications are therefore needed to evaluate our artifacts. These mobile patient monitoring applications allow then a refinement of the suggested conceptualizations.

New theories offer promise to explain the richer patterns of real-life practice, and we see various interesting avenues for future research. As mentioned, more research is needed to further formalize the concepts of context and context-awareness. These models are fundamental to designers for identifying and defining the context-aware behavior they would like to implement in their mobile patient monitoring applications. Our study might provide the basis to formalize domain-specific design principles that guide the development of frameworks that help software developers to implement context-aware features in mobile patient monitoring. Our model on the relevant context dimensions in mobile patient monitoring illustrates that context-aware mobile patient monitoring impacts various stakeholders such as care providers, relatives, the patient community, and – eventually – medical researchers. While our paper investigated these phenomena from a fairly technical perspective, we encourage IS scholars to also look into the more social aspects (e.g., impact of physicians’ work patterns and patients’ behavior) of mobile patient monitoring. We hope to be able to discuss these issues more fully in follow-up work.
References


