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Pervasive Computing for Hospital, Chronic, and Preventive Care

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Abstract

An emerging area of great impact and significance is the application of pervasive computing technologies in healthcare. Pervasive healthcare refers to the set of technologies designed to seamlessly integrate health education, interventions, and monitoring technology into our everyday lives, regardless of space and time. This approach can increase both the coverage and quality of care. Over the last decade, pervasive computing solutions for healthcare have become increasingly prevalent in both research and commercial efforts. This survey analyzes a variety of research projects and commercial solutions devoted to understanding, designing, and implementing pervasive healthcare applications in support of preventive care, hospital care, and chronic care.

Taking into account the working conditions of clinicians and the needs of patients, pervasive computing offers a variety of attractive solutions for many of the challenges to care delivery in these domains. The work of clinicians is intrinsically tied to the physical domain of

the patient, not to digital material available in computer systems; clinicians as well as other non-clinical caregivers continually switch between different caregiving contexts. Furthermore, their work is characterized by high mobility, *ad hoc* collaboration, and interruptions. At the same time, patients and family members frequently demonstrate poor adherence to both behavioral and pharmaceutical interventions and experience inadequate communication with those providing care. The use of health education to promote motivation, reinforcement, advice, and tools for capturing and tracking health information supporting self-monitoring can help patients to overcome these challenges. Pervasive computing offers solutions for clinicians, patients, and a variety of other caregivers to assist them with these problems including applications and mechanisms to:

- ease the recording, tracking, and monitoring of health information;
- allow communication, collaboration, and coordination among the varied stakeholders;
- encourage clinical adherence and disease prevention;
- support the nomadic work of clinicians and seamless integration of the physical and digital worlds; and
- enable the development of novel medical devices.

In this survey, we present an overview of the history of pervasive healthcare research as a human-centered vision driven by a healthcare model that includes preventive, hospital, and chronic care. We then summarize the research in this space, outlining research challenges, current approaches, results, and trends. Finally, we discuss future research directions as a springboard for new focus in pervasive healthcare. This survey is based on analysis of the literature as well as our own research experiences and those of many of our colleagues.

1

Introduction

The challenges of integrating more complex interventions into both hospital and home care are changing how healthcare is delivered. Many experts now advocate a move toward a more patient-centered approach. In this model, patients take greater responsibility and accountability for their own health with clinicians often acting more as expert consultants than the primary caregivers. A key feature of this patient-centered approach is that care is provided in a more distributed manner. As Bardram et al. argue:

> *"The [current] healthcare model needs to be transformed into a more distributed and highly responsive healthcare processing model, where locally available and distributed [tools] can help empower patients to manage their own health in the form of wellness management, preventive care and proactive intervention" [58].*

Mobile, pervasive, and ubiquitous computing technologies offer promising solutions to documenting progress, diagnosing conditions, and treating and managing care in this patient-centered approach. In this survey, we examine the role that novel mobile, pervasive, and ubiquitous computing technologies can play in monitoring and analysis of health conditions to support preventive, hospital, and chronic care. Additionally, we examine the ways in which many of these technologies are reinventing the modern healthcare experience. This broad area of research and practice is often referred to as pervasive health, a term we use throughout this survey.

1.1 The Opportunity of Pervasive Healthcare

Pervasive computing, ubiquitous computing, and ambient intelligence are concepts evolving from the development and deployment of pervasive applications, frequently in the healthcare domain and are most of the time mentioned in the healthcare context [32]. Initial visions of pervasive and ubiquitous computing describe environments furnished with computational artifacts that remain in the background and have intelligent capabilities to support user-centered activities [201, 236, 237, 238]. Mark Weiser described a future of smart environments as:

> *"a physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, embedded seamlessly in the everyday objects of our lives, and connected through a continuous network [238]."*

The increasing availability of heterogeneous devices wirelessly interconnected, and advances in both hardware and software are gradually making Weiser's vision a reality.

The application of this vision to healthcare demands an interdisciplinary approach, borrowing methods and techniques from computing fields, such as Ubiquitous Computing, Context-aware Computing, Human–Computer Interaction (HCI) and Artificial Intelligence (AI) as well as medicine, nursing, public health, occupational therapy and health education. The complex healthcare environment requires a detailed understanding of user context. Additionally, these settings necessitate design that accounts for diverse and non-specialist users through simple and natural means of interaction. Finally, pervasive health systems need intelligent capabilities to be adaptive to users, reactive to context, and capable of learning from user's behavior to provide high quality services based on user preferences.

Pervasive health applications range from wearable and embedded sensors that assist in self-care (e.g., [39, 78, 87, 88, 102, 144]) to hospital environments enhanced with pervasive computing technology (e.g., [13, 14, 15, 16, 21]). Pervasive health includes a variety of definitions, often emphasizing different aspects of the research agenda in this domain [58]; but all emphasize the primary goal of supporting the patient, the caregiver, and the clinician through the use of mobile, pervasive, and ubiquitous computing technologies.

> *"...the use of mobile/wearable/environmental technologies that have come out of the ubicomp/pervasive research communities that is targeted at some challenge associated to health. The health part of it could be addressing issues of diagnosis or treatment that leads to increased medical knowledge(what we would consider medical or biomedical research) or it could be related to work that is contributing to the science or engineering of healthcare delivery." (Gregory Abowd)*[1] [58]

> *"...research on ubiquitous technologies both for supporting clinicians working in a hospital or other health institutions,as well as patients — and more generally citizens — themselves.The goal in the former case is to create technologies that help clinicians better treat and care for patients; in the latter case that patients become more capable and resourceful in their own disease management. Pervasive healthcare technologies can of course also be a hybrid of these two types of systems — that is,having systems that help patients manage health-related issues inclose cooperation with clinical staff at a hospital" (Jakob Bardram) [58]*

[1] *Discussed definitions were presented in the first pervasive health column of IEEE Pervasive Computing [58].*

> *"A new wireless health research field and industry . . . at the convergence of personal mobile wireless devices, networked sensing, and new embedded computing systems directed to advancing the quality and accessibility of healthcare" (Bill Kaiser) [58]*

As the quotes highlight, healthcare is a promising research area for pervasive computing, and likewise, pervasive computing is a promising new direction for health research. Pervasive computing capabilities can be used not only to support hospital work [13, 21] but also to shift care toward the home, thereby enhancing patient self-care and independent living. *"Anywhere and anytime"* are becoming keywords that are often associated with pervasive health. Due to the emphasis thus far on the design and development of pervasive health technologies, there has been less focus on understanding the impact of pervasive health applications on important healthcare issues such as medical errors and users' concerns such as privacy and security. The social, economic and ethical concerns regarding the use of pervasive computing [31, 219] are also extremely relevant in this domain and open new areas of research for scholars to pursue.

In this survey paper, we briefly note the origins of pervasive health and relevant projects that describe key areas of interest, providing an overview of the extensive literature in pervasive technologies that support patients, clinicians, and other stakeholders. In this survey, we highlight design issues and the impact of using these technologies in everyday practices. We primarily draw on the research literature in relevant conferences, such as CHI,[2] Ubicomp,[3] PervasiveHealth,[4] and Pervasive,[5] as well as relevant journals, such as Personal and Ubiquitous Computing[6] and IEEE Pervasive Computing,[7] as well as our own research experiences and those of many of our colleagues. However, readers should be aware that there is a great deal of related literature

[2] *http://www.chi2011.org/*
[3] *http://www.ubicomp.org/*
[4] *http://www.pervasivehealth.org/*
[5] *http://pervasiveconference.org/*
[6] *http://www.springerlink.com/content/106503/*
[7] *http://www.computer.org/portal/web/pervasive/home*

in the medical informatics domain primarily focused on tools, devices, and methods required to optimize the acquisition, storage, retrieval and use of information in healthcare. Additionally, relevant literature can be found scattered amongst public health, nursing, medical, gerontology, mental health, and other journals. Our aim, here, is not to provide a comprehensive review of all of the relevant literature in this vast interdisciplinary space. Instead, this survey describes the field of pervasive healthcare in a way that prepares newcomers to tackle some of the most important issues and that identifies upcoming trends in this important research space. The general inclusion criteria for the projects discussed in this paper included, papers discussing issues related to:

- mobile devices (e.g., laptops, PDAs, tablet PCs, mobile phones),
- wearable and on-body sensors (computer-enhanced textiles or medical sensors),
- natural interfaces,
- stationary devices embedded in "everyday objects" or infrastructure, such as buildings, furniture, etc.
- systems and context-aware services with elements of "intelligence,"
- pilot studies and case studies conducted in health care settings for understanding healthcare needs and the use of pervasive applications

1.2 The Healthcare Model and Contemporary Computer Technology in Healthcare

Pervasive computing entered health care in a variety of settings, making it difficult to frame a paradigmatic vision of a pervasive health system. The relevant settings that the pervasive computing literature has tended to examine can generally be divided across two axes (Table 1.1): system users and system purposes. System users include health care professionals (i.e., nurses, psychologists, and clinicians), caregivers (i.e., family, friends) and patients. Even though, in most cases, several stakeholders are involved in the use of a system (e.g., a *patient* captures

Table 1.1. Overview of the projects discussed in this survey[8]

Application themes by domain (total)/(%)	Healthcare Users		Care purpose		
	Caregivers	Patients	Preventive	Hospital	Chronic
Natural interfaces	4	14	1	4	13
Context-aware computing and pervasive monitoring	22	21	1	22	20
Capture and access tools and self-care management	17	25	15	6	11
Collaboration and coordination	10	22	15	6	11
Pervasive games		7	7		
Robots		6	1		5
Total (n = 148)	**53**	**95**	**39**	**39**	**70**

his/her heart rate that could be later reviewed by his/her *relatives* and *healthcare providers*), in most cases, we can still identify a primary user who benefits from using the system. For the purpose of this survey we define the user as the *"person who primarily interacts with and has benefited from the system."* The system's purpose can be divided into preventive, hospital, and chronic care. In this survey paper, we discuss close to 150 projects from the academic and commercial domains. Although we tried to balance the discussed projects according to each dimension (i.e., healthcare users and the purpose of care), the selected projects reflect the body of work we identified in each domain. Certainly, this discussion does not and cannot include every piece of technology related to healthcare. The field is moving quickly; new products reach the market and new research projects are launched each day. In this survey, we focus on those technologies that have been empirically validated in the literature and only highlight those commercial products that are particularly popular or relevant to the evidence-based solutions from research.

[8] *We did not include in the table projects discussing methods and tools in support of the research and Pervasive Healthcare, and studies conducted for understanding healthcare user needs because we wanted to reflect on the application themes available in this community.*

In this section, we discuss the different areas of health and wellness and current health technology to highlight how computing research in healthcare is evolving toward pervasive health.

1.2.1 Personal Informatics and Games for Preventive Care

Behavior and lifestyle choices (e.g., smoking, obesity, and inactivity) contribute to increased prevalence of chronic degenerative diseases and premature deaths [52]. For example, the worldwide obesity phenomenon and associated diabetes are "*becoming the main epidemic of the 21st century*" [223]. This growing phenomenon — largely as a result of changes in the modern lifestyle and food systems — placed a heavy burden on the hospital and healthcare sectors. Indeed, many chronic diseases and premature deaths are linked to common preventable risk factors (Figure 1.1).

Prolonged alcohol and tobacco use, unhealthy nutrition, and physical inactivity are some of the major causes of preventable chronic degenerative diseases [52]. Public health researchers and officials alike have argued heavily for strategies to enable and support behavior change in those with high risk factors. Thus, in recent years, a variety of governments have created preventive health programs targeting behavior

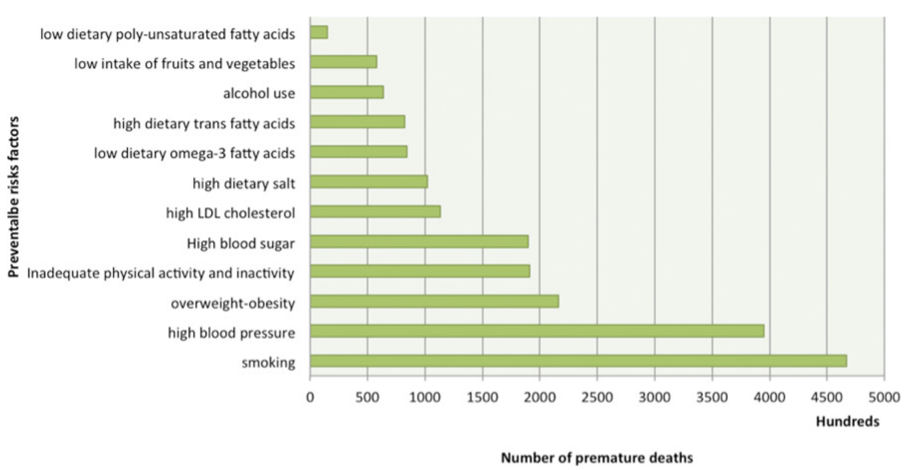

Fig. 1.1 Preventable risk factors for premature death in the United States [52].

change (e.g., obesity, food safety, and infectious disease prevention[9]) as an alternative method using health education to preventing diseases and encouraging people to take on the responsibility of self-care. Preventive *health care or preventive medicine* refers to measures taken to prevent diseases, or injuries, rather than curing or treating them [199]. It is about giving *"your body the best chance of remaining free from disease"* [199].

One historical root of pervasive health applications derives from interest in this kind of preventive support as well as the general concepts of persuasive technology [45]. These applications have included technologies to support preventive health education (e.g., media for health education), personal self-reflection (e.g., personal health informatics and personal healthcare information management) and behavior change (e.g., games). Some of the available technologies in this space include multimedia educational videos and web-based portals, virtual communities (e.g., [215]) and games (e.g., BrainAge). Most of these solutions include a variety of print, graphic, audiovisual, and broadcast media programs intended to influence behavior change. For example, the Brain Age games from Nintendo DS *"help to stimulate your brain and give it the workout it needs through solving simple math problems, counting currency, drawing pictures on the Nintendo DS touch screen, and unscrambling letters."*[10] Educational health games facilitate learning through simulation of disease consequences or trivia-based designs [12].

Other available solutions for supporting preventive healthcare are tools for empowering users to collect *"the necessary personal information for insightful reflection"* [139]. As defined by Li et al. [139] personal informatics systems are those that

> "*help people collect personally relevant information for the purpose of self-reflection and gaining self-knowledge.*"

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[9] *http://www.healthyamericans.org/*
[10] *http://brainage.com/launch/index.jsp*

In personal informatics, people participate in both the collection and analysis of behavioral information. Indeed, integrating personal health information helps people manage their lives and actively participate in their own health care [186]. For example, the Personal Healthcare Record (PHR) [1, 225], is a self-managed personal medical record where individuals update their own health data.[11] A PHR [225] is an:

> *"An electronic application through which individuals can access, manage and share their health information, and that of others for whom they are authorized, in a private, secure, and confidential environment."* [225]

The health data in a PHR might include family history, lab results, imaging reports, data gathered from medical devices, illnesses, and hospitalizations. Current implementations of PHR include electronic and web-based PHR(e.g., iHealthRecord[12] and IBM[13]). Some of the benefits of the PHR for patients include more knowledge about their health, increased participation in their medical care, and more knowledge about clinical decision-making [147]. Furthermore, pervasive health applications could be potentially connected to these PHRs and provide a variety of patient data to the record.

1.2.2 Information Technology for Hospital Care

Hospital environments are filled with increasingly complex technologies, and in these environments, highly mobile staff require greater coordination and collaboration among specialists for adequately and timely patient care delivery. Traditional computer technology in hospitals includes technology for managing and sharing health information and applications for support health provider's decision-making [213]. Electronic medical records (EMRs) aim to make hospital workflows more efficient, improve the quality of patient care and reduce costs [99, 216]. Likewise, the use of voice-over-IP (VoIP) systems has started to unify

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[11] *The personal health record provides also a summary of the Electronic Medical Record (EMR) managed within health institutions.*

[12] *iHealthRecord. Available at: http://www.ihealthrecord.org. Accessed March 14, 2006.*

[13] *IBM breathes new life into healthcare. Available at: http://www.ibm.com/news/us/en/2005/11/2005_11_08.html. Accessed March 14, 2006.*

and streamline communications,[14] and the use of Picture Archiving and Communication Systems (PACS) offers faster access to diagnostic information, reduces the need for film and film storage, and increases radiologist and clinician satisfaction and productivity [226].

Clinical decision support systems (CDSS) are tools to assist clinician decision-making [213]. Although, these systems have mainly had a positive impact for drug dosing and other aspects of medical care, there are still open questions about whether these tools help in diagnosing [111]. The opportunity to integrate these devices, databases, and networking in the current hospital environment into a truly interconnected pervasive health experience represents that primary challenge for the branch of pervasive health applications focused on supporting the clinical experience.

1.2.3 Assisted Technologies for Chronic Care

As the population ages and acute care improves survival rates for a variety of illnesses affecting all age ranges, the prevalence of chronic diseases continues to grow. The increasing growth rate of individuals managing chronic conditions will increase the demands on healthcare workers, family members, the pharmaceutical industry, medical technology, and insurers to meet their needs. Consequently, many leading experts and policy advocates predict a severe strain on resources in trying to meet this demand.[15] According to the World Health Organization (WHO), between 1950 and 1980 the percentage of older adults of the world population was approximately 8%; after 2000 it was estimated that this figure will increase to 21.4%.

Chronic health conditions typically include all impairments or deviations from the norm [195] that last three or more months [182]. Chronic care refers to medical care that addresses preexisting or long-term illness, as opposed to hospital care, which is concerned with short-term or severe illnesses of brief duration. Although chronic care is more

[14] *Why VoIP is the Becoming the Telephone System Choice For Hospitals in the UK. http://EzineArticles.com/?Why-VoIP-is-the-Becoming-the-Telephone-System-Choice-For-Hospitals-in-the-UK&id=2110277*

[15] *American Productivity and Quality Center. Available at: http://www.apqc.org/portal/apqc/site/generic2?path=/site/industry_focus/industryfocus_healthcare.jhtml*

common in the elderly, children, teenagers, and young adults also have to deal with chronic issues as well.

Assistive technologies help people with chronic and debilitating illnesses to live with greater independence, safety, and community integration. Assistive Technologies [133] is an umbrella term for defining:

> *"devices and other solutions that assist people with deficits in physical, mental or emotional functioning to perform actions, tasks and activities."*

Available assistive technologies for chronic care include applications for rehabilitation or compensation, health monitoring and community informatics.

Most traditionally available assistive technologies include systems and special devices for rehabilitation and/or the compensation of a lost skill. Examples of these technologies include electronic wheelchairs, visual and hearing aids, cognitive support systems, and augmentative and alternative communication technology. For example, patients with verbal impairments can use paper and electronic-based pictures, choice boards [159, 160], or text-to-speech software [207] to communicate their needs (e.g., requesting food).

The long-lasting nature of chronic illness makes record-keeping and long-term analysis of diagnostic and evaluative measures both extremely important and also very challenging. Not only must symptoms, interventions, and progress be documented over very long periods, but they must also often be recorded in the midst of daily activity. Thus, technologies in support of chronic care include applications for facilitating health data capturing. For example, health monitoring systems include biometric devices for the monitoring of patients, physiological parameters, and biological measurements (e.g., ECG, arterial oxygen saturation, and blood pressure). There is also increased interest in telemedicine and surveillance systems for monitoring patients' activities and behavior [56, 125]. The main goal of health monitoring is to allow caregivers and health providers to detect potential problems reducing unnecessary hospitalizations and health emergencies. As conditions grow in complexity and care moves from a centralized clinic setting to being distributed throughout homes and other environments, health records management will require equally complex, distributed, and integrated solutions. Pervasive health not only offers a variety of opportunities in this kind of connectivity and multi-device platforms but also represents a kind of paradigm shift from a model of manual clinician-directed documentation to one that includes system automated and patient-initiated documentation.

Finally, applications for social support can be particularly important to help people with chronic conditions meet people with the same needs, exchange experiences, and find the needed social support for coping with their diseases. In the domain of community informatics [90], traditional information and communications technology is being used to enable users share experiences and gain social support empowering community process. In the medical area, virtual communities have been successfully used in the care of patients [107, 215]. Their benefits include the reduction of stress, social satisfaction, opportunistic access to information relevant to their disease, and increased communication between patients and clinicians [211]. For example, PatientsLikeMe is a virtual community through which people with chronic diseases have an online community for both resources and support [7]. Pervasive health offers a compliment to these current solutions in terms of supporting socialization and support through a variety of mobile, location-aware, and networked systems.

1.3 Conclusion

As seen through this brief examination of current technologies that support health and wellness, pervasive health has a diverse set of origins addressing a variety of challenges. Current IT solutions, while beneficial in many ways, do not provide the natural affordances that enable access to healthcare *"anywhere and anytime."* For example, when hospital information systems are evaluated, about three quarters of these systems are said to have failed [10, 239] and there is no evidence that they improve health professionals' productivity [82]. In the modern hospital environment, workers spend only a fraction of their work shift in front of a computer and more than twice of their time "on the move" [22, 23, 164, 196, 197]. Consequently, pervasive computing may be very useful in supporting preventive, hospital, and chronic care.

There are many ways to organize and discuss the literature in pervasive healthcare: across domains, across diseases or across users' roles. In this survey, we describe the literature in light of the paradigm shift currently occurring as healthcare is more decentralized geographically and administratively but connected technologically, following the patient-centered model of care. Specifically, we first describe the use of highly networked innovative services in the hospital and clinical setting. We then describe the ways in which some of these technologies as well as new ones not seen in clinics are making their way into home care and assistive technologies for the chronically ill. We then describe a vision for the future that involves some of the most recent trends toward preventive health and wellness applications. Finally, we close with a discussion of the pervasive health design space in light of common methods and application areas in ubiquitous and pervasive computing. This organization enables the reader to follow how specific problems in contemporary healthcare have motivated and driven many researchers to design, develop, and deploy pervasive health applications as well as to understand the potential future trends and open research questions in the community.

2

Pervasive Computing for Hospital Care

The desire to improve patient care drives the design and implementation of new technologies in the hospital. In the past few decades, there has been an enormous investment worldwide in hospital information systems. Even though healthcare is often slower than other industries in adopting new information technologies, hospitals have moved quickly to deploy technologies to improve patient care, reduce costs, and medical errors [73]. However, a number of challenges still remain.

Health care providers face working conditions that are substantially different from those of office workers — the basis for the design of traditional desktop based hospital information systems [22, 23, 33]. Clinical work demands close coordination and collaboration amongst specialists distributed across both space and time. So, most clinicians need to continuously move around hospital premises to access people, knowledge, and resources [22]. For instance, clinicians make daily "rounds" to evaluate and diagnose patients. In addition to seeing patients, clinicians and nurses also may need to go physically to various locations to find relevant clinical information (e.g., patient records, x-ray images). This information is not generally concentrated in a single place but distributed among a collection of artifacts in different locations.

For instance, even in hospitals that have implemented substantial electronic medical records infrastructure, patient records can be found electronically and in paper folders located in patient rooms, labs, common areas, or offices. Consequently, the hospital is a large and complex information space and clinicians have to navigate this space effectively in order to do their work [33].

The challenge of supporting mobile work in this information space is motivating the widespread adoption of handheld devices in support of clinical work. Clinicians, in particular, are increasingly using handheld computers in their professional practice. It was estimated that 26% of all clinicians in the United States used a handheld in 2001, a number that was expected to grow to 50% for 2004 or 2005 [38]. In fact, several medical schools in the United States require students to have mobile devices. Approximately 60% to 70% of medical students and residents use PDAs for educational purposes or patient care [117]. The UCLA's David Geffen's School of Medicine established this requirement *"to enable 'point of contact' access to information resources; and to prepare students for practicing medicine in the 21st century"*[1]; and the UCI medical school as part of their iMedEd Initiative developed a comprehensive iPad-based curriculum *"reinventing how medicine is taught in the 21st century and becoming the first in the nation to employ a completely digital, interactive learning environment for entering students"*.[2]

This trend has generated interest in the development of medical applications for mobile devices [131]. Mobile devices wirelessly connected to hospital information systems can give clinicians access to patient medical records from anywhere in the hospital. Even with their limited screen size there are clear advantages from having this increased availability of information [132] such as allowing clinicians to more quickly respond to a change in the patient's condition. However, based on several systematic reviews of the use of hospital information systems by clinicians, the most popular handheld medical applications are ones that provide access to reference material. In these reviews, more than

[1] *www.medstudent.ucla.edu/pdareq/*
[2] *http://today.uci.edu/news/2010/08/nr_ipad_100803.php*

half of the presented systems are mobile-based and include pharmacological databases or clinical decision support systems [129, 188, 189].

A more recent trend in supporting highly mobile clinicians includes the development of pervasive computing environments [17], context-aware information systems [168], record-keeping and note-taking applications [11, 154, 155, 243] and hospital groupware and collaborative applications for hospitals [15, 66, 149]. These efforts aim to provide clinicians with access to relevant information from anywhere within the hospital through a variety of heterogeneous devices. The design of these systems has been inspired by formative design studies that indicate that the deployment of pervasive technologies in hospitals can be particularly beneficial for the clinicians. In this section, we describe these research efforts and results in the pervasive computing literature in support of clinical work.

In this section we describe the available solutions to overcome these challenges. We first describe solutions that make use of context to present information relevant to medical workers. Then we present solutions that support collaboration and improve the arduous task of record-keeping. We close by discussing tools that enable medical workers to quickly switch between different medical contexts due to frequent interruptions.

2.1 Context-Aware Services and Awareness

Clinicians make decisions that are highly influenced by contextual information, such as time, location, and available resources. For example, access to a patient's medical record is more relevant when the clinician is in front of a patient's bed. Therefore, a clinician's location is useful in determining the type of information she/he might require at a given moment [168]. Field studies of clinical work have shown that clinicians maintain a peripheral awareness of people at work in order to maintain the temporal patterns or "rhythms" [196, 197] of work which is often used to coordinate activities and contribute to the regular temporal organization of the hospital [22, 23, 38, 196].

To provide clinicians with the required awareness for their work, the AwarePhone enables clinicians to use their mobile phones to get an overview of their location, status, and the activity in an operating room [14] (see Figure 2.1, right). The AwarePhone is an interactive phone book that enables clinicians to exchange calls and messages while displaying each user's location, and his current and self-reported activity. Examples of reported activities include "patient arrived," "patient anaesthetized," "operation started," and "patient left the operating room." Clinicians might use available contextual information to determine the right time to call a colleague, thereby reducing the number of disruptive calls a clinician receives. Similarly, the AwareMedia application shows clinicians the location, status, and current activity of all surgical personnel, the operating schedule for each operating room and a video feed from inside the room [15, 16, 38]. AwareMedia also includes a chat feature as an easy communication channel amongst the surgical personnel. For example, a clinician in the operation ward can broadcast a message to nurses and other clinicians notifying the cancellation of the next surgery. Figure 2.1 shows the AwareMedia deployed in the hospital. The results of a one-year evaluation of these systems (i.e., the AwareMedia and the AwarePhone), showed that clinicians

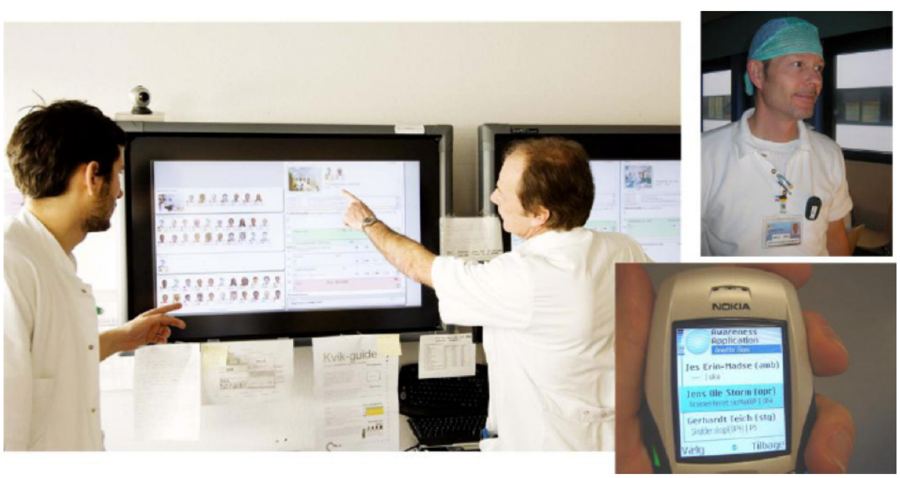


Fig. 2.1 The AwareMedia deployed in the coordination center (left), an operating technician wearing a location tag (right, top), and the AwarePhone (right, bottom) showing a list of users, their location, status, and scheduled operation (source: proceedings of ubicomp 2006, acm digital library, permission requested).

found the contextual information useful for helping them to improve their coordination and rapidly find the resources they need in their work. However, some of the pitfalls when using context-awareness in hospitals include privacy and accuracy. Clinicians reported that some times was very difficult to have "confidence" on the technology because the estimation was not always accurate. This work leaves questions for identifying the situations when the context-aware application may act automatically based on a desired level of confidence open. Open issues remain for uncertainty mechanisms for managing errors when sensing information.

Besides monitoring their own information, clinicians need to closely monitor patient activities and their health status to determine the appropriate time for care delivery. Because clinicians are often mobile, they encounter problems with maintaining awareness of patient activities and consequently overlook emergencies. At the same time, continual alerting could disturb both the restful environment hospitals attempt to create and the work of other clinicians in the nearby area, but in contrast, public alerts can compromise patient privacy.

To overcome these challenges, in the commercial sector, there are several biomedical devices that help hospital workers monitor vital signs, physiologic trends, heart rate and control respiratory ventilators.[3] Likewise, researchers have explored the use of wearable sensors to monitor nurses' activity of medication [172].

Academic researchers have explored the use of ambient displays, *"aesthetically pleasing displays of information which sit on the periphery of a user's attention"* [22], for monitoring patient information. For example, the ADL monitor project (Figure 2.2, left) enables nurses to monitor patients' urine habits [228]. This application uses a bracelet that contains five buttons with embedded lights — each button represents a patient under the nurse's care. The bracelet's lights turn on when a patient is urinating and nurses can consult details on a SmartPhone. A second version of the ADL monitor was integrated with the FlowerBlink (Figure 2.2, right): a fixed ambient display that notifies nurses of patient urine output and urine bag status [67, 210].

[3] *http://www.himssanalytics.org/docs/HA_MedDevices.pdf*

Fig. 2.2 A nurse using the bracelet of the ADL Monitor (left), and the FlowerBlink (right) notifying nurses that a patient is urinating.

The FlowerBlink includes a wooden box containing twelve “emergency flowers” with stems and twelve stemless “situation flowers.” Emergency flowers blink to indicate current urination or a full urine bag. Situation flowers indicate the location of each patient. Integrating various ambient displays for a comprehensive information environment requires careful decisions regarding which devices can and should display which information. These decisions must take into account the device capabilities and users’ context and remain a primary challenge for device integration [67, 210]. In both cases, the goal is to make clinicians more aware of their environment, colleagues, and artifacts locations or patients’ information.

Beyond these notions of awareness, Munoz et al. [168] investigated the problem of identifying what contextual information is relevant to support hospital work through the development of the Context-aware Hospital Information System (CHIS). The CHIS enables users to send messages, which include a set of context rules that must be satisfied before the system delivers the messages. This contextual information, the message’s delivery context, can include the recipients’ location and role and the status of any related artifacts. In addition, the CHIS uses this contextual information to decide how to adapt and personalize the information shown to the user and to provide location awareness on a floor map. So, when a clinician is near a particular patient bed, the system might automatically display the relevant medical record.

Other studies have also highlighted the role that location can play in managing concerns about privacy, surveillance, and control of data in hospitals. In a research deployment of the CHIS, clinicians identified some areas in which they did not want to be tracked; however, sharing context information generally did not produce major privacy concerns [229]. To address the concerns that did arise, the CHIS incorporate mechanisms to allow users to manage their privacy settings based on context [229]. For instance, clinicians can configure the floor map to only show the room-level presence information instead of the detailed location, and highlight generic roles instead of the exact names. In contrast with the AwarePhone and the AwareMedia, the CHIS not only uses context to provide awareness to clinicians but it also uses this information as triggers for adapting and personalizing the presented information. By doing so, the CHIS reduces information overload thereby potentially providing enough benefit to overcome some of the concerns around control of shared data and privacy.

The amount of information clinicians must handle is extremely large. They often manage a large number of patients who each have voluminous medical records. Hence, navigating through all of this information on a small screen while working in a highly mobile environment can be particularly challenging. A second version of the CHIS was extended to integrate interactive displays that personalize the information shown to a clinician and offer opportunistic access to medical information [66]. For instance, when clinicians approach a CHIS display, it detects their presence, and based on their location, provides them with personalized views of the CHIS system. These views highlight recent additions to patient medical records, any messages addressed to the clinicians, and the most relevant services to her current activities.

Similarly, other research projects have extended traditional hospital information systems, such as PACS or EMRs, with context-aware services that enable clinicians to find relevant information [26]. For example, researchers have developed context-aware PACS that can show relevant medical images for an ongoing surgery [7, 26]. These systems usually take into account the patient's identity, the type of surgery, the surgeon, and the progression of the surgery to decide which images are relevant to display. Similarly, the MobileWard is a context-aware application that provide nurses with relevant information during their work [216]. The system uses the nurse's location, patient's identity and temporal-oriented events for selecting the information that is relevant at a given moment. For example, when the nurse is in the corridor the system shows the patient chart; in contrast, when the nurse is in a patient's room the system will show the patient's medical record and upcoming and conducted tasks or surgical procedures. The evaluation of these applications showed that contextual information was very useful for facilitating information capture by automatically recording health data. Nevertheless, clinicians explained that sometimes they were uncertain if the information automatically recorded by the system was useful and relevant, so they started to record this information manually to be used as a "back up plan" in case the system did not capture the required information. The problem with these applications is the lack of feedback and awareness of the captured information to clinicians. So, although clinicians were confident that the system would automatically record information, not knowing what, when and how health information was recorded generated anxiety and concerns. Open questions remain for developing adequate feedback services to notify clinicians what information is being automatically recorded giving them opportunities to change and update this information.

Overall, these projects highlight many of the ideas behind context-aware computing and the usefulness of context-aware applications in hospitals.

2.2 Pervasive Groupware and Collaboration Support

Collaboration and communication is a crucial part of patient care [23, 164]. Through a variety of formal and informal means, clinicians frequently interact with their colleagues to locate and gather information and coordinate activities that are necessary for patient care. A central research area within the pervasive healthcare field is to develop new kinds of pervasive computing technologies to support these types of formal and informal encounters in hospitals.

Clinicians often work together with colleagues in other departments or even in other hospitals to provide appropriate care for a patient. Pervasive groupware and collaboration technologies can enable online and real-time meetings through video-conferencing and shared access to medical information. In the Intelligent Hospital Project, researchers have developed an infrastructure for multimedia conferences in settings where users exhibit a high degree of physical mobility [161]. A caller using the Intelligent Hospital system can request a connection to a user instead to a specific computer. Therefore, it does not matter if the user is near or using the computer normally used for videoconferencing, the system will automatically identify which computer is available for establishing the connection. For example, a caller would request a connection to theon-call surgeon and be connected directly to a speakerphone or wireless headset in the operating room. If the clinicians move while engaged in teleconferences, the sessions "roam" with them.

The principle of "activity roaming" expands beyond communication to support nomadic and mobile computing by transferring user sessions and ongoing tasks to appropriate devices, including embedded and handheld devices [25]. The Activity-Based Computing (ABC) project was designed to enable both collaboration and roaming. In this project, any activity can be shared synchronously with two or more participants [13]. In comparison to the infrastructure of the Intelligent Hospital project, the ABC infrastructure establishes the collaborative session among activities rather than users.

To support synchronous activity sharing, the ABC infrastructure provides different collaborative widgets including telepointers, voice links between participants, and lists of active participants. Favela et al. [149] extended the telepointer widget with a remote control component that enables clinicians to remotely control a public display with a mobile device. Although the component is capable of handling concurrent controllers, only one clinician is able to move the cursor and type on the controlled device. The rest of the participants are only able to point at the screen using a telepointer (Figure 2.3).

Fig. 2.3 Two clinicians using the remote control tool during a clinical case discussion (left), a screenshot of the remote control tool (right).

Although pervasive computing support for formal meetings has met with some success in hospital work, most communication among clinicians is informal [154]. Informal interactions are unplanned and brief interactions, typically co-located, during which the topic of conversation changes rapidly [127]. Because of the complex characteristics of hospital work, clinicians' informal interactions happen mostly due to opportunistic encounters. People often perceive hallways as an "availability space" where clinicians can be interrupted. One study found that clinicians spend almost 10% of their time in hallways where they have meaningful encounters with other health providers and get work done [164].

Informal interactions present the technological challenge of knowing neither who the participants might be nor when the meetings could potentially occur. Thus, several projects have focused on context-awareness to encourage informal interactions and suggest potential collaborators. For example, clinicians using the CHIS or the AwarePhone can use the location and current activities of peers to decide when and with whom to start an interaction. An *in situ* evaluation of the AwarePhone and the AwareMedia systems found that clinicians extensively used this contextual information as cues to improve coordination and determine a potential collaborator [16]. Similarly, the SOLAR project explored other contextual information that might be helpful in addressing this problem. In addition to clinicians' location and activity, the SOLAR system also recognizes that the location and states of artifacts can be important triggers for informal interactions [154, 156]. For example, a clinician might decide to call a specialist after receiving a patient's lab analysis. Also, beyond providing awareness, the eMemoris system enables clinicians to manually request an interaction after reviewing this information, mimicking Facebook's "friend me" functionality [155].

Many collaborative interactions involve the exchange and analysis of documents. A recent study reported that 11% of clinicians' informal interactions involved the exchange of documents [154, 164]. To help support these exchanges, pervasive computing researchers have explored solutions to improve the sharing and exchanging of information during both formal and informal encounters. Furthermore, because hospitals are technology-rich environments, transferring, sharing and controlling these devices should be seamless, so as not to interrupt on-going activities. The eMemoris system enable clinicians to transfer seamlessly information among heterogeneous devices and establish proximity-based application sharing [154, 156]. Proximity-based application sharing allows clinicians to take control of any device in a given area to display information from the source device on the target screen. Once a session is established, multiple users can control the shared device facilitating collaboration.

2.3 Record-keeping and Note Taking in Hospitals

Hospital interactions not only involve the exchange of documents but also the creation of new content as a result of discussions around these documents. Thus, clinicians usually take written or typed notes to store relevant information for future reference. Additionally, legal concerns and hospital policies often result in specific documentation practices that must be followed (e.g., in the United State — HIPAA[4]). However, the task of recording data can interfere with the participants' ability to fully engage in a physical activity or in the interaction itself [2].

[4] *http://www.ahcancal.org/facility_operations/hipaa/Pages/HIPAAPolicyProcManual.aspx*

In a clinical setting, others have noted several problems with current recording practices including the late arrival of a dedicated recorder, the management of parallel activities, and multitasking [204]. For example, clinicians often use both hands for specific medical activities such as surgery. Thus, having to directly manipulate an application by selecting the information that would be impractical to capture. Consequently, capture and access tools [4, 6, 232] are particularly promising in supporting the

> *tools to support the automated capture of and access to live experiences aimed at augmenting the inefficiency of human record-taking, especially when there are multiple streams of related information that are virtually impossible to capture them manually* [6]

One example of a pervasive health capture and access application, the ActivityTheatre project (Figure 2.4), focused on enabling the automatic capture of relevant events [91]. An "event" in this system can be an audio note, a picture or a video clip. The system is voice activated to

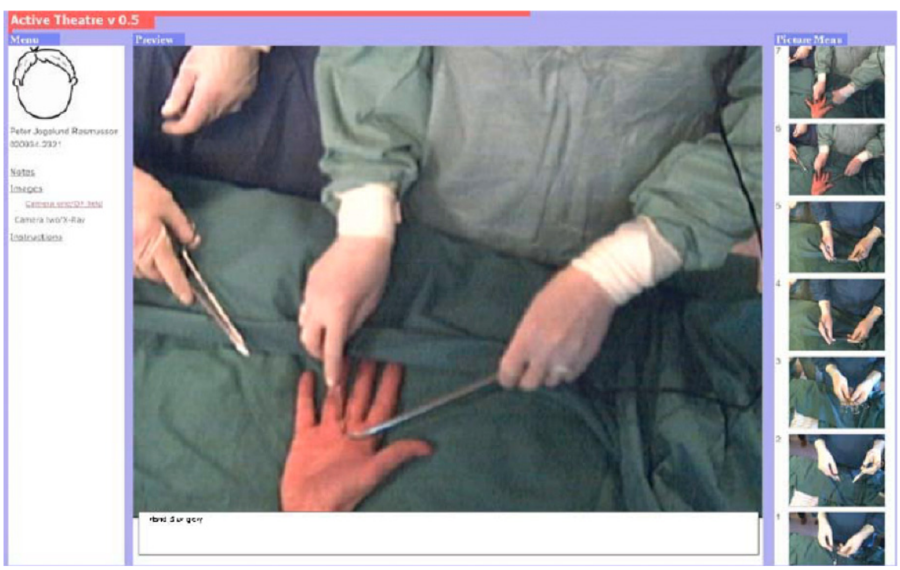


Fig. 2.4 A screenshot of the ActivityTheathre (*source*: Thomas R. Hansen, PhD Dissertation, with permission).

capture events. The system uses the palette metaphor, in which users can hold different types of data, place and take things from the palette at any time, and access them from the palette as needed. After the operation, a clinician carries the palette to an office where the data is used to automatically create different documents, which can be later edited by clinicians.

Similarly, the eMemoirs system allows clinicians to capture a conversation for future reference [155]. Although the system automatically captures conversations when detected, a clinician can manually request or cancel the capturing. Similarly, the system automatically stops recording when it detects participants who are no longer co-located. This system uses the context of an informal meeting (i.e., who was there, when and where it occurred) to help an individual find a "potential collaboration partner." Clinicians may browse recording through a map displaying various meetings based on who, where, or when the meeting took place. These projects show that voice activated and zoomable interfaces can be useful interaction techniques for capture and access applications in hospitals.

Given the focus on record-keeping in hospitals and the challenges of bridging traditional paper records with new electronic systems, it is natural that substantial research has focused on augmenting paper with computational capabilities. This approach is meant to provide the benefits of the digital technology while maintaining the flexibility, ubiquity, and ease of use provided by the paper. For example, the augmented patient chart system allows nurses to update a paper-based patient chart with a digital pen based on the Anoto™[5] technology that automatically digitalizes its content [242, 243] (Figure 2.5). This technology involves a digital pen with an embedded camera that takes pictures as the device moves across the surface while making annotations on the paper. The nurse annotates information on the chart, which is transferred to a server every time the pen is placed in a cradle base, thus bridging the physical and digital realm. Nurses may review the information and confirm it to minimize errors in the captured information. The paper contains a special printed pattern of dots that works

[5] *http://www.anoto.com/*

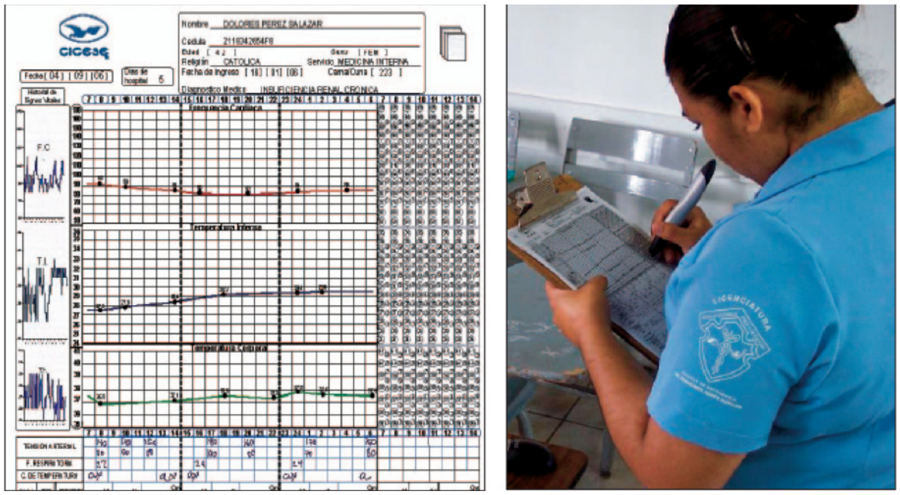


Fig. 2.5 A picture of the patient chart augmented with the ANOTO pattern (left) and a nurse using the augmented patient chart with the ANOTO pen (*source*: Selene Zamarripa, MsC Dissertation, with permission).

with the camera to identify the exact position of the paper where the annotation is made. The augmented patient chart replaces manually generated graphs with a set of widgets to annotate accurate values used to plot graphs.

Similarly, the NOSTOS system combines multiple technologies such as digital pens, radio frequency identification (RFID) tags and computer-vision techniques to augment a paper-based patient record [11]. NOSTOS also uses the ANOTO technology to digitize information paper-based medical records. However, NOSTOS extends this functionality by enabling clinicians to digitize the act of stapling two paper-based documents, using a pen-based gesture. NOSTOS uses the RFID identifier to recognize which documents must be stapled. This practice of attaching notes to the medical record is very important and frequent in hospitals [21].

As the NOSTOS prototype showed, RFID technology can be used to integrate physical objects to the digital world. Similarly, other researchers have used RFID tags to augment medical devices used in hospitals. Fishkin et al. [70] developed a prototype to help clinicians assess the skills of their residents when setting up medical equipment for surgery or for a patient's intubation. To identify the objects selected, each resident wore a glove with an antenna in the palm [183] for identifying the RFID tags associated with the medical equipment. The assessment focuses on identifying the "correctness" of the set of instruments residents set out for the procedure. Along with barcode readers, RFID have been also used in hospitals for tracking both patients [69] and medication [43, 235]. These solutions offer hospitals a way to automate much of the tracking required for efficient and safe patient care. As more of these systems are used, monitoring of hospital error rates to determine the ultimate success of these systems will be of particular interest to a researcher.

Although the keyboard and mouse are still the dominant user interfaces available in home and office environments; in hospitals, with the growing increase in mobile device usage and the availability of many new interaction technologies, the way clinicians interact with computers is becoming richer and more diverse. Touch-enabled surfaces, natural gestures, implicit interaction, and sensors that enable the automatic capture of relevant information are some examples of these emergent but popular interaction mechanisms. Because hospital work is highly tied to the physical world, pervasive computing solutions are most useful to clinicians when they are integrated with the physical world. This integration requires sensory capabilities to enable systems to be aware of and make use of their physical environments. Consequently, there are a number of open questions concerning new devices, methods, and approaches to create natural and intuitive forms of human–computer interaction that make it easier for clinicians to achieve their goals while using computers as tools.

2.4 Handling Multiple Activities and Supporting Rapid Context Switching

Hospital work is highly fragmented; clinicians spend on average only 90 seconds engaged in an activity before switching tasks [228]. So, clinicians must cope with frequent interruptions and continually adjust and readjust their activities [22]. In addition, clinicians are faced with a wide variety of systems that they must use [18]. Thus, carrying out a single activity could involve the use of several systems, each with different functionality and data presentation, and frequent interruptions to engage with other systems and tasks. For example, if a clinician is discussing a clinical case with a colleague, they might need to share the medical record, highlight areas from an X-Ray image, and consult a journal article relevant to the clinical case being discussed. This fragmented work results in clinicians spending much of their time selecting the right application to run and setting up the computational infrastructure that they need [18].

Pervasive health offers some solutions to this inefficient use of technological resources through the application of context-aware task and system switching. For example, the mobileSJ system helps clinicians manage multiple activities and achieve the necessary context when switching between them. Through mobileSJ, clinicians can associate participants, devices, applications and medical information to an activity. For example, a clinician can create the activity of "surgery" and then associate resources to it, including a video-conferencing application with a specialist and the medical record of the patient. Later the clinician requests the "surgery" activity, which then automatically starts the video-conferencing and displays the medical record and lab results. As described in Section 2.2, the ABC project also organizes work by activities rather than applications and documents [19]. Thus, a video conferencing tool developed on top of the ABC infrastructure allows clinicians to associate a collaboration session to an activity. Clinicians can "juggle" computational activities while switching among tasks without being concerned with direct manipulation of the infrastructure.

Both mobileSJ and the applications built on top of the ABC infrastructure can provide users with mechanisms to easily manage their activities and their associated resources. However, users must predefine their activities and explicitly specify which resources are relevant to them. Additionally, while executing a given task, users must also explicitly select an associated pre-defined activity. A useful next step is to include mechanisms that enable these applications to automatically infer the user's current activity to proactively retrieve the relevant activity and its associated resources at a given moment. In this direction, some projects have explored how to extend activity-based infrastructures with context-aware services that help clinicians to create and retrieve relevant activities automatically when needed. For instance, the CHIS system was extended with a mechanism that takes into account clinicians' activities for adapting the location information presented in the map [227].

2.5 Conclusion

This chapter outlines a variety of pervasive solutions that support hospital work. Through field and evaluation studies, these projects highlight design, technological, and practical issues facing the adoption of this technology. Although there are a number of challenges including mobility, coordination and work fragmentation, to full integration of pervasive technologies in hospitals, there are some factors in favor the adoption of these types of technology. For instance, hospital work requires a great deal of mobility, which is much better supported by pervasive health solutions than traditional Health IT. However, there are a number of open questions that might serve as a guide for the development of future pervasive applications in this domain.

Most of the projects proposed in the pervasive healthcare literature in support of hospital work rely in the use of context-aware computing. However, these results showed that the use of context information poses numerous challenges regarding clinicians "confidence" when using context-aware healthcare systems. In an environment where medical errors are frequent having applications that might put human life at risk, jeopardize the privacy of personal records might lead to the rejection of the technology. This research leaves open questions regarding the identification and management of uncertainty information when using context-aware healthcare applications.

Also the difficulties of the evaluation of pervasive healthcare technologies poses numerous challenges involving the level of integration of a pervasive healthcare with existing hospital information systems deployed in the hospital, the distribution of information and people, the intense collaboration and high fragmentation of activities as well as the level of risk associated to system failures. These leave open questions as to what current methods used for evaluating pervasive healthcare applications are suitable for this domain, and what are the metrics that will help to measure the adoption of pervasive healthcare applications in hospitals.

3

Chronic Care Management and Assisted Cognition

A chronic condition is a health condition or disease with long-lasting effects.[1] Some examples of chronic conditions include cancer, asthma, diabetes, and high blood pressure as well as cognitive disabilities, such as Alzheimer's and autism. Long-term chronic care-management often requires a variety of pharmaceutical and behavioral interventions to monitor and maintain the patient health over time. However, hospitals and other clinical environments are not well equipped to provide the kind of care required for chronic care management, and support long-term diagnostic and patient remote-monitoring. At the same time, patients with chronic illnesses undergo a number of changes in their lifetime, a problem that is particularly acute in children — who are naturally growing and developing at a rapid pace — and elders — who often are declining both cognitively and physically.

People with chronic conditions, especially individuals with cognitive disabilities can experience deficits in memory, executive function, and other cognitive processes such as learning and use of language. These deficits can in-turn lead to lower perceived quality of life and self-care

[1] *World Health Organization.Chronic diseases.*

abilities [138]. In contrast with physically oriented chronic conditions, severe cognitive disabilities often lead to the need for regular assistance from caregivers for successful performance of Activities of Daily Living (ADL)[2] [81]. Caregivers provide directions, prompts and guidelines that can enable individuals with cognitive impairments to accomplish their goals. However, this type of support, paradoxically, might hamper their independence and their opportunities to fit into society and have positive self-images.

At the same time, caregivers (e.g., family and friends) can experience substantial difficulties themselves from the time required for and stress imposed by caregiving responsibilities for individuals with chronic illnesses. These challenges can lead to time away from employment, less time for leisure activities, and activities with other family members [163]. These issues require the design of tools that will facilitate the care of people with such impairments.

In recent years, many research projects in pervasive computing have focused on providing tools for the independent execution of ADLs in support of people with cognitive disabilities and chronic illnesses. In particular, many of these projects aim to help elders "age in place." Other available solutions help people with chronic illness to improve their communication with health providers and facilitate easy archiving of health data for self-management. Finally, a considerable number of projects have focused on developing tools to facilitate caregiving activities and support collecting evidence for diagnosis and monitoring of the chronic care conditions.

In this section, we first describe solutions supporting real-time monitoring, assisted navigation and social connectedness for maintaining physical and psychological wellbeing of people with chronic illness. Then we discuss present solutions that provide step-by-step guidance to improve the execution of ADLs supporting people with cognitive disabilities. We finally, summarize the pervasive chronic care management and discuss open research challenges.

[2] *The term of activities of daily living is used in healthcare to refer to the things we normally do for basic self-care such as feeding ourselves, bathing, dressing, walking and so on.*

3.1 Pervasive Monitoring for Self-management

One substantial challenge for an individual with a chronic condition who is living independently is the ability to monitor physiological and behavioral indicators at a distance. Advances in pervasive healthcare technologies have enabled the development of monitoring systems that can continuously track individual's basic metabolic and behavioral parameters such as vital signs, activities, social interactions, sleep patterns, and other health indicators. Some of these projects have proposed the use of wearable sensors, smart clothing and advanced integrated sensors systems to build personalized heath profiles and promptly alert family and professional caregivers of health complications. As Pentland stated:

> *"Widespread adoption of sensors that monitor the wearer's vital signs and other indicators promises to improve care for the aged and chronically ill while amassing a database that can enhance treatment and reduce medical costs"* [181].

In the commercial sector, several companies have devoted their efforts to developing "out of the box" sensors that enable easy monitoring of these parameters and prompt communication of emergencies. For example, the Fitbitsensor[3] is a wearable activity and sleep tracker that shows users real-time statistics on their activities. Other popular monitoring devices include personal health buttons[4] that enable individuals to simply push the button to ask for assistance in the case of an emergency.

Several academic research projects have focused on the problem of passive monitoring of an individual's vital information [20, 151]. For example, the Advanced Health and Disaster Aid Network is a wearable system that monitors user's heart rate, blood pressure and oxygenation in the user's home to determine if immediate medical treatment in the emergency room is needed [151]. AIDN uses a wireless sensor network to transmit sensed information to a hospital. In addition, fabrics with

[3] *www.fitbit.com*
[4] *http://www.lifelinesys.com*, *http://www.medicalalarm.com/*

embedded sensors known as "smart garments" enable the continuous remote monitoring of multiple vital functions [60, 124, 181, 194]. For example, the SenseVest is a cotton vest with embedded wearable technology that measures, records and transmits the wearer's heart rate, temperature and movement [124]. Sensors can also be combined with other technologies (e.g., mobile phones or handheld devices) available to patients to allow for continuous home-based monitoring and communication of health information [20]. Through use of these systems, patients may became more aware of their own health by increasing involvement in their own treatment [20, 130, 234].

Passive monitoring requires systems to gather data continuously to ensure all relevant information is captured. As a consequence, these systems produce large quantities of data. Reviewing all these data is time consuming and requires substantial computing capacity for storage and indexing. To address these limitations, some researchers have suggested utilizing "selective archiving" [94] to identify which information is worth capturing and how these moments of interest could be stored and indexed. These solutions use a sensor-augmented environment to detect relevant events of interest and archive information related to these events. Most of the research in this direction has been focused in proposing approaches for fall, gait and activity detection. For example, the Smart Inactivity Monitor uses wall mounted low-cost and array-based passive infrared sensors to detect inactivity and falls [214]. Similarly, others have revisited the problem of detecting falls using vision-based techniques [51, 136]. In the Intelligent Emergency Response Project, researchers use a ceiling-mounted video camera to track objects and learn movement patterns for detecting falls [136]. The system learns the user's paths and identifies suspected falls when the person being monitored becomes inactive in a path that is commonly active. These kinds of approaches can balance the need for identification of important events with concerns about privacy of patients, storage of irrelevant data, and so on. However, the false positive and false negative rates of these solutions must be more fully evaluated in real-time before these applications are ready for clinical use.

To ease the development of applications to collect individuals relevant health data several researchers have proposed different sensor–based monitoring infrastructures [75, 103, 198] that combined with pattern recognition algorithms enable the capture of behavioral data (e.g., activity, stress). For example, available solutions for activity recognition have largely been focused on the automatic recognition of ADLs (e.g., hand washing [158] or meal preparation [30]). Lee and Mase reported a dead-reckoning method to recognize and classify a user's sitting, standing, and walking activities using the acceleration and angular velocity of wearable sensors on the users' bodies [135]. Activities have also been inferred by detecting users' interaction with particular objects [183]. For example, the use of a toothbrush indicates tooth-brushing. For fall detection, vision techniques [85, 158] in conjunction with sound recordings [30] are also used for inferring activity. For example, in the Intelligent Emergency Response Project the system uses composite filters to analyze video frames and associate hand positions (2D coordinates) with specific hand washing steps, such as turning on the water and using the soap.

Despite the advances in sensor-based infrastructures and in the techniques used for context recognition, there are still some open technical issues, such as cost and energy consumption that must be addressed before any wide-ranging implementation and adoption. The viability of projects based on a vast number of sensors combined with other techniques will depend significantly on the cost of the devices, replacement period, and automated network configuration [128]. Furthermore, using pattern recognition algorithms requires substantial effort from users to train and calibrate devices. For example, for the kinect[5] sensor, a user needs to stand in front of the sensor holding a specific posture for 30 seconds to calibrate it. Beyond the demands that the calibration task imposes on the users, people with cognitive impairments, the elderly, or even just those who are untrained might not be able to execute some of the requested calibration activities. Miss-calibration will generate several errors that hamper the way systems rely on these settings behave. In the healthcare setting where errors can have critical consequences, this could be potentially dangerous. For example, if a

[5] *http://www.xbox.com/es-MX/kinect*

heart rate sensor fails, a caregiver might think that the user is having a heart attack while in reality she is asleep.

Unfortunately, the reverse is also true. Sensors misfiring might indicate patients are healthy and resting when in fact, they have experienced some health or safety critical event. Indeed, the acquisition of context is a difficult and complex task due to the variety and nature of sensors and technologies. Uncertainty in context-aware applications could be caused by the presence of uncertain, ambiguous or incorrect contextual information. This uncertainty may cause users to lose their confidence in the robustness of the device. Thus, it is necessary to include in applications an uncertainty management mechanism for allowing these devices to be more robust and tolerant to the presence of uncertain contextual information and to increase their reliability. Indeed, there are still several open questions as to how current available mechanisms (e.g., [59, 89, 192, 193]) might be used in healthcare environments.

There are still open questions about the challenges of deploying pervasive monitoring applications for health including reliability and privacy issues [150, 181]. Indeed, all pervasive monitoring technologies that rely on some sort of context estimation will carry some risks. The question that must be answered is does the benefit outweigh the risk. Home automation and the manual control of medical devices using natural interfaces to improve the manipulation of the sensor-based infrastructure and pervasive monitoring applications could alleviate some of these issues [76, 118].

Another related area is to understand what it means "to perform poorly" for different healthcare activities and applications. For example, medication errors are common in homes, with adverse drug events reported among 13 percent of home-patients [157]. These errors primarily occur because patients forget to record the administered medication dose resulting at times in double doses or because they forget to take a medication dosage at all. However, a context-aware application could automatically infer when a patient took a medicine and automatically register this information or remind the patient to do so. In this case, an application with estimation accuracy less than 13% would likely improve the current error rate when administering medicines.

Consequently, the user would still benefit even when the application "performs poorly." So, designers might interpret and use these behaviors and the existing error rates for current practices to establish an adequate threshold of acceptable estimation errors. Additionally, systems that provide feedback about and control over errors would also improve patient experiences.

There are several issues regarding how to display this information, when to display and how much information is relevant to display. Determining what information is required and the presentation of this information in ways that can be used by caregivers and patients is equally important and challenging. One of the biggest issues with visualizing this kind of information is the tradeoff between presenting detailed information and supporting users' information privacy. For example, as Figure 3.1 (left) shows, the Digital Family Portrait provides qualitative visualizations of a family member's daily life [169].

These qualitative icons include butterflies or trees and are shown in a digital frame with a pattern of 28 icons. The size of each icon provides

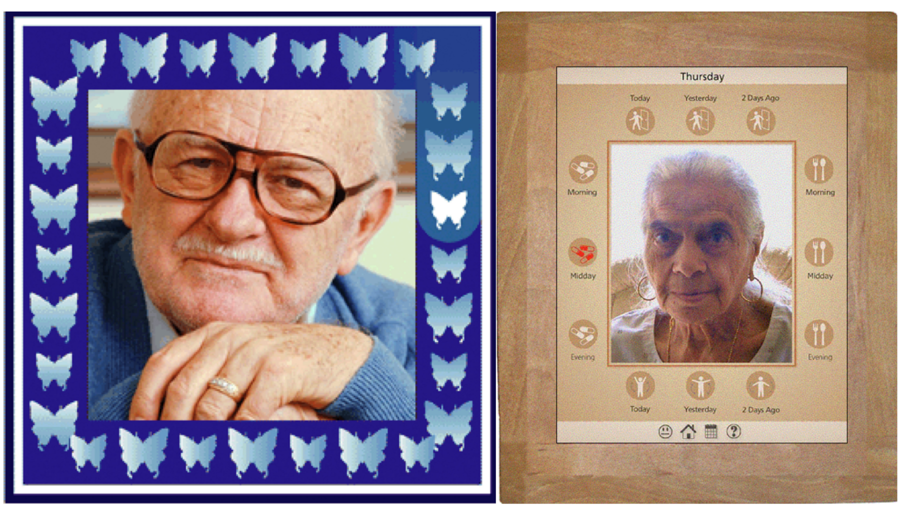


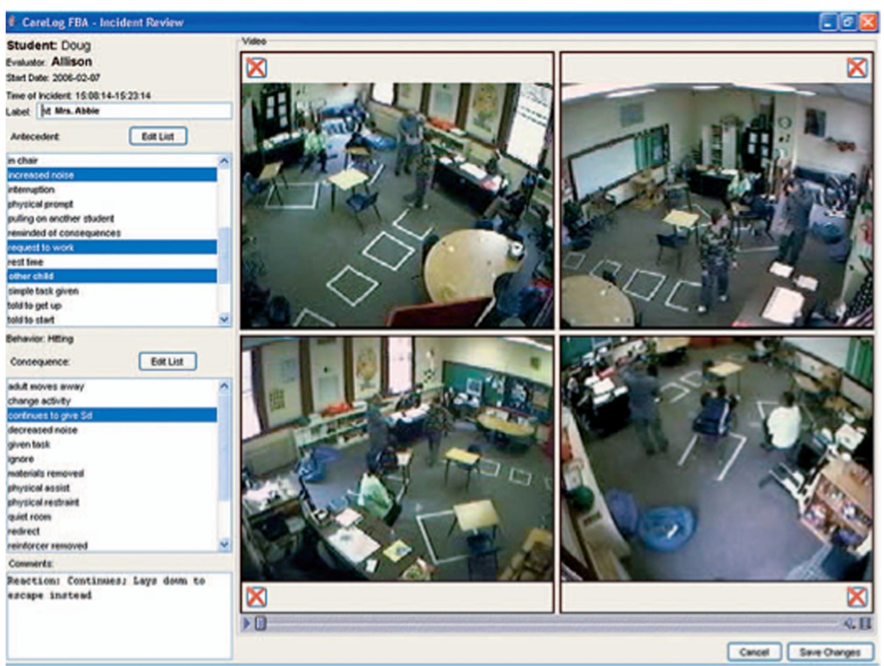
Fig. 3.1 Situated digital portraits for conveying activity awareness. The Digital Family Potrait (left) and the CareNet Display (right) (Source: Conference in Human Factors, ACM, permission requested).

a general sense of the individual's activity level on a given day. For example, a very active elderly person who during the day has talked in the phone, had breakfast, and watched television will have colored half of the icons. Similarly others have explored the use of digital portraits to provide caregivers awareness of individual's activities. The CareNet Display (Figure 3.1) is a digital portrait that has a frame with a pattern of pre-defined activities that are highlighted to convey an individual's level of activity [47]. This system monitors her activities including falls, meals, medications, and visits. The individual would choose the relative with whom she would like to share this information.

While this information could be used to get a sense of an individual's life, it would be very difficult to use it for clinically relevant assessment activities. Therefore, other researchers have explored the use of "capture and access" for presenting the health and behavioral data with as much level of detail as possible [3, 96, 121]. For example, CareLog is a system that facilitates the functional behavior assessment (FBA), in which caregivers try to understand the *function* of inappropriate behaviors of children with autism [92, 94, 96, 121]. To augment caregivers' abilities to document and analyze specific, unplanned incidents of interest as part of an FBA, CareLog uses audio and video buffering enabling the selective archiving of these incidents. Selective archiving refers to the method in which recording services in an environment are always on and available, but they require explicit action to save any recorded data. Caregivers use a wireless button to trigger archiving [94]. They then use a standard desktop computer to watch the videos and tag them with metadata (Figure 3.2, left). CareLog provides graphs and other analytic tools for functional assessment (see Figure 3.2, right) [94]. The combination of automated and manually collected data was seen in this work to provide an appropriate balance between ensuring that all relevant data could be collected and concerns about surveillance of work activities by the caregivers.

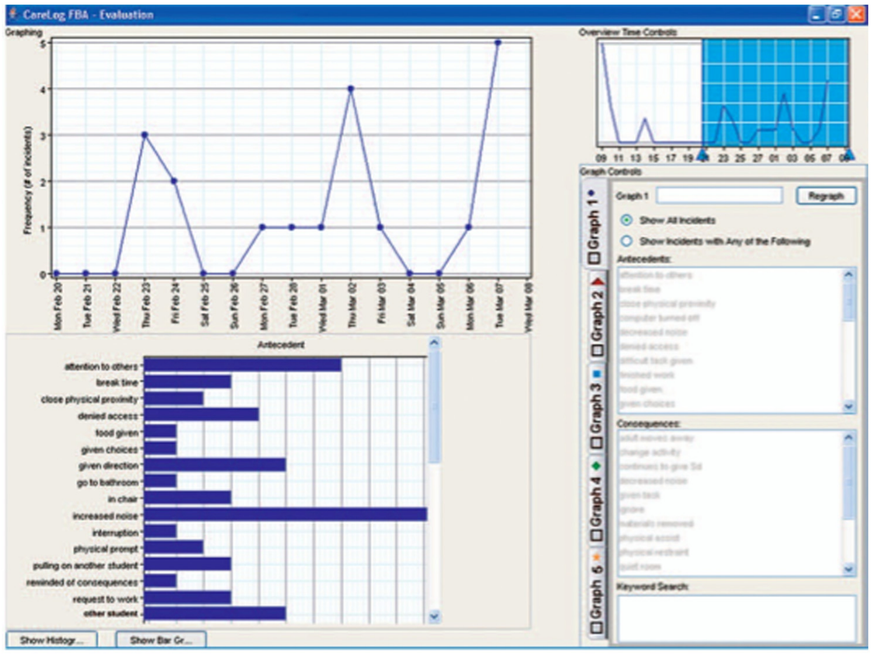
Similarly, SeniorWatch is a capture and access tool that enables caregivers of elderly individuals to consult, classify and share videos of elderly activities [68]. The system uses an activity recognition algorithm to index captured video streaming of relevant behaviors. Caregivers use a web-based application to consult these videos after the events have happened. In a home evaluation, caregivers use the videos to train new caregivers, share interesting events with relatives, and log data for clinical purposes [68]. The result of this project shows that surveillance technologies have a positive impact in nursing homes surpassing the privacy risks frequently associated with the rejection of the use of such systems.

Overall, these projects demonstrate that pervasive monitoring can provide substantial benefits for caregivers while balancing against the potential risks associated with the invasiveness of this kind of monitoring. These systems were found to be easy to use, require minimal training, and minimally disrupt everyday activities [68, 92, 94, 96, 233].



(a)

Fig. 3.2 Screen shots from the CareLog functional behavior assessment systems: (a) video viewing and annotation screen with four camera angles and (b) automatically generated graphs showing when and how often a particular behavior occurs. (*Source*: Conference in Human Factors, ACM, permission requested).



(b)

Fig. 3.2 (*Continued*)

3.2 Social Connectedness and Communication Support

Social ties and social integration often play a beneficial role in maintaining psychological wellbeing, which can in turn support physiological health and healing. Strong social networks may enhance the quality of life for older adults [83] and those with chronic illnesses, improving their health [28], reducing the chances for developing cognitive decline [71], and eventually preventing an earlier death [101]. However, people who struggle with chronic health conditions and have limited independence may also experience challenges in gaining access to social activities. These challenges can lead to diminished social skills and have the potential of increasing their isolation.Thus, several projects have explored mobile and pervasive technologies to help people with cognitive disabilities stay in touch with their social networks. Research in this area has been mostly directed toward supporting the needs of older adults (e.g., [49, 65, 74, 169, 170]). A few projects have started to investigate the impact of this technology in support of other populations such as children (e.g., [53, 72, 110]).[6]

In this section, we highlight innovative interaction techniques being developed for facilitating interaction between different user groups (i.e., the elderly and people with cognitive disabilities) with sites or natural objects augmented with computational capabilities.

Common objects and photographs can serve as interfaces for communication, information retrieval, and sharing experiences. For example, the Familyware system provides specific support for sharing feelings between family members [84]. Various objects, such as a plush toy, can be manipulated to send a signal to a family member. Likewise, situated displays have been used to share photos and other information between families at a distance. For example, the exchange of photographs help users to enrich "off-line" conversations [74]. The "Sharing the Day's events" [65] project and the "Communication of experiences" system both enable users to send pictures, drawings or videos to a fixed screen with the aim of providing awareness of relatives everyday life. The CareNet display [46] and the Digital Family Portrait [170] also provide relatives with continuous awareness of the elder activities to connect elders and their relatives. Beyond this kind of communication of health information, the Virtualbox system [53] was designed to mediate intimacy between grandparents and their grandchildren. This system incorporates a "hide and seek" game in which grandparents add virtual content to the virtual box and hide it in a virtual floor plan. Using a PDA, the grandchildren can search for the hidden virtual box and see the virtual items. Once the grandchildren find the virtual box they can add virtual items and hide again the virtual box. The results of a laboratory evaluation of the Virtual Box demonstrate that the exchange of multimedia between grandparents and their grandchildren proved to be asymmetric in its content, that is, older adults were more thoughtful in the process of adding meaningful items to their grandchildren [53]. Similarly, Tlatoque (Figure 3.3) provides the elderly knowledge of the

[6] *Readers should be aware that there is a great deal of related literature in the Computer Supported Cooperative Work (CSCW) domain but a review of that literature is beyond the scope of this paper.*

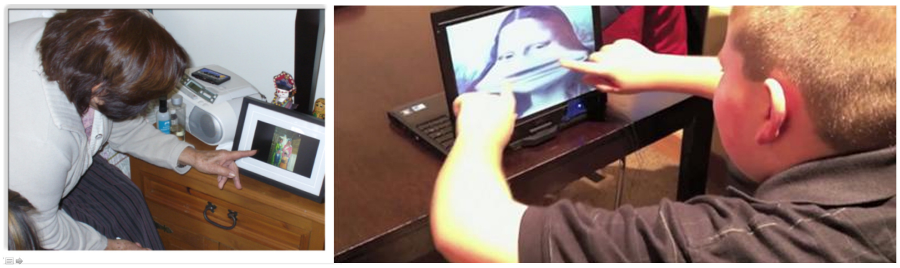


Fig. 3.3 Interactive displays for enriching the social experience. Tlatoque (left) and PhotoGoo (right).

information shared by their family members through a social network site (e.g., facebook) [48, 49]. This shared information includes uploaded photographs, news and weather feeds relevant to various family members. The system is embedded in a digital portrait to engage reluctant, first-time computer users.

These projects demonstrate that pervasive health technologies can support social interaction for individuals with chronic illnesses but at the same time highlight an open area of research — the need to identify whether these systems have an impact on the long-term health and wellness of their users. Although these projects have shown that pervasive assistive technologies can enhance social encounters at a distance, we still need to examine more closely the potential impacts of these systems on supporting independent living. Additionally, there are challenges surrounding what information users can control and how best to allow them to do so.

3.3 Assisted Navigation and Wayfinding Support

Mobility can be a substantial challenge for people with chronic illnesses and cognitive disabilities attempting to live independently. The inability to move independently reduces the quality of life [200]. These challenges can include problems working, driving, or taking public transportation. Beyond outdoor mobility, others face orientation issues when navigating indoors, even in well-known spaces such as a home. To support wayfinding, many research projects have worked toward helping disoriented people with sensory impairments to navigate — in both indoor and outdoor environments — using a variety of technological solutions.

The Intelligent Mobility Platform is a walker-based device that uses a laser beam range-finder, a mobile device, and a navigation software to orient a person in the proper direction [165]. In the Indoor wayfinding project, researchers designed an interface for mobile devices to send directions and prompts to the user. Images, audio, and text messages combine to provide prompting and directions. For example, image-based directions include photos of the outlined area overlaid with direction arrows. Others have explored the use of tour-guide robots as a natural way for providing mobility guidance [165, 173], facilitating walking (e.g., the walk training assist robot), adjusting to the individual's weight, and supporting rehabilitation training (e.g., the balance training assistant).[7] Currently, robots have been proven to be very beneficial in helping individuals with restricted mobility to live with greater independence[8] The Robotic Walker [165] includes a robot that physically guides the elderly within an assisted living home. In this project, a Nomad mobile robot was equipped with an omnidirectional drive and software with capabilities to planning paths, tracking people and avoiding collision. The robotic walker has a touch interface for receiving commands from the individual. Simple directions in the form of an arrow are shown in a mounted display. This system provides not only physical support for walking but also wayfinding support. In all of these projects, a variety of pervasive computing technologies are used together in a sort of assistive assemblage to provide the level of support required. Thus, pervasive health applications not only provide motivation for technologists to develop these new systems but also a means for understanding the potential for and evaluating the impact of these vast and varied collections of technologies.

Indoor wayfinding is a challenge for many populations beyond the elderly, including those with visual [98] and cognitive impairments (Figure 3.4). For example, the BlueClues system [64] uses augmented reality and audible cues to steer a child with autism in the right

[7] *Toyota healthcare robots http://mashable.com/2011/11/01/toyota-healthcare-robots/*
[8] *http://www.networkworld.com/news/2009/041609-robots-will-aid-in-health.html*

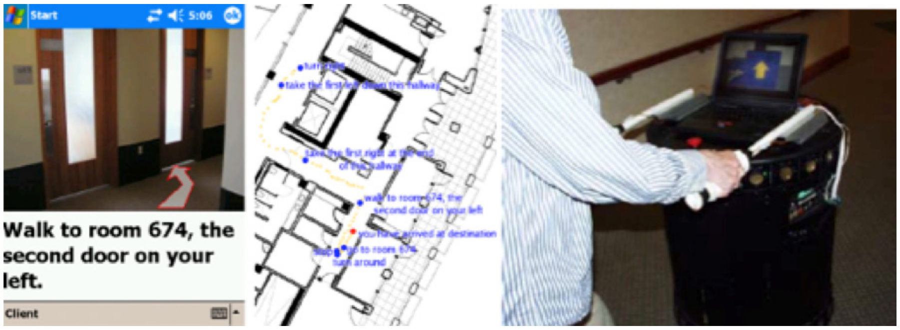


Fig. 3.4 The Indoor Wayfinding System showing directions (left), the map of the Indoor Wayfinding System showing paths where participants had difficulties (center) and the Robotic walker (right).

direction, routing him to a target destination. Children use projectors around their necks that display blue footprints in the floor indicating the path to follow. The system monitors the position of the children and their adherence to the path directed by the system. When they do not follow the suggested path, audible cues lead them back to their destinations. These indoor navigation systems can provide support for those with severe disabilities. However, thus far, they have largely been tested with groups of people who might already be using other assistive devices. This approach avoids the stigmatization and other social issues that might come with using such systems. For example, if an elderly person is already using a walker, adding some computation to this physical platform does not substantially change the overall look of it. However, a younger able bodied person with a brain injury might not wish to use a walker that would add further stigma. The design of less obtrusive systems for those who may have different types of disabilities and therefore not be willing to wear or use such obvious assistive systems remains an open design challenge for the future.

Beyond these indoor navigation systems [62], others have explored the use of auditory aids [27] and photograph-based navigation interfaces [86] for outdoor navigation guidance. For example, Opportunity Knocks is a mobile phone based device using GPS and Bluetooth that learns the user's standard routes in the community to route an individual from their current location to a chosen destination [180].

Opportunity Knocks requires very little user input. Instead it relies on observed user history as a basis for predicting likely destinations and identifying novel and erroneous behavior. It alerts the person of a navigational error by making a knocking sound and subsequently recalculating the proper route.

In contrast, most other outdoor wayfinding systems have concentrated on assisting people while driving (e.g., [62, 171, 208, 231]). Commercial applications for using GPS and mobile phone towers to triangulate location and provide directions are numerous and out of the scope of this survey, which focuses on independent living for individuals with chronic health conditions. Wayfinding technologies can assist people with a variety of health impairments who may be disoriented but still need mobility both at homes and in the outdoor environment. Research in this area has demonstrated that current technologies can enable limited assistance. However, more work is needed to improve accuracy when estimating location, particularly indoors and with the kind of precision required to support the activities of the chronically ill at home.

3.4 Prompting and Reminders

Another domain that has been widely explored in the assisted cognition literature includes projects that provide step-by-step guidance and schedule management services to remind people how to adequately execute their activities. These projects have mainly focus on supporting the needs of people with cognitive disabilities, memory impairment, and attention problems. These populations often include children with developmental disabilities and elders with cognitive impairments, such as Alzheimer's disease or dementia.

Pervasive health applications may be particularly amenable to supporting children with developmental disabilities, particularly autism, because computing systems are inherently consistent in ways that human caregivers can find difficult. Additionally, the stressed and overburdened caregivers of children with autism and other developmental disorders often cannot take on additional responsibilities, such as documenting progress, that computational systems can perform automatically in the background. Researchers have explored a variety of assistive technologies for prompting these children and supporting them in their daily activities, including developing interactive visual schedules for providing step-by-step direction to children with autism (e.g., [95]). For example, vSked is an interactive assistive technology that presents and controls children with autism schedules and activities on a touch screen display at the front of the classroom [100]. The vSked system is comprised of an ultramobile PC (UMPC), a touch screen handheld device, for each child wirelessly connected to a large, central display. Software links the student handhelds with the information on the large monitor, creating a collaborative assistive technology for the entire classroom. The touch screen acts as a master timetable showing the daily schedule for each student. A picture and nametag for the student appears at the top of each schedule. Each UMPC has personalized features: the student's name and photo, tokens earned and rewards. The teacher starts an activity by using the large touch screen, pressing on the picture of an activity. The results of three deployments of vSked showed that vSked can promote student independence, reduce the quantity of educator-initiated prompts, encourage consistency and predictability, reduce the time required to transition from one activity to another, and reduce the coordination required in the classroom [50]. In a similar direction, the Mobile Social Compass is a social skills curriculum for children with autism that combines visual supports, visual schedules and story-based interventions to develop age and functioning-level appropriate social skills [36]. The *Mobile Social Compass* is a mobile augmented reality application that uses a visual schedule to guide children throughout an interaction, helps them detect potential interaction partners, and gives them social cues [230]. By receiving this information through the mobile devices, each child gets direct assistance and reinforcement for practicing their social skills.

Despite the preliminary success of prompting and reminding systems for children with developmental disabilities, there are still open questions related to identifying when the reminders and notifications should be sent, because these systems still use a model that triggers a "pre-defined" reminder for a "pre-specified" time. In environments where the activity rather than the time dictates the scheduling process, these systems cannot adapt appropriately to the current context. To provide this kind of flexibility, other projects have researched the use of AI planning techniques to introduce flexibility into a schedule-management system [137, 185]. For example, the PEAT system is a memory notebook that helps users to stay on task [137]. To do this, the system uses a cue card that provides information about the current executed activity including people involved, date, how to start and finish the activity. This system uses intelligent systems to customize the schedules with activities adapting to each user's needs.

Other projects, utilizing general concepts of user behavior to inform the adaptation of pervasive health technologies, have explored the use of activity-aware computing to provide step-by-step guidance. For example, COACH [158] is designed to assist a person with severe dementia who has difficulty remembering the proper sequence of everyday activities. The current version of COACH assists a person with hand washing. The COACH system uses a video camera to observe the user as she attempts to wash her hands. The video image is processed to identify the step currently executed (e.g., turning on the water, using soap, drying hands). If the system recognizes a problem — for instance, that the subject is using the towel before wetting her hands — a prerecorded verbal prompt is provided.

Similarly, applications for providing step-by-step guidance have been proposed to help elders comply with their medicine prescription. For example, Garcia-Vazquez et al. [77] have designed an ambient information notification system to help older adults identify when it is time to take a medicine (Figure 3.5). The authors use the characteristics of the pillbox to notify the elderly of the time and the dosage of the drug that needs to be taken. For example, a square pillbox reminds the older adult that such medicine should be taken four times a day. The pillbox illuminates 5 minutes before a scheduled dosage and an alarm is also sent to a mobile phone. As with exercise applications, data visualization techniques are used to motivate elderly compliance with their medications [134]. The results of this study emphasizes that only after people have seen how poorly or well that they have been complying will they are more willing to improve their behavior. Finally, there has also been an interest in the use of social competition to help elders adhere

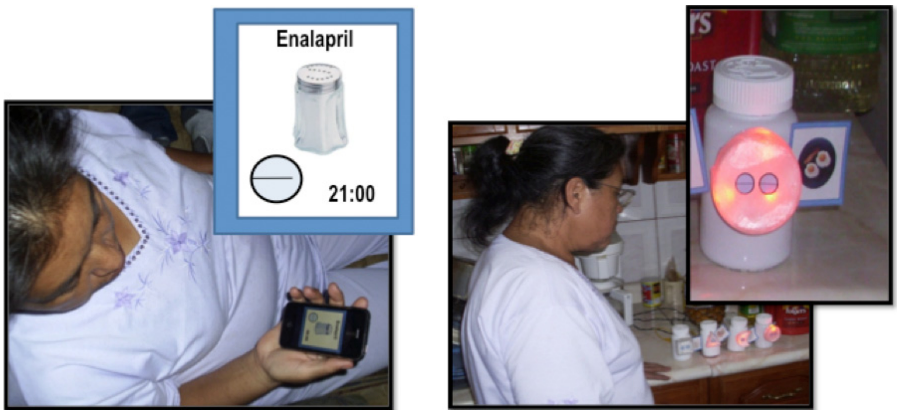


Fig. 3.5 Activity-aware system providing aids for medicating on different objects: (a) Mobile medication reminder; (b) Medicine container providing ambient aids.

to their medication. The MoviPill [55] is a game running in a mobile phone with the primary objective of letting the user take the medicine before an alarm is triggered. MoviPill sends an alert 15 minutes after a dose has to be taken so the user earns points whenever s beats the alarm. MoviPill also uses a social network to create a social competition among participants.

3.5 Conclusion

In this section, we focused our attention on the role that pervasive health technologies can play in settings that are less traditionally associated with healthcare than the clinic, such as homes and schools. However, with an increase in the aging population and a shift from an acute to chronic health problems, these alternative settings are increasingly becoming the site of care rather than the clinic.

The projects in this chapter highlighted how far we have come in providing support for a variety of activities that seemed impossible just a few decades ago. However, we are just at the beginning of exploring this space. A number of issues still require greater attention: reducing the cost of these devices and improving the usability of these systems among other issues.

4

Personal Informatics and Wellness Management for Preventive Care

As previously mentioned, life expectancy in industrial nations is increasing every year [63, 114, 174, 175, 205], and alongside this greater longevity is a growing "prevalence of chronic conditions and their associated pain and disability" [114]. Consequently, preventing these chronic illnesses from developing in the first place is becoming a more substantial priority. Indeed, many countries have created preventive programs encouraging healthy behaviors in an attempt to curb health-care costs on a large scale. Many pervasive computing applications for personal informatics [139] center on medication compliance and adherence (e.g., [77, 113, 146]) or persuasive technologies for disease prevention and wellness management (e.g., [44, 45]). Other applications focus on documenting medically significant events for chronic patients (e.g., [120, 144]) and on social health issues (e.g., [142, 169]). In this section, we describe several projects that focus on pervasive technologies to facilitate the automatic and selective archiving of health data. We also discuss persuasive technologies to support self-monitoring and social health to prevent cognitive decline and maintain physical and psychological well-being.

4.1 Automated and Selective Capture and Access of Health Information

Managing personal health information can be particularly challenging for chronic patients whose conditions span years and are often complex. Despite the growth in methods and technologies for documenting and managing personal health information, there are still a number of open questions about how pervasive technologies can facilitate the capture, management, and access to health information [186]. Therefore, many research projects have focused on developing capture and access tools [233] to facilitate the management of health information using various levels of manual and automatic capture.

One of the primary ways to capture data is through manual mechanisms that are triggered by the users. Using manual data gathering techniques, researchers have begun to examine particular issues related to the early detection of chronic health conditions in children and infants. Jeong et al. [108] noted several opportunities for computing to help parents manage healthy children. These results indicate that in households in which both parents work, parents can often forget to administer medication or conduct other caregiving tasks. Building upon several results surrounding the understanding of the care of babies and infants [88], researchers have implemented capture and access tools for managing baby health information. Baby Steps is an application designed to act as a child development milestone repository. Through Baby Steps, parents and other caregivers collect data to foster communication and understanding, particularly for children who may be at higher risk for developmental disabilities [120].

Similarly, the Estrellita system is an automated capture and access tool that allows parents of premature infants to capture relevant information about their newly born child and share it with health providers, close relatives, and friends [144, 224]. The system includes two interfaces: a mobile application (Figure 4.1) and a web-based interface through which professionals can access and analyze data. The mobile application allows parents to update their baby's health information, consult computer-generated or professional-generated warnings, update data about their own health and well-being, and flag data points of

Fig. 4.1 The mobile application showing left to right: (a) the Estrellita dashboard, (b) the interface for capturing diaper use, and (c) the widget for the phone home-screen.

concern. The web-based interface allows professionals to check patient information. Parents and professionals can also use the system to securely communicate with one another.

In the fitness domain, several projects have explored the use of mobile phones for capturing and consulting relevant health data (e.g., [41, 105]), as others have shown that mobile devices are more attractive and fun to use for capturing health information [79]. The PmEB is a mobile phone application for monitoring food injection and level of physical activity [41]. A user uses the mobile phone to input any episode of eating and/or physical activity. The system uses this information to compute a caloric balance (either positive or negative). Users may also use the phone to review the history of their entries. The results of an evaluation conducted with the system showed that the presented information plays an important role in persuading the user to maintain a positive caloric balance. My Food Phone[1] is a mobile commercial application that helps users to keep track of the food that he/she ingests every day by taking pictures of the food ingested and getting reviews from the nutritionist. Similarly, others have explored how to present just-in-time information to help people make an informed decision about their health. For example, Intille et al. [105] developed a mobile application for helping people decide what food purchase based

[1] *My Food Phone https://www.myfoodphone.com/home.aspx*

on their diet. In this application, users enter the name of the food, and the system indicates with a percentage the appropriateness of such food according to the user's diet. This information helps the user to make an informed decision of what to purchase.

Advanced record-keeping tools are just a first step in improving health information management using pervasive computing technologies. However, self-monitoring is labor-intensive, and compliance is often difficult. In addition to being *able* to document this information, patients and caregivers must be *willing* to manually capture this information. Consequently, there is growing interest in integrating pervasive monitoring technologies with these applications to facilitate automatic data capture.

Advances in pervasive monitoring technologies have enabled the development of automated monitoring systems that can continuously track user's basic metabolic and behavioral parameters such as vital signs, activities, social interactions, sleep patterns, and other health indicators. These projects have mainly focused on supporting the monitoring of: hospital patients (e.g., [146, 203, 234]), the elderly (e.g., [183, 244]), and people's lifestyle habits (e.g., [40, 44, 187]).

To monitor lifestyle habits, several commercial products have proposed the use of on-body sensing devices that work with mobile phones to monitor users' physical activity. For example, Polar Watches[2] enable users to keep track of their exercise routines, allowing them to monitor their heart rates and view reports on their mobile phones of the number of calories expended. Several projects have proposed the use of pedometers for counting the number of steps taken by a user. To capture the steps, the pedometer counts any ascending and descending accelerations that are interpreted as steps. Even though these are very popular devices that provide off-the-shelf solutions for sensing physical activities, many are not very reliable nor suitable for a wider range of activities. To address this issue, several projects have proposed the use of multiple devices worn on different parts of the body combined with pattern recognition algorithms for estimating physical activities. For example, the Shakra application [9] uses a neural network to analyze

[2] *Polar Watches http://www.polarusa.com*

the cellular network signal strength to estimate users' movement. The Mobile Sensing Platform (MSP) [40] is a pager-sized, battery-powered computer, augmented with sensors and a set of boosted decision stump classifiers trained to infer physical activities, such as walking, running and cycling. The inferred activity is communicated via Bluetooth to a mobile phone. The results of an evaluation using the MSP showed that users need to correlate the data captured over time with more information to have a better understanding of the meaning of that data [40]. Similarly, the Wellness Diary (WD) is a mobile journaling tool for recording a wide variety of wellness-related self-observation parameters including weight, exercise, steps, diet habits, stress level, sleep duration and quality, and tobacco and alcohol consumption. Users can personalize their phone views, selecting the parameters they want to review. The evaluation of this system showed that users perceived the captured information as useful, but the displayed information was not particularly motivating because it is not correlated with other relevant information and because of its poor visual representation [8].

As the WD evaluation highlights, the presentation of health information is just as important as the collection of the data. Therefore, there is a focus on identifying the best ways to display captured information and related context. For example, in [187], users used a glucometer and a mobile phone camera to record their blood glucose and photograph their meals. The evaluation results highlighted that having both the photographs and the blood glucose numbers enabled users to improve their decisions regarding their daily drug dosages. However, a challenge to using sensors is the amount of time that users have to invest in configuring them and how intrusive users perceive them to be. To cope with these challenges, some projects have explored how to develop specialized hardware and devices for capturing specific data. For example, the GlucoPhone developed by HealthPia integrates a glucometer and a cellphone for monitoring users' blood glucose levels.[3] Indeed, these projects focused on integrating physical

[3] *HealthPia America. GlucoPhone: A Cellphone for Diabetics. http://healthpia.us, August 2006.*

and digital devices have raised some interesting issues about designing, developing and deploying such systems. These issues include the development of new devices for health monitoring, battery issues, privacy and communication protocols for the transmission of health data over wireless networks, and new models for data visualization.

Several pervasive health projects focus on the visual representations of the data that enable multiple stakeholders to view and understand relationships in the data. In particular, researchers have explored the selective sharing of health information using mobile devices and ambient or natural displays. For example, the Careview project [148] focused on the capture and access of medical information to support work practices and information needs of homecare nurses. This project proposed a set of interface design guidelines for displaying clinical data including temporal visualization, integrated data gathering and data analysis, and hands-free speech-driven operation. The CareNet display [47] and the Digital Portrait [118], discussed in Section 3, also include different options for sharing the sensed data with others. In these particular cases, the tradeoff was to balance users' privacy and the amount of awareness needed by the caregivers. As with situated displays, others have explored the use of natural objects (e.g., mirrors) for displaying health information and provide continuous awareness of health data to the user. For example, the ScaleMirror [241] uses an special mirror augmented with sensors and LCD displays to show a user his/her weight and calculated BMI with a chart of how his/her weight changed over the past few months.

These projects demonstrate the use of capture and access tools to facilitate the personal health management in a setting that is predominantly nonmedical, which is the home. With new tools for manually capturing and selectively sharing data, there is potential for greater information awareness. However, at the same time, this awareness may lose some of the rich context that can be automatically provided through the monitoring users' everyday activities. Therefore, we need solutions that advantage of an environment furnished with sensors capable of detecting what relevant information is worth sharing instead of requiring users to decide what to share. Consequently, there are opportunities for designing and developing automatic capture and access services enabled with pervasive sensing technology that will identify which data are worth capturing and how to share the rich context and information. Indeed, when designing these services, tensions arise between how much information can be automatically or selectively shared. This imbalance between a user's desired level of control over the information being shared and the loss of value if the information is not shared requires further exploration.

4.2 Persuasive Technologies for Self-monitoring

Researchers have begun to examine the use of persuasive technologies [12] for encouraging people to take on the responsibility of managing, capturing and analyzing their own health information and behaviors. Research on persuasive technology draws from psychological theories such as goal-setting theory [145] and the trans-theoretical model [190]. The former describes how individuals respond to different types of goals, while the latter identifies the stages through which an individual progresses to intentionally modifying his/her behavior. In keeping with these theories, different persuasive health-related applications have been proposed in the literature and have shown promising results in encouraging people to manage their health information and in positively changing people's behavior. In this domain, there are a wide variety of applications for fitness and wellness technologies. These include sports instruments such as pedometers, heart rate monitors, wrist-top computers and cross-country running to software designed for tracking, encouraging, and reporting. Some projects in this domain have explored the use of pervasive games as a means to discourage unhealthy behaviors, such as watching too much television [26] or encourage healthy behaviors, such as physical activity [22], following the notion of celebratory technology [87]. In this section, we describe the main persuasive applications including the use of aesthetic images, games, reminders and communication services used in the fitness and medical compliance domains.

In both the research and commercial product space, a variety of applications are available to promote a healthy lifestyle by helping users maintain a healthy diet and keep up with their exercise. For example, as we discussed in the last section, My Food Phone[4] and Polar Watches enable users to keep track of their physical activity and dietary habits. The variety of tools available in this space is a scope much too large to document in this survey because new tools, particularly in the commercial space, are being developed and released continually. At the time of writing, the Apple iTunes store lists 1687 "apps" for "diet" and 1638 for "exercise." Our aim is to highlight some of the common features of these applications as well as the results of research done on a subset of these tools. A more detailed review of the literature in this particular area can be found in [45].

The UbiFit Garden system (Figure 4.2) was designed to encourage regular physical activity [44] that was monitored with the Mobile Sensing Platform (MSP) [40]. People's physical activities are displayed to the user through an aesthetic image in the form of a flower garden. When the MSP detects a new physical activity, it improves the appearance of the plants in the garden and adds new elements, such as butterflies. If no physical activity from a user is detected, the flowers in the garden might perish. The results of an evaluation of UbiFit showed that "aesthetic images" are a very high motivator for persuade users to continue changing their behavior while helping them to maintain engaged with the system. Open questions remain to investigate how aesthetic images positive impact users behavior for long-term.

Fig. 4.2 The Ubifitgarden showing left to right: (a) a user wearing the activity sensor, (b) the actual activity sensor, and (c) the ubifit for the phone home-screen.

[4] https://www.myfoodphone.com/home.aspx

Other projects have explored the use of aesthetic images in conjunction with games for encouraging a healthy lifestyle [39, 140, 148]. For example, the PlayfulBottle [39] measures how much water is drunk to motivate people to drink healthy quantities of water. It uses lego bricks attached to a water bottle to present how much water has been drunk and hydration games to encourage people to daily and regularly drink water. The hydration games use the metaphor of caring for a tree by "watering your body." When a user does not regularly drink enough water, his virtual tree would slowly transform from a beautiful green tree with many leaves to one with bare and withered branches. Similarly, Fish'n'Steps [140] uses a pedometer to count steps and associates a user daily foot step to the growth and activity of a virtual pet (i.e., a fish) and the appearance of the fish tank that shelters the virtual pet. The evaluation of Fish'n'Steps showed that the game served as a catalyst for promoting healthier lifestyle but the game was perceived to be too repetitive. People stopped using it after a while. This poses new questions regarding the design and use of games for encouraging long-term behavior change.

To try to address this challenge, several projects have proposed exergames, serious and casual games that use a social motivation scheme to promote a healthy competition among users and establish a long-term commitment. Mueller et al. [167] developed a variety of exergames that allow people to compete in structured physical activity sessions (such as playing a ball game) with remote third parties. The Neat-O-Games [115] offer a set of games for mobile devices which, through continuous monitoring of users steps and social competition help the user to avoid a sedentary lifestyle. Users select configurable avatars that participate in virtual races against their invited competitors [115]. Yet another, and perhaps the most researched serious game, Dance Dance Revolution connects a sensor-enabled dance floor with a video interface and provides stimulating exercise as a social activity — dance competition [102]. A recent trend is the use of motion sensing controllers (e.g., WiiMote,[5] *Kinect sensor*[6]) to allow individuals to

[5] *http://www.nintendo.com/wii*
[6] *http://www.xbox.com/es-MX/Kinect*

natural means to manipulate digital services available in games. Taken together, this body of work demonstrates that games and social competition can be used to establish long-term commitments and are more sustainable than other available persuasive mechanisms. This has motivated the use of games for caring elders and also for help people with physical impairments in their rehabilitation. The Therapy Top [126] is a spinning top used in sports studios and physiotherapy for enhancing the equilibrium sense, improving muscle balance in the legs and ankles and manoeuvrability in the lower body parts. The Therapy Top is a disk that has a rounded bottom and a flat top to stand on. Therapy Top comes with several games that requires a user to mimic the positions standing on the Therapy Top to those made by an avatar in the game. The information captured by the device is then shared with the specialist for improving the rehabilitation therapy. Similarly, "Taga-boo" [153], a collaborative children's game, focuses on developing coordination through playful interaction. Overall, the evaluation of these projects have emphasized the importance of sharing the information with close relatives, friends and health providers to keep the users engaged and improve the results of the therapy.

Overall, this research stream has emphasized the importance of sharing the captured information for social motivation and behavior compliance. However, there are still some open questions regarding the impact of sharing this information. Indeed, there is substantial work in this regard centering on social health.

4.3 Social Health

Medical research has provided strong evidence of the beneficial role of social ties and social integration in maintaining physical and psychological well-being [54, 184]. This dimension of an individual's health focuses on how well an individual gets along with other people, how other people react to that individual, and how that individual interacts with social institutions and societal mores has been defined as "social health." Virtual communities and social network sites allow many individuals to collaborate and share experiences with people who are geographically distributed [109]. Virtual communities have been successfully used in the care of patients [107]. Their benefits include reduced stress, social satisfaction, the availability of information relevant to their disease, and increased communication between patients and clinicians [212]. In this section, we describe an extension of these technologies for social support through the addition of pervasive computing technologies.

Researchers have explored how to use virtual communities and social networks integrated with body sensors as persuasive tools to help people with chronic diseases share their experiences and problems providing community support, motivational reinforcement, or encouragement for healthy lifestyles and clinical adherence. For example, *Houston*, a software application that promotes healthy lifestyles in social groups, allows users to register physical activities and send instant messages [222]. *Houston* uses a pedometer to measure the physical activity and mobile phones to support the social group. *Houston's* main function is to record physical activity, goals, message exchanges with friends, and activity time lines. However, these applications do not provide mechanisms that allow patients to communicate with specialists or vice-versa. This lack of communication might decrease patients' satisfaction [240]. Similarly, but focused on supporting communication between patients and specialists, pHealthNet (see Figure 4.3),

Fig. 4.3 pHealthNet (a) A patient receives a notification of a challenge on her mobile phone (b) A patient reviewing her record.

a persuasive virtual community, aims at promoting a healthy lifestyle in patients with chronic degenerative diseases who participated in a national program for the prevention of diseases, education, and self-care [15]. pHealthNet helped patients change eating habits and increase their physical activity. To encourage and support communication between patients and health care providers, the system allows users to exchange messages and video and audio logs. Also, health providers can review patients' diet and exercise logs to create contextualized messages. For example, a nutritionist can send a message about a photograph of a specific meal the patient uploaded to let the patient know if that specific instance of the patient's diet journal fits with the patient's diet. Or she could write a congratulations message when a patient's steps increased. The system sends some of these messages automatically through a virtual specialist agent configured by the specialist. Health providers can also upload educational and motivational videos to inform their patients how to maintain a healthy lifestyle.

This research highlights the specific design issues for pervasive health applications in the domain of fitness. The requirements include persuading users through personal and group tools for motivational reinforcement and the exchange of their experiences, empowering a social network community with asynchronous and synchronous communication channels on a diversity of devices, enabling users to self-measure their progress, promoting friendly competition, and providing customizable educational cues for behavior improvement.

In the eldercare domain, the use of social networks in conjunction with mobile devices and body sensor devices for the automated captured of data has also been an active area of research. Strong social networks can also enhance quality of life for older adults [83] by improving their health [54], reducing the chances for developing cognitive decline [71], and also prevent an earlier death [101]. Older adults with poor or weak social networks are 60% more likely to experience cognitive decline due to isolation or the high stress levels caused by the loss of the spouse [209]. Thus, there have been a variety of efforts dedicated to improving the social health of elders through pervasive computing. For example, Morris et al. [166] conducted a series of prototype designs for encouraging elderly users to reach out to their peers and family members for social support. Additionally, efforts in designing natural interfaces for connecting younger relatives and older adults have been explored [47, 142, 169]. In these projects, issues surrounding the levels of symmetry and reciprocity between the elderly users and other members of the social network consistently emerged. Symmetry in relationships is important because people expect to receive as much as they provide to their contacts; however, within families, reciprocity often behaves asymmetrically, especially with older adults [141]. Older adults expect to maintain their role as providers within the family, contributing more in family relationships than receiving, which can make the elderly less likely to ask for and receive the social support they need.

Consequently, researchers have explored the use of multimodal interfaces to support family connections and social connectedness. Studies have explored situated displays to keep older adults in touch with people they care about. These situated displays make use of the primary goal of photo sharing: "the communication of experience" [74], providing suitable ways for serving as context for conversations. The Epigraph [143] system divides the screen into a fixed number of channels, one representing each relative. Channels can be updated via email, text, or picture message. This prototype provides different ways of sending content to the older adult. Taking into account the need for intergenerational connections, GustBowl [116] was designed to reconnect mothers and sons. When the son's bowl detects the presence of an object, it records its movement and takes a snapshot of it. Then this information is sent to the parents' home, where another bowl will wobble and display the snapshot of the object, transmitting the message of "arriving home." Other technological designs have aimed to connect grandparents and little grandchildren by integrating playful situations to enrich conversations. As described earlier, the Virtual box system [53] is designed to connect grandparents and grandchildren. It is based on a hide and seek game where grandparents add virtual content to the virtual box and hide it in a virtual floor plan. Using a PDA, the grandchildren can search for the hidden virtual box and see the virtual items. Once the grandchildren find the virtual box they can add virtual items and hide the virtual box, thus promoting reciprocity. Other designs use photographs of an everyday object such as a portrait [46, 170] aim to support aging in place, by providing a qualitative sense of an older adult's daily activities to other family members. The awareness provided to the relatives may support family connections by triggering discussions about the older adult's activity.

4.4 Conclusions

In this section, we described a variety of tools to support personal health and wellness management. Some of these tools focused on the capture and access of personal health data. This an important area for further research because while it is important to capture relevant health data, it is also just as important to be able to present the data in such a way that it is understood by the user in her own home. An important aspect of health and wellness management is the support that is provided by social connections either through online communities or family. We discussed a set of tools that support these different types of interactions.

However, there still remain a variety of issues surrounding the design, development, and deployment of these tools. These issues include identifying the best interaction approaches for different groups of users, designing the technology so that it is affordable to the user, and providing relevant and contextualized information to the user.

5

Conclusion

The healthcare field is rapidly changing. First, the need for greater efficiency, cost-effectiveness, and safety in hospital settings is driving the need for increased connection between record-keeping, monitoring, and patient care systems [21, 168, 228]. Second, there is a growing movement to empower patients to manage their health in a more effective manner [199], inviting the development of a variety of personal health applications for mobile devices (e.g., [40, 44, 123]) and home sensing platforms and applications (e.g., [80]). Third, there is a growing emphasis on providing more effective care for patients with long-term, chronic conditions (e.g., [5, 93]) as well as addressing health and wellness issues over a lifetime-areas that are particularly amenable to the application of pervasive health technologies (e.g., [5, 96, 121, 178]). This survey has covered pervasive computing approaches to supporting various aspects of health delivery, in particular issues such as "mobility, collaboration, interruptions, ad hoc problem solving, and physical work" that are integral to healthcare [21]. We have described the use of pervasive technologies in support of hospital care, to support assisted living and chronic disease management, and as part of personal health and wellness management for preventive care. Despite the extensive work in this area, however, there are still a number of open areas of research.

In this concluding section, we first provide an overview of often used research methods for pervasive health. We then summarize some of the major approaches to pervasive health in light of general areas of research within mobile, pervasive, and ubiquitous computing. Based on these dimensions and on the reviewed work, we then conclude with a discussion of future work, open challenges and future trends.

5.1 Pervasive Health Methods

We currently live in a world embedded with computational devices, many of which are often simultaneously used by many individuals. Thus, in considering pervasive health we must engage the milieu of present-day medical technologies. At the same time, progress marches onward with visions of the where pervasive health technologies can take us. This duality of approaches requires research methods for examining both current and future technologies, for comprehending both incremental and transformative innovations, and for engaging with those innovations that occur on the ground using existing technologies as well as those that are derived from new visions.

5.1.1 Ethnographic Methods

Pervasive health research has always been of and in the world outside the computer and often outside the lab. Even when describing those applications and technologies that currently only exist within the laboratory, pervasive health publications frequently begin with a vision for use "in the world." The pure physicality of the science requires understanding the context in which these technologies will exist. Thus, ethnographic methods are regularly utilized for both understanding the human needs for the development of new technologies as well as the ways in which these technologies are adopted, appropriated, and engaged (e.g., [34, 112, 162, 177]). Ethnographic methods are a leading technique for investigating organizational and technological settings in HCI and CSCW research [29, 35]. These methods are useful for examining complex settings where technical, organizational, and social factors intersect [152, 176], such as in healthcare. Ethnographic observation is designed to provide a deep understanding and support rich analytical description of a phenomenon, as part of an iterative cycle of observation and analysis [220, 221]. It seeks not just to document actions, but to examine what is experienced in the course of these actions.

Using fieldwork and ethnographic methods enables researchers to engage with the physical artifacts, environmental context, and variety of socio-cultural influences that may impact the need for, design of, and ultimate adoption of new technologies. In terms of pervasive health, these methods allow researchers and designers to envision how a technology can blend seamlessly into the background of an environment as well as to see clearly the ways in which technologies do or do not ultimately accomplish that goal. The use of these techniques, largely borrowed from anthropology, sociology, and other field-oriented sciences, enables designers and researchers alike to recognize the important role "played by the environment in which the work takes place." Dourish [61] the engagement with the "real world" of hospitals, clinics, and homes reveals how work gets done in ways that are not present in process models, workflow diagrams, nor procedural manuals [97]. Finally, this kind of engagement and attention to the physical embodiment of artifacts — both computational and non-computational — reveals how these artifacts can play multiple different roles within the same environment [61].

5.1.2 Rapid Prototyping and *In Situ* Deployments

Weiser's visionary article setting for the ubiquitous computing agenda [236] and the research group he formed around his vision also set forth a practice by which prototyping has become an integral part of the research process for the area of ubiquitous computing (Ubicomp). This practice has carried over into pervasive health research. This trend of building working (or semi-working) technologies as quickly as possible as part of rapid design and development iterations such that one can receive feedback, perform small trials, and test the systems in practice in the world has become central to Ubicomp research methodology.

Evolving out of this desire to move prototypes rapidly into the field, *living laboratories* are spaces specifically constructed for the investigation of novel computational solutions embedded within everyday practices [104, 118, 122, 179]. The living laboratory concept allows for small-scale experimental experiences with novel technologies that are truly embedded in the environment as they could be on the large scale in the future.

5.1.3 Simulation

Despite Ubicomp's push generally to get prototypes into the field, or at the least into a living laboratory, other constraints can make it impossible. The domain problems for which true field testing is impossible — or nearly so — include many areas of medicine and other safety critical domains. For example, the Clinical Surfaces system, which supports context-aware information retrieval in hospital-based multi-display environments, was evaluated in a large hospital by clinical personnel but with hospital staff members playing the roles of patients [24]. Simulations can enable simple usability testing as well as more nuanced probing of adoption and acceptance issues for pervasive health without full scale trials that might put patients at undue risk or require prototypes that are more developed than possible with current technological capabilities. In describing some of the challenges and opportunities for simulation in pervasive health, Dahl et al. argue that *"equipment/prototype fidelity, environmental fidelity, and psychological fidelity... need to be adjusted according to which design aspects evaluators want to gather feedback on."* [106] Furthermore, we further argue that these aspects must be considered and adjusted according to the cultural and political needs and mores of the particular environments in which testing and eventual deployment might take place.

5.2 Pervasive Health Application Themes

Taking an explicitly technological viewpoint on ubiquitous and pervasive computing, Abowd and Mynatt [6] describe three classes of applications: natural interfaces, context-aware computing, and capture and access. We describe each of these application areas in turn and provide insight into how pervasive health applications fit into these categories and how use of ubiquitous and pervasive computing approaches and frameworks can support design, development, use, and evaluation in healthcare settings.

5.2.1 Natural Interfaces

Natural interfaces include a wide variety of interaction styles between humans and computers but generally include those interaction modalities that are the most *natural* in terms of being familiar to the average person. These interfaces are intended to blend seamlessly into the everyday behaviors of individuals. Typical natural interfaces include the use of speech, pens, and gestures.

The benefits to a "natural" approach to interfacing with computational devices are enormous. They have the potential for significant hands-free interaction. Furthermore, their use could limit the need to retrain individuals who have advanced medical expertise but minimal technical interest and skill. In the long-term, the emphasis on dictation and transcription within medicine lends itself to the use of these systems. However, integrating speech and other natural interfaces into legacy systems with tightly constrained requirements on input and output and into existing environments that may be noisy and chaotic has continued to challenge researchers and systems implementers. Furthermore, these natural interfaces are not simple to build particularly in ways that allow them to be robust and error free. In recent years, vast improvements have been made in this space with speech recognition and audio output software now being used regularly in customer support systems, in-vehicle navigation and control systems.

As healthcare technologies expand in number and complexity and become more prevalent in both clinical and non-clinical environments, the integration of the digital data and functionality with the physicality of the spaces they inhabit becomes even more important. The path forward for pervasive health almost certainly includes utilizing commonly requested natural interfaces, such as speech recognition and audio output. Large-scale electronic medical records systems already integrate such services as Dragon Dictate/Naturally Speaking[1] to speed dictation and reduce costs for inserting data into the medical record.

[1] *http://www.nuance.com/dragon/index.htm*

At the same time, however, pervasive healthcare technologies are likely to include greater emphasis on embedded and implanted systems for monitoring, diagnosis, and even treatment. Few ways of interacting with computational systems could be more natural — and perhaps unnatural at the same time — than interfacing directly between the human body and the machines with no explicit intervention by the "user" at all.

5.2.2 Context-aware Computing

Context-aware computing, often also referenced as activity-based computing or activity-aware computing, emerged from a focus on helping systems to respond more appropriately to the dynamic, improvisational nature of human behavior. This area of research typically includes applications that leverage awareness of what is occurring in the physical and computational environments surrounding them through the collection, fusion, and interpretation of complex sensor streams. These applications might use simple contextual cues (e.g., who is logged into the system) or more advanced recognition of meta-activities (e.g., the triage status of an entire Emergency Department) to enhance the user experience.

One of the most fundamental challenges to context-aware computing is understanding just what the context of a particular situation is and how to define, sense, and represent that context. The collection and representation of context is not only challenging in terms of technological capabilities (e.g., how to sense context, store context elements in a database, etc.) but also in terms of the inherent complexities of the human and organizational actors. Context has largely been considered "any information that can be used [by a computer] to characterize the situation of an entity," in which entities could be people or artifacts [57]. Examples of relevant context data include location, identities of nearby people and objects, and changes to those objects [206]. The appropriate calibration of sensors and interpretation of their data have long been issues of concern in context-aware computing, further complicated by the rapid speed with which context can change (e.g., in a hospital environment). Dourish further problematizes the issues of context by expanding our understanding of "context" from "a set of descriptive features of settings" to "forms of engagement with those settings." [61]

Despite these challenges, however, numerous researchers have continued to explore the use of context-aware computing for a variety of applications, including healthcare [16, 168, 216, 228]. Context-aware systems can adapt to human behavior over time and provide greater personalization in both interfaces and in functionality. Furthermore, they can be used to take action proactively, such as delivering needed information to save time.

In pervasive health, context-aware computing is particularly helpful in retrieving patient-specific information in a timely manner as well as in providing context-sensitive clinical decision support. Decision support systems in clinical practice tend to focus on the context of what is in the chart, and other information that is readily available in large scale clinical information systems. However, the future trends for pervasive health in these settings indicate that decision support systems could be enhanced even further if they included not only information present in clinical information systems but also other "context" such as the weather, how busy various pharmacies are in the area, traffic conditions, or even the level of distractedness or emotional well-being of the clinicians, patients, and other caregivers.

5.2.3 Capture and Access

Documentation is an integral part of medical work. Clinicians use documents and medical records to examine patient data long-term to diagnosis complicated disorders and monitor the health of their patients [216]. They also use the records themselves as a means for communication and professional development [22, 23, 33, 34]. Despite continued growth in methods and technologies for documenting and managing personal health information, people still experience a variety of challenges related to personal health information management [186]. Civan et al. found that the *"fragmentation of personal health information and reliance on human memory" are two of these significant challenges.*" [42] The aggregation of information for ease in both recall and analysis is a major goal of capture and access technologies. Thus, these technologies may represent a potential part of the solution of managing this information as it grows in scope and complexity.

Recordkeeping and documentation are significant themes in computing and applications research generally. Fundamentally, this inclination derives from a desire to recall and sometimes to share details from lived events even within the constraints of often-limited human memory and communication. Ubicomp researchers have been particularly concerned with the notion of recording and providing access to these records in a relatively automated, flexible, and seemless manner. The class of applications deriving from this notion of automated and simplified record-keeping is typically called *capture and access applications.*

Beginning with Vannevar Bush's visionary *memex*, computational systems have been viewed as a means for documenting, providing access to and understanding everyday experiences [37]. Weiser's article then expressed this vision as occurring off the desktop, lived out in the world, most notably in the following scenario:

> *Sal doesn't remember Mary, but she does vaguely remember the meeting. She quickly starts a search for meetings in the past two weeks with more than 6 people not previously in meetings with her, and finds the one.* [236]

Since then, a multitude of projects in both the commercial and research space have been dedicated to this goal [233]. These applications indicate a variety of challenges and opportunities in this space.

The capture of information can be extremely difficult when a recording was not planned beforehand or when the setting is so unstructured that it does not naturally afford recordation. Anyone who has jotted down a note on the proverbial cocktail napkin to remember a brilliant idea hatched during a hallway conversation can attest to the need for and difficulty of data capture in those situations. Although people have developed strategies for managing recording and documentation, these strategies can still fail, particularly when the strategies break down (e.g., the perpetually lost scrap of paper). Similarly, recording often interrupts the human participants in an activity. Thus, automated recording seems a promising solution to allow the human users to concentrate on the task at hand. However, this solution creates further challenges. First, automated capture can strain the ability of a system to document everything the human users want and nothing the human users do not want. Second, the creation of this much data naturally brings further challenges in the accessing — including indexing, analyzing, and visualizing — of the mass quantities of captured data.

Despite these challenges, the opportunities available through automated capture and access of data can be enormous. First, automation can decrease the amount of time required for documentation. Second, as previously noted, automating the recording process can increase the amount of attention participants can pay to an activity rather than to documenting the activity. Finally, there is potential for future scientific, clinical, and epidemiological insight based on analysis of vast volumes of automatically collected data. One of the most obvious applications of capture and access technologies for healthcare is the creation of an better electronic medical record, through which healthcare providers can focus their attention on patient care while the system automatically documents procedures, results, and health data. Within pervasive health, a variety of enabling technologies have been developed and tested that would support this kind of automated capture or selective archiving (e.g., [40, 44]). Additionally, some researchers have gone so far as to develop automated capture technologies for limited settings (e.g., [91, 204, 217, 218]). Embedding access of this information seamlessly into the physical environment of both clinical and home settings would expand the utility of these data and potentially the efficiency with which people act on it [119]. However, there is still substantial work to be done to create automated capture and access applications for both home and clinical settings that can work over long periods of time with enough robustness to be appropriate for critical health situations.

5.3 Trends and Open Challenges

As we look to the future of mobile, ubiquitous, and pervasive computing in healthcare, the rapid proliferation of small devices, large displays, and networked interfaces seems assured. How these might interact with each other, with patient data, and with clinicians and patients themselves, however, is still largely to be determined. In light of these open questions, there are also a variety of challenges to be addressed for widespread adoption, acceptance, and use of pervasive health technologies and applications. In this section, we briefly outline some of these challenges and new trends as a future agenda for the research of pervasive healthcare.

5.3.1 Behavior-aware Computing

One of the main characteristics of pervasive healthcare applications is their reliance on contextual information (e.g., from the 148 discussed projects 30% of them involved the use of context-aware computing). The first wave of context-aware healthcare applications used individual's location as the main trigger to present individuals with information relevant to the task a hand and adapt the behavior of such applications (e.g., CHIS [168], AwareMedia [15, 16]). The advances in machine learning techniques for context-recognition gave birth to the second wave of context-aware applications moving from location-aware applications to activity-aware applications (e.g., the ADL monitor [228], UbifitGarden [44], COACH [158]). However, open challenges remain to discovering significant long-term patterns of behaviors that will enable individuals to reflect upon and handle healthcare tradeoffs (e.g., drinking a beer will contribute to your happiness today but might damage your health in the longer term). We argue that a new trend for developing context-aware healthcare applications is to infer and display patterns of behavior that may help individuals reflect on their own behavior and take action to change abnormal behavior patterns. These correlations between context and behavioral patterns that emerge over time taking into account the archived health data poses new challenges for the collection, inference, representation and displaying of behavior patterns and long-term effects.

5.3.2 Uncertainty Management

For many pervasive health applications to perform at their highest capabilities — or in some cases to work at all — some amount of context must be sensed, recognized, and presented to the system or its users. However, sensors and recognition algorithms are rarely error-free. Understanding how to present and to manage uncertainty remains an open area of research. The presence of uncertainty information in pervasive healthcare applications represents one of the main challenges and one of the greatest barriers to the long-term success of pervasive healthcare applications. Uncertainty in pervasive healthcare could originate because of the presence of uncertain, ambiguous or incorrect contextual information. Uncertainty may cause malfunctions in applications, rendering them useless to users given their lack of confidence in their robustness.

Despite these concerns, designers have overlooked uncertainty issues and ignored the uncertain nature of context often using it and considering it 100% reliable when developing pervasive healthcare applications [5]. Unfortunately, most available toolkits and architectures designed for the development of pervasive healthcare applications (e.g., Context Toolkit [202], Open Data Kit [191], SALSA [198], ABC [13]) do not provide support for the management of uncertainty information.

Open challenges remain for developing adequate mechanisms for uncertainty management to make pervasive healthcare applications tolerant to the presence of uncertain contextual information. These mechanisms beyond the use of context as a level of implicit input need substantial human input enabling individuals to control errors and have feedback on the application accuracy.

5.3.3 Integrating Clinical and Computing Research Methods

Many of the methods used currently in the design and evaluation of pervasive healthcare applications have been inspired from methods used in the social sciences. However, there is still a huge gap between the methods used in clinical research and computer science. Thus, new tools and techniques for design and development of pervasive healthcare applications must be brought into the clinical research, and evaluation in clinical research must be integrated with the summative methods we used for evaluation.

Similarly, design and evaluation methods must be developed that focus on the physicality of the built environment and the infrastructure present in these settings. Beyond field studies and participatory design meeting, methods for the "co-design" of pervasive application still remain unexplored. This focus has long been known in pervasive and ubiquitous computing research but may be new to the world of medical informatics. Finally, the medical model of privileging randomized blinded clinical trials over other forms of scientific inquiry must be examined in light of rapid design, prototyping, and deployment practices more prevalent in computing.

5.3.4 Socio-technical Issues

Beyond the technical challenges for the design and development of pervasive healthcare applications, their deployment poses a variety of social, cultural, legal, and policy-based issues that are often exacerbated by the healthcare focus. For example, although privacy is an often cited — but just as often dismissed — concern of many mobile, ubiquitous, and pervasive computing projects, it takes on new meaning when considering health data, much of which is regulated more substantially than other kinds of data and which has greater risk associated with disclosure. Likewise, securing these data becomes not only a moral imperative but a legal one as well when considering health information. Finally, the complex geographical, international, and cultural forces at work that shape the kind of medicine practiced, views on preventative health and wellness, and other related issues must be taken seriously in the design and development of pervasive health applications.

Scalability and costs are other challenges that hamper the deployment and adoption of pervasive healthcare technologies in real-world settings. In particular, new standards for communication and design across a wide array of medical devices and legacy health information systems might help to reduce challenges and associated costs in when deploying new pervasive and ubiquitous computing technologies in real-settings.

5.3.5 Gestural Interaction

Moving from the development of natural interfaces and implicit interaction using most of time unreliable contextual information, open questions concerning new the creation of natural and intuitive forms of human–computer interaction that make it easier for clinicians and patients to achieve their goals while using computers, are needed. In healthcare environment were clinicians can't use a keyboard or a mouse to control the computer as they are in the operating room, or patients with cognitive impairments unable to interact with the computer having devices, methods, and approaches to easy the manipulation of digital services is paramount.

With the rapid growth of sensors and hardware, and with robust algorithms for speech and object recognition, we are nowadays able to envision new interaction models based on gestural interaction. These new models will enable users to experience a more natural interaction with digital services. Take for example the use of kinnect for developing exergames to encouraging people to exercise. We no longer need to depend on implicit interaction, now we can empower the user with natural gestures (e.g., wave your hand to turn off a computer) to provide a better engaging experience. Open questions remain for the development of approaches and hardware that will better help us to understand the human body to create new gestures that will enable clinicians and patients manipulate the pervasive environment.

In summary, the research being done in pervasive health can lead to patients being provided better care in hospitals, people with a variety of issues related to health and aging being able to live more independently, and better management of chronic conditions. This field is one with a number of challenges but also with tremendous opportunities.

References

[1] "Computerisation of personal health records," *Health Visitor*, vol. 51, no. 6, p. 227, 1978.

[2] G. Abowd, "Classroom 2000: An experiment with the instruction of a living educational environment," *IBM System Journal*, vol. 38, no. 4, pp. 508–530, 1999.

[3] G. Abowd and E. Mynatt, "The humen experience," *IEEE Pervasive*, vol. 1, no. 1, pp. 48–57, 2002.

[4] G. D. Abowd, C. G. Atkenson, J. Brotherton, T. Enqvist, P. Gulley, and J. Lemon, "Investigating the capture, integration and access problem of ubiquitous computing in an educational setting," in *ACM Conference on Human Factors in Computing Systems (CHI '98)*, pp. 18–23, Los Angeles, CA, April 1998.

[5] G. D. Abowd, G. R. Hayes, J. A. Kientz, L. Mamykina, and E. D. Mynatt, "Challenges and opportunities for collaboration technologies for chronic care management," in *The Human-Computer Interaction Consortium (HCIC 2006)*, 2006.

[6] G. D. Abowd and E. D. Mynatt, "Charting past, present, and future research in ubiquitous computing," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 7, no. 1, pp. 29–58, 2000.

[7] S. Agarwal, A. Joshi, T. Finin, Y. Yesha, and T. Ganous, "A pervasive computing system for the operating room of the future," *Mobile Networks and Applications*, vol. 12, nos. 2–3, pp. 215–228, 2007.

[8] A. Ahtinen, E. Mattila, A. Väätänen, L. Hynninen, J. Salminen, E. Koskinen, and K. Laine, "User experiences of mobile wellness applications in health promotion, user study of wellness diary, mobile coach and selfrelax," in *International ICST Conference on Pervasive Computing Technologies for Healthcare 2009*, London, UK, 2009.

[9] I. Anderson, J. Maitland, S. Sherwood, L. Barkhuus, M. Chalmers, M. Hall, B. Brown, and H. Muller, "Shakra: Tracking and sharing daily activity levels with unaugmented mobile phones," *Mobile Networks and Applications*, vol. 12, no. 2, pp. 185–199, 2007.

[10] J. A. Ash, M. Berg, and E. Coiera, "Some unintended consequences of information technology in health care: The nature of patient care information system-related errors," *Journal of American Medical Informatics Association*, vol. 11, pp. 104–112, 2004.

[11] M. Bång, A. Larsson, and H. Eriksson, "NOSTOS: A paper–based ubiquitous computing healthcare environment to support data capture and collaboration," in *AMIA Annual Symposium Proceedings*, 2003.

[12] T. Baranowski, R. Buday, D. I. Thomson, and J. Baranowski, "Playing for real: Video games and stories for health-related behavior change," *American Journal of Preventive Medicine*, vol. 34, no. 1, pp. 74–82, 2008.

[13] J. Bardram and H. B. Christensen, "Pervasive computing support for hospitals: An overview of the activity-based computing project," *IEEE Pervasive Computer*, vol. 6, no. 1, pp. 44–51, 2007.

[14] J. Bardram and T. Hansen, "The AWARE architecture: Supporting context-mediated social awareness in mobile cooperation," in *Computer Supported Cooperative Work*, Chicago, Illinois, USA, 2004.

[15] J. Bardram, T. Hansen, and S. Mads, "AwareMedia — A shared interactive display supporting social, temporal, and spatial awareness in surgery," in *Computer Supported Cooperative Work*, Banff, Alberta, CAN, 2006.

[16] J. Bardram, T. R. Hansen, M. Mogensen, and M. Soegaard, "Experiences from real-world deployment of context-aware technologies in a hospital environment," in *International Conference on Ubiquitous Computing*, Orange County, CA, USA, 2006.

[17] J. E. Bardram, "Applications of context-aware computing in hospital work: Examples and design principles," in *ACM Symposium on Applied Computing*, Nicosia, Cyprus: ACM Press, 2004.

[18] J. E. Bardram, "The trouble with login — on usability and computer security in ubiquitous computing," *Personal and Ubiquitous Computing*, vol. 9, no. 6, pp. 357–367, 2005.

[19] J. E. Bardram, "Activity-based computing: Support for mobility and collaboration in ubiquitous computing," *Personal and Ubiquitous Computing*, vol. 9, no. 5, pp. 312–322, 2006.

[20] J. E. Bardram, "Pervasive healthcare as a scientific discipline," *Methods of Information in Medicine*, vol. 47, no. 3, pp. 178–185, 2008.

[21] J. E. Bardram, H. Baldus, and J. Favela, "Pervasive computing in hospitals," in *Pervasive Healthcare: Research and Applications of Pervasive Computing in Healthcare*, (I.P.H.R.a.A.o.P.C.i. Healthcare, ed.), pp. 49–78, CRC Press, 2006.

[22] J. E. Bardram and C. Bossen, “Moving to get aHead: Local mobility and collaborative work,” in *International Conferences on Computer Suppprted Cooperative Work*, Helsinki, Finland: Kluwer Academic Publishers, 2003.

[23] J. E. Bardram and C. Bossen, “Mobility work: The spatial dimension of collaboration at a hospital,” in *International Conferences on Computer Suppprted Cooperative Work*, Paris, France: Kluwer Academic Publishers, 2005.

[24] J. E. Bardram, J. Bunde-Pedersen, A. Doryab, and S. Sorensen, “Clinical surfaces-activity-based computing for distributed multidisplay environments in hospitals,” in *Human-Computer Interaction — INTERACT 2009*, 2009.

[25] J. E. Bardram, A. K. Kjær, C. Nielsen, and N. Dk- Århus, “Supporting local mobility in healthcare by application roaming among heterogeneous devices,” in *Proceedings of the International Conference on Human Computer Interaction with Mobile Devices and Services*, pp. 161–176, Springer-Verlag, 2005.

[26] J. E. Bardram and N. Nørskov, “A context-aware patient safety system for the operating room,” in *International Conference on Ubiquitous Computing*, pp. 272–281, Seoul, Korea, 2008.

[27] J. Baus, R. Wasinger, I. Aslan, A. Kruger, A. Maier, and T. Schwartz, “Auditory perceptible landmarks in mobile navigation,” in *Proceedings of the International Conference on Intelligent User Interfaces*, pp. 302–304, Honolulu, Hawaii, USA, 2007.

[28] A. G. D. Belvis, M. Avolio, L. Sicuro, A. Rosano, E. Latini, G. Damiani, and W. Ricciardi, “Social relationships and HRQL: A cross-sectional survey among older Italian adults,” [cited 2009 16 Noviembre]; Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2569037/?tool=pubmed, 2008.

[29] R. Bentley, K. Horstmann, J. Sikkel, and P. Trevor, “Supporting collaborative information sharing with the World Wide Web: The BSCW shared workspace system,” in *World Wide Web’94*, 1994.

[30] X. Bian, G. D. Abowd, and J. M. Rehg, *Using Sound Source Localization to Monitor and Infer Activities in the Home*. T. Report; GIT-GVU-04-20, Georgia Institute of Technology, 2004.

[31] J. Bohn, V. Coroama, M. Langheinrich, F. Mattern, and M. Rohs, “Living in a world of smart everyday objects — Social, economic, and ethical implications,” *Human and Ecological Risk Assessment*, vol. 10, pp. 5763–785, 2004.

[32] G. Borriello, V. Standford, C. Narayanaswami, and W. Menning, “Pervasive computing in healthcare,” *IEEE Computer Society*, pp. 17–19, 2007.

[33] C. Bossen, “The parameters of common information spaces: The heterogeneity of cooperative work at a hospital ward,” in *Computer Supported Cooperative Work*, New Orleans, Lousiana: Kluwer Academic Publishers, 2002.

[34] C. Bossen and R. Markussen, “Infrastructuring and ordering devices in health care: Medication plans and practices on a hospital ward,” in *Computer Supported Cooperative Work (CSCW)*, 2010.

[35] J. Bowers, G. Button, and W. Sharrock, “Workflow from within and without,” in *European Conference on Computer Supported Cooperative Work*, 1995.

[36] L. Boyd, C. McReynolds, and K. Chanin, *A Story-Based Intervention Package for Social Skills*. Fullerton, CA, USA, 2010.

[37] V. Bush and J. Wang, "As we may think," *Atlantic Monthly*, vol. 176, pp. 101–108, 1945.

[38] T. Chin, "Untapped power: A physician's handheld," in *American Medical News*, 2005.

[39] M. C. Chiu, S. P. Chang, Y. C. Chang, H. H. Chu, C. C. H. Chen, F. H. Hsiao, and J. C. Ko, "Playful bottle: A mobile social persuasion system to motivate healthy water intake," in *International Conference on Ubiquitous Computing*, Orlando, Florida, USA, 2009.

[40] T. Choudhury, S. Consolvo, B. Harrison, J. Hightower, A. LaMarca, L. LeGrand, A. Rahimi, A. Rea, G. Bordello, B. Hemingway, P. Klasnja, K. Koscher, J. A. Landay, J. Lester, D. Wyatt, and D. Haehnel, "The mobile sensing platform: An embedded activity recognition system," *IEEE Pervasive Computing*, vol. 7, no. 2, pp. 32–41, 2008.

[41] C. T. Christopher, L. Gunny, F. Raab, G. J. Norman, T. Sohn, W. G. Griswold, and K. Patrick, "Usability and feasibility of PmEB: A mobile phone application for monitoring real time caloric balance," *Mobile Networking Applications*, vol. 12, pp. 173–184, 2007.

[42] A. Civan, M. M. Skeels, A. Stolyar, and W. Pratt1, "Personal health information management: Consumers' perspectives," in *AMIA Annual of Symposium Proceedings*, 2006.

[43] J. Collins, "RFID cabinet manages medicine," *RFID Journal*, 2004.

[44] S. Consolvo, D. W. McDonald, T. Toscos, M. Y. Chen, B. Froehlich, J. Harrison, P. Klasnja, A. LaMarca, L. LeGrand, R. Libby, I. Smith, and J. A. Landay, "Activity sensing in the wild: A field trial of UbiFit garden," in *Conference on Human Factors in computing Systems (CHI)*, Florence, Italy, 2008.

[45] S. Consolvo, E. Paulos, and I. Smith, *Mobile Persuasion for Everyday Behavior Change*. E. F. a. E. Eckles, ed., Stanford Captology Media, p. 166, 2007.

[46] S. Consolvo, P. Roessler, and B. Shelton, *The CareNet Display: Lessons Learned from an In Home Evaluation of an Ambient Display*. pp. 1–17, 2004.

[47] S. Consolvo, P. Roessler, and B. E. Shelton, "The CareNet display: Lessons learned from an in home evaluation of an ambient display," in *International Conference on Ubiquitous Computing*, Notingham, England: Springer, 2004.

[48] R. Cornejo, J. Favela, and M. Tentori, "Ambient awareness to connect older adults with their families," *International Conferences on Computer Supported Cooperative Work*, (in press).

[49] R. Cornejo, J. Favela, and M. Tentori, "Ambient displays for integrating older adults into social networking sites," *Collaboration Researchers International Working Group*, pp. 321–336, 2009.

[50] M. Cramer, G. R. Hayes, M. Tentori, S. Hirano, and M. Yeganyan, "Classroom-based assistive technology: Collective use of interactive visual schedules by students with autism," in *Conference on Human Factor (CHI)*, Vancouver, Canada, 2011.

[51] R. Cucchiara, C. Grana, M. Picardi, and A. Prati, "Detection moving objects, ghosts, and shadows in video streams," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 25, no. 10, pp. 1337–1342, 2003.

[52] G. Danaei, E. L. Ding, D. Mozaffarian, B. Taylor, J. Rehm, C. L. Murray, and M. Ezzati, "The preventable causes of death in the United States: Comparative risk assessment of dietary, lifestyle, and metabolic risk factors," *PLoS Medicine*, vol. 6, no. 4, 2009.

[53] H. Davis, M. B. Skov, M. Stougaard, and F. Vetere, "Virtual box: Supporting mediated family intimacy through virtual and physical play," in *Proceedings of the Australasian Conference on Computer-Human Interaction: Entertaining User Interfaces*, pp. 151–159, Adelaide, Australia, 2007.

[54] A. de Belvis, M. Avolio, L. Sicuro, A. Rosano, E. Latini, G. Damiani, and W. Ricciardi, "Social relationships and HRQL: A cross-sectional survey among older Italian adults," *BMC Public Health*, vol. 8, no. 1, p. 348, 2008.

[55] R. de Oliveira, M. Cherubini, and N. Oliver, "MoviPill: Improving medication compliance for elders using a mobile persuasive social game," in *International Conference on Ubiquitous Computing*.

[56] P. DeToledo, S. Jimenez, F. Pozo, J. Roca, A. Alonso, and C. Hernandez, "Telemedicine experience for chronic care in COPD," *IEEE Transactions IT in BioMedicine*, vol. 10, no. 3, pp. 567–573, 2006.

[57] A. Dey, "Understanding and using context," *Personal and Ubiquitous Computing*, vol. 5, no. 1, pp. 4–7, 2001.

[58] A. K. Dey and D. Estrin, "Perspectives on pervasive health from some of the field's leading researchers," *IEEE pervasive Computing*, vol. 11, pp. 4–7, 2011.

[59] A. K. Dey, J. Mankoff, G. D. Abowd, and S. Carter, "Distributed mediation of ambiguous context in aware environments," in *Proceedings of the Annual ACM Symposium on User Interface Software and Technology*, Paris, France, 2002.

[60] M. Di-Rienzo, F. Rizzo, and G. Parati, "A textile-based wearable system for vital sign monitoring: Applicability in cardiac patients," *Computing in Cardiology*, pp. 699–701, 2005.

[61] P. Dourish, *Where the Action Is: The Foundations of Embodied Interaction*. Cambridge: MIT Press, 2001.

[62] J. Duncan, L. Jean-Camp, and W. R. Hazelwood, "The portal monitor: A privacy-enhanced event-driven system for elder care," in *Proceedings of the International Conference on Persuasive Technology*, 2009.

[63] K. Dychtwald, *Age Power: How the 21st Century will be Ruled by the New Old*. Putman, 1999.

[64] L. Escobedo and M. Tentori, "Blue's clues: An augmented reality positioning system," *Presented at the Child Computer Interaction Workshop (CHI)*, 2011.

[65] B. Evjemo, G. B. Svendsen, E. Rinde, and J.-A. K. Johnsen, "Supporting the distributed family: The need for a conversational context," in *Proceedings of the Nordic Conference on Human-Computer Interaction*, Tampere, Finland, 2004.

[66] J. Favela, M. D. Rodríguez, A. Preciado, and V. M. Gonzalez, "Integrating context-aware public displays into a mobile hospital information system," *IEEE Transactions IT in BioMedicine*, vol. 8, no. 3, pp. 279–286, 2004.

[67] J. Favela, M. Tentori, D. Segura, and G. Berzunza, "Adaptive awareness of hospital patient information through multiple sentient displays," *International Journal of Ambient Computing and Intelligence*, vol. 1, no. 1, pp. 27–38, 2009.

[68] R. Fernandez, J. Favela, and M. Tentori, "SeniorWatch: A video browsing system to monitor elders with dementia in a nursing home," in *Congreso Latinoamericano de la Interaccin Humano-Computadora*, Merida, Yucatan, 2009.

[69] J. A. Fisher and T. Monahan, "Tracking the social dimensions of RFID systems in hospitals," *International Journal of Medical Informatics*, vol. 77, no. 3, pp. 176–183, 2008.

[70] K. P. Fishkin, S. Consolvo, J. Rode, B. Ross, I. Smith, and K. Souter, "Ubiquitous computing support for skills assessment in medical school," in *UbiHealth Workshop at International Conference on Ubiquitous Computing 2004*, Nottingham, UK, 2004.

[71] L. Fratiglioni, H.-X. Wang, K. Ericsson, M. Maytan, and B. Winblad, "Influence of social network on occurrence of dementia: A community-based longitudinal study," *The Lancet*, vol. 355, no. 9212, pp. 1315–1319, 2000.

[72] N. Freed, W. Burleson, H. Raffle, R. Ballagas, and N. Newman, "User interfaces for tangible characters: Can children connect remotely through toy perspectives?," in *DC '10: Proceedings of the International Conference on Interaction Design and Children*, 2010.

[73] C. Friedman and J. Wyatt, *Evaluation Methods in Medical Informatics*. New York: Springer-Verlag, 1997.

[74] D. Frohlich, A. Kuchinsky, C. Pering, A. Don, and S. Ariss, "Requirements for Photoware," in *Proceedings of the 2002 ACM Conference on Computer Supported Cooperative Work*, pp. 166–175, New Orleans, Louisiana, USA: ACM, 2002.

[75] A. Gaggioli, G. Pioggia, G. Tartarisco, G. Baldus, D. Corda, P. Cipresso, and G. Riva, "A mobile data collection platform for mental health research," *Personal and Ubiquitous Computing*, pp. 1–11, 2011.

[76] M. Gandy, T. Starner, J. Auxier, and D. Ashbrook, "The gesture pendant: A self-illuminating, wearable, infrared computer vision system for home automation control and medical monitoring," in *EEE International Symposium on Wearable Computers*, Washington, DC, 2000.

[77] J. P. Garcia-Vazquez, M. C. Rodriguez, M. Tentori, D. Saldana, A. G. Andrade, and A. N. Espinoza, "An agent-based architecture for developing activity-aware systems for assisting elderly," *Journal of Universal Computer Science*, vol. 16, no. 12, pp. 1500–1520, 2010.

[78] E. Gasca, J. Favela, and M. Tentori, "Persuasive virtual communities to promote a healthy lifestyle among patients with chronic diseases," in *CRIWG 2008*, Omaha, Nebraska, 2008.

[79] R. Gasser, D. Brodbeck, M. Degen, J. Luthiger, R. Wyss, and S. Reichlin, "Persuasiveness of a mobile lifestyle coaching application using social facilitation," in *Persuasive Technology*, 2006.

[80] W. Gaver, W. Sengers, T. Kerridge, J. Kaye, and J. Bower, "Enhancing ubiquitous computing with user interpretation: Field testing the home health horoscope," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*, 2007.

[81] M. Giangreco and S. Broer, "Questionable utilization of paraprofessionals in inclusive schools: Are we addressing symptoms or causes?," *Journal of Focus on Autism and Other Developmental Disabilities*, vol. 20, pp. 10–26, 2005.

[82] W. Gibbs, "Taking computers to task," *Scientific American*, no. 278, pp. 64–71, 1997.

[83] L. C. Giles, G. F. V. Glonek, M. A. Luszcz, and G. R. Adrews, "Effect of social networks on 10 year survival in very old Australians: The Australian longitudinal study of aging," *Journal of Epidemiology and Community Health*, vol. 59, pp. 574–579, 2005.

[84] K. Go, J. Carroll, and A. Imamiya, "Familyware: Communicating with someone you love," *IFIP HOIT Conference*, 2000.

[85] J. Gonzalez-Fraga, M. Tentori, and F. Martinez, *Artifacts' Roaming Beats Recognition for Estimating Care Activities in a Nursing Home*. Pervasive-Health, ed., Munchen, Germany, March 22–25 2010.

[86] J. Goodman, S. A. Brewster, and P. Gray, "How can we best use landmarks to support older people in navigation?," *Behav Inf Technol*, vol. 24, no. 1, pp. 3–20, 2005.

[87] A. Grimes, R. Harper, and R. E. Grinter, "Celbratory health technology," *Journal of Diabetes Science and Technology*, vol. 5, no. 2, pp. 319–324, 2011.

[88] A. Grimes, D. Tan, and D. Morris, "Toward technologies that support family reflections on health," in *GROUP 2009*, 2009.

[89] T. Gu, H. K. Pung, and D. Q. Zhang, "A bayesian approach for dealing with uncertain contexts," in *International Conference on Pervasive Computing (Pervasive 2004)*, 2004.

[90] M. Gurstein, *What is Community Informatics (and Why Does It Matter)?* Polimetrica, 2008.

[91] T. R. Hansen and J. E. Bardram, "ActiveTheatre — A collaborative, event-based capture and access system for the operating theatre," in *International Conference on Ubiquitous Computing 2005, Lecture Notes in Computer Science, Toyko, Japan, October 2005*, 2005.

[92] G. R. Hayes and G. D. Abowd, "Tensions in designing capture technologies for an evidence-based care community," in *SIGCHI Conference on Human Factors in Computing Systems*, Montréal, Québec, Canada, 2006.

[93] G. R. Hayes, G. D. Abowd, J. S. Davis, M. Blount, M. Ebling, and E. D. Mynatt, "Opportunities for pervasive computing in chronic cancer care," in *Pervasive 2008*, 2008.

[94] G. R. Hayes, L. M. Gardere, G. D. Abowd, and K. N. Truong, "CareLog: A selective archiving tool for behavior management in schools," in *Conference in Human Factors (CHI)*, 2008.

[95] G. R. Hayes, S. Hirano, G. Marcu, M. Monibi, D. H. Nguyen, and M. Yeganyan, "Interactive visual supports for children with autism," in *Personal and Ubiquitous Computing*, vol. 14, pp. 663–680, 2010.

[96] G. R. Hayes, J. A. Kientz, K. N. Truong, D. R. White, G. D. Abowd, and T. Pering, "Designing capture applications to support the education of children with autism," in *International Conference on Ubiquitous Computing*, Nottingham, UK, 2004.

[97] G. R. Hayes, C. P. Lee, and P. Dourish, "Organizational routines, innovation, and flexibility: The application of narrative networks to dynamic workflow," *International Journal of Medical Informatics*, vol. 80, no. 8, pp. 161–177, 2011.

[98] S. Helal, S. E. Moore, and B. Ramachandran, "Drishti: An integrated navigation system for visually impaired and disabled," in *IEEE International Symposium on Wearable Computers*, Washington, DC, USA, 2001.

[99] R. Hillestad, J. Bigelow, A. Bower, F. Girosi, R. Meili, R. Scoville, and R. Taylor, "Can electronic medical record systems transform health care? Potential health benefits, savings, and costs," *Health Affairs*, vol. 24, no. 5, pp. 1103–1117, 2005.

[100] S. Hirano, M. Yeganyan, G. Marcu, D. Nguyen, and G. R. Hayes, "vSked: Evaluation of a system to support classroom activities for children with autism," in *Proceedings of the International Conference on Human Factors in Computing Systems (CHI) 2010*, pp. 1633–1642, Atlanta, Georgia, 2010.

[101] J. S. House, K. R. Landis, and D. Umberson, "Social relationships and health," *Science (New York, N.Y.)*, vol. 241, no. 4865, pp. 540–545, 1988.

[102] J. Hoysniemi, "International survey on the dance dance revolution game," *ACM Computers in Entertainment*, vol. 4, no. 2, 2006.

[103] D. Husemann, C. Narayanaswa, and M. Nidd, "Personal mobile hub," in *International Symposium on Wearable Computers (ISWC '04)*, Washington, DC, USA, 2004.

[104] S. S. Intille, L. Bao, E. Munguia-Tapia, and J. Rondoni, "Acquiring in situ training data for context-aware ubiquitous computing applications," in *Conference on Human Factors in Computing Systems*, 2004.

[105] S. S. Intille, C. Kukla, R. Farzanfar, and W. Bakr, "Just-in-time technology to encourage incremental, dietary behavior change," in *American Medical Informatics Association (AMIA) Symposium*, 2003.

[106] J. Jacko, Y. Dahl, O. A. Alsos, and D. Svanæs, "Evaluating mobile usability: The role of fidelity in full-scale laboratory simulations with mobile ICT for hospitals," in *Human-Computer Interaction. New Trendes*, Springer Berlin/Heidelberg, 2009.

[107] A. R. Jadad, M. V. Enkin, S. Glouberman, P. Groff, and A. Stern, "Are virtual communities good for our health?," *British Medical Journal*, vol. 332, no. 7547, pp. 925–926, 2006.

[108] H. Jeong, S. Park, and J. Zimmerman, "Opportunities to support parents in managing their children's health," in *Extneded Abstracts of CHI 2008*, 2008.

[109] K. Joon, K. Young-Gul, B. Brian, and B. Gee-Woo, "Encouraging participation in virtual communities," *Communications of ACM*, vol. 50, no. 2, pp. 68–73, 2007.

[110] T. K. Judge, C. Neustaedter, S. Harrison, and A. Blose, "Family portals: Connecting families through a multifamily media space," in *CHI '11: Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems*, 2011.

[111] B. Kaplan, "Evaluating informatics applications — clinical decision support systems literature review," *International Journal of Medical Informatics*, vol. 64, no. 1, pp. 15–37, 2001.

[112] B. Kaplan, R. Farzanfar, and R. H. Freeman, "Research and ethical issues arising from ethnographic interviews of patients' reactions to an intelligent interactive telephone health behavior advisor," in *IFIP TC8 WG8.2 International Working Conference on New Information Technologies in Organizational Processes: Field Studies and Theoretical Reflections on the Future of Work*, The Netherlands, 1999.

[113] P. Kaushik, S. Intille, and K. Larson, "Observations from a case study on user adaptive reminders for medication adherence," in *Proceedings of Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

[114] J. Kaye and T. Zitzelberger, "Overview of healthcare, disease, and disability," in *Pervasive Computing in Healthcare*, (J. Bardram, A. Mihailidis, and D. Wan, eds.), pp. 3–20, CRC Press, 2006.

[115] K. Kazakos, T. Bourlai, Y. Fujiki, J. Levine, and I. Pavlidis, "NEAT-o-Games: Novel mobile gaming versus modern sedentary lifestyle," in *Proceedings of the International Conference on Human Computer Interaction with Mobile Devices and Services, MobileHCI '08*, Amsterdam, The Netherlands: ACM Press New York, 2008.

[116] I. Keller, W. V. D. Hoog, and P. J. Stappers, "Gust of me: Reconnecting mother and son," *IEEE Pervasive Computing*, vol. 3, pp. 22–28, 2004.

[117] A. Kho, L. E. Henderson, D. D. Dressler, and S. Kripalani, "Use of handheld computers in medical education a systematic review," *Journal of General Internal Medicine*, vol. 21, no. 5, pp. 531–537, 2006.

[118] C. D. Kidd, R. Orr, G. D. Abowd, C. G. Atkeson, I. A. Essa, B. MacIntyre, E. Mynatt, T. E. Starner, and W. Newstetter, "The aware home: A living laboratory for ubiquitous computing research," in *Cooperative Buildings. Integrating Information, Organizations and Architecture. Lecture Notes in Computer Science*, 1999.

[119] J. A. Kientz, "Supporting data-based decision-making for caregivers through embedded capture and access," in *Ubiquitous Computing*, Innsbruck, Austria, 2007.

[120] J. A. Kientz, R. I. Arriaga, M. Chetty, G. R. Hayes, J. Richardson, S. N. Patel, and G. D. Abowd, "Grow and know: understanding record-keeping needs for tracking the development of young children," in *Conference on Human Factors in Computing Systems 2007*, 2007.

[121] J. A. Kientz, G. R. Hayes, T. L. Westeyn, T. Starner, and G. D. Abowd, "Pervasive computing and autism: Assisting caregivers of children with special needs," *IEEE Pervasive Computing*, vol. 6, no. 1, pp. 28–35, 2007.

[122] J. A. Kientz, S. N. Patel, B. Jones, E. Price, E. D. Mynatt, and G. D. Abowd, "IT systems to support aging in place: Aware home research initiative at the georgia institute of technology," in *International Future Design Conference on Global Innovations in Marco- and Micro-Environments for the Future*, Seoul, Korea, 2007.

[123] P. Klasnja, S. Consolvo, D. W. McDonald, J. A. Landay, and W. Pratt, "Using mobile & personal sensing technologies to support health behavior change in everyday life: Lessons learned," in *Annual Conference of the American Medical Informatics Association*, 2009.

[124] F. Knight, A. Schwirtz, F. Psomadelis, C. Baber, H. W. Bristow, and T. N. Arvanitis, "The design of the SensVest," *Personal Ubiquitous Computing*, vol. 9, pp. 6–19, 2005.

[125] L. Kobza and A. Scheurich, "The impact of telemedicine on outcomes of chronic wounds in the home care setting," *Ostomy Wound Manage*, vol. 46, no. 10, pp. 48–53, 2000.

[126] M. Kranz, P. Holleis, W. Spiessl, A. Schmidt, and F. Tusker, "The therapy top measurement and visualization system — an example for the advancements in existing sports equipments," *International Journal of Computer Science in Sport*, vol. 5, no. 2, pp. 76–80, 2006.

[127] R. Kraut, R. Fish, R. Root, and B. Chalfonte, "Informal communication in organizations: Form, function and technology," in *The Claremont Symposium on Applied Social Psycology*, 1990.

[128] J. Krumm and K. Hinckley, "The nearme wireless proximity server," in *International Conference on Ubiquitous Computing*, 2004.

[129] K. A. Kuhn and D. A. Giuse, "From hospital information systems to health information systems–problems, challenges, perspectives," *Methods Information in Medicine*, vol. 40, no. 4, pp. 275–287, 2001.

[130] E. Kyriacou, M. S. Pattichis, C. S. Pattichis, A. Panayides, and A. Pitsillides, "m-Health e-Emergency systems: Current status and future directions," *Ieee Antennas and Propagation Magazine*, vol. 49, no. 1, pp. 216–231, 2007.

[131] J. Lapinsky, S. Weshler, M. Mehta, D. Varkul, T. Hallett, and T. Stewart, "Handheld computers in critical care," *Critical Care*, vol. 5, no. 4, pp. 227–231, 2001.

[132] S. E. Lapinsky, R. Wax, R. Showalter, J. C. Martinez-Motta, D. Hallett, S. Mehta, L. Burry, and T. E. Stewart, "Prospective evaluation of an internet-linked handheld computer critical care knowledge access system," *Critical Care*, vol. 8, no. 6, pp. 414–421, 2004.

[133] M. P. LaPlante, G. E. Henderson, and A. J. Moss, "Assistive technology devices and home accessibility features: Prevalence, payment, need, and trends," *Advance Data*, vol. 16, no. 217, pp. 1–11, 1992.

[134] M. L. Lee and A. K. Dey, "Reflecting on pills and phone use: Supporting self-awareness of functional abilities for older adults," in *Proceedings of CHI*, 2011.

[135] S. W. Lee and K. Mase, "Activity and location recognition using wearable sensors," *IEEE Pervasive Computing*, vol. 1, no. 3, pp. 24–32, 2002.

[136] T. Lee and A. Mihailidis, "An intelligent emergency response system: Preliminary development and testing of automated fall detection," *Journal of Telemedicine and Telecare*, vol. 11, pp. 194–198, 2005.

[137] R. Levinson, "PEAT: The planning and execution assistant and training system," *Journal of Head Trauma Rehabilitation*, vol. 12, pp. 769–775, 1997.

[138] R. Levy, "Aging-associated cognitive decline," *International Psychogeriatrics*, vol. 6, pp. 63–68, 1994.

[139] I. Li, A. Dey, and J. Forlizzi, "A stage-based model of personal informatics systems," in *Conference on Human Factors in Computing Systems, 2010*, Atlanta, GA, USA, 2010.

[140] J. Lin, L. Mamykina, S. Lindtner, G. Delajoux, and H. B. Strub, "Fish'n'Steps: Encouraging physical activity with an interactive computer game," in *International Conference on Ubiquitous Computing*, 2006.

[141] S. E. Lindley, R. Harper, and A. Sellen, "Designing for elders: Exploring the complexity of relationships in later life," in *Proceedings of the British HCI Group Annual Conference on HCI 2008: People and Computers XXII: Culture, Creativity, Interaction* — vol. 1, Liverpool, United Kingdom, 2008.

[142] S. E. Lindley, R. Harper, and A. Sellen, "Desiring to be in touch in a changing communications landscape: Attitudes of older adults," in *Human Factors in Computing Systems*, Boston, MA, USA, 2009.

[143] S. E. Lindley, R. Harper, and A. Sellen, "Desiring to be in touch in a changing communications landscape: attitudes of older adults," in *Proceedings of the International conference on Human factors in Computing Systems*, Boston, MA, USA, 2009.

[144] L. S. Liu, S. H. Hirano, M. Tentori, K. G. Cheng, S. George, S. G. Park, and G. R. Hayes, "Improving communication and social support for caregivers of high-risk infants through mobile technologies," in *International Conferences on Computer Supported Cooperative Work*, 2011.

[145] E. A. Locke and G. P. Latham, "Building a practically useful theory of goal setting and task motivation: A 35-year odyssey," *American Psychologist*, vol. 57, no. 9, pp. 705–717, 2002.

[146] M. Lopez-Norris, J. Pazos-Arias, J. Garcia-Duque, and Y. Blanco-Fernandez, "Monitoring medicine intake in the networked home: The iCabiNET solution," in *International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

[147] J. S. Luo, "Personal health records," *Primary Psychiatry*, vol. 13, no. 4, pp. 19–21, 2006.

[148] L. Mamykina, S. Goose, D. Hedqvist, and D. V. Beard, "CareView: Analyzing nursing narratives for temporal trends," in *ACM Conference on Human Factors in Computing Systems*, 2004.

[149] A. Markarian, J. Favela, M. Tentori, and L. Castro, "Seamless interaction among heterogeneous devices in support for co-located collaboration," in *International Workshop on Groupware: Design Implementation and Use*, Valladolid, Spain, 2006.

[150] T. Martin, E. Jovanov, and D. Raskovic, "Issues in wearable computing for medical monitoring applications: A case study of a wearable ECG monitoring device wearable computers," in *IEEE International Symposium, p. 43, International Symposium on Wearable Computers (ISWC'00)*, Atlanta, Georgia, 2000.

[151] T. Massey, T. Gao, D. Bernstein, A. Husain, D. Crawford, D. White, L. Selavo, and M. Sarrafzadeh, "Pervasive triage: Towards ubiquitous, real-time monitoring of vital signs for pre-hospital applications," in *Proceedings of the International Workshop on Ubiquitous Computing for Pervasive Healthcare*, 2006.

[152] D. W. McDonald and M. S. J. Ackerman, "Just talk to me: A field study of expertise location," in *Proceedings of the ACM Conference on Computer-Supported Cooperative Work (CSCW '98)*, 1998.

[153] N. G. S. McLean, K. Toney, and W. Hardeman, "Family involvement in weight control, weight maintenance and weight-loss interventions: A systematic review of randomized trials," *International Journal of Obesity*, vol. 27, pp. 987–1005, 2003.

[154] D. A. Mejia, J. Favela, and A. L. Moran, "Understanding and supporting lightweight communication in hospital work," *IEEE Transactions on Information Technology in Biomedicine*, vol. 14, pp. 140–146, 2010.

[155] M. Mejia, J. Favela, and A. L. Moran, "Preserving interaction threads through the use of smartphones in hospitals," in *Proceedings of the International Conference on Groupware: Design, Implementation, and use (CRIWG'09)*, (N. Baloian and B. Fonseca, eds.), pp. 17–31, Berlin, Heidelberg, 2009.

[156] M. Mejia, L. Moran, J. Favela, and M. Tentori, "On the move collaborative environments: Augmenting face to face informal collaboration in hospitals," *e-Service Journal (eSJ)*, vol. 6, no. 1, pp. 98–124, 2007.

[157] S. Meredith, P. H. Feldman, D. F. Pharm, K. Hall, K. Arnold, N. J. Brown, and W. A. Ray, "Possible medication errors in home healthcare patients," *Journal of the American Geriatrics Society*, vol. 49, no. 6, pp. 719–724, 2001.

[158] A. Mihailidis, G. R. Fernie, and J. Barbenel, "The use of artificial intelligence in the design of an intelligent cognitive orthosis for people with dementia," *Assistive Technology*, vol. 13, pp. 23–39, 2001.

[159] P. Mirenda, "Autism, augementative communication, and assistive technology: What do we really know?," *Focus on Autism and Other Developmental Disabilities*, vol. 16, no. 3, pp. 141–151, 2001.

[160] P. Mirenda, "Toward functional augmentative and alternative communication of students with autism: Maneal signs, graphic symbols, and voice output communication aides," *Language, Speech, and Hearing Services in School*, vol. 34, pp. 203–216, 2003.

[161] S. Mitchell, M. Spiteri, J. Bates, and G. Coulouris, "Context-aware multimedia computing in the intelligent hospital," in *SIGOPS EW2000 the Ninth ACM SIGOPS European Workshop*, Kolding, Denmark, 2000.

[162] A. Moen and P. F. Brennan, "Health@Home: The work of health information management in the household (HIMH): Implications for consumer health informatics (CHI) innovations," *Journal of American Medical Informatics Association*, vol. 12, no. 6, pp. 648–656, 2005.

[163] R. Montgomery and K. Kosloski, "Family caregiving: Change, continuity and diversity," in *Alzheimer's Disease and Related Dementias: Strategies in Care and Research*, (R. L. Rubenstein, ed.), Springer, 2000.

[164] E. B. Moran, M. Tentori, V. M. González, A. I. Martinez-Garcia, and J. Favela, "Mobility in hospital work: Towards a pervasive computing hospital environment," *International Journal of Electronic Healthcare*, vol. 3, no. 1, pp. 72–89, 2007.

[165] A. Morris, R. Donamukkala, A. Kapuria, A. Steinfeld, J. Matthews, J. DunbarJacobs, and S. Thrun, "A robotic walker that provides guidance," in *IEEE International Conference on Robotics and Automation*, 2003.

[166] M. Morris, J. Lundell, E. Dishman, and B. Needham, "New perspectives on ubiquitous computing from ethnographic study of elders with cognitive

decline," in *UbiComp 2003: Ubiquitous Computing, International Conference, Lecture Notes in Computer Science 2864*, Seattle, WA, USA, 2003.

[167] F. F. Mueller, G. Stevens, A. Thorogood, S. O'Brien, and V. Wulf, "Sports over a distance," *Personal Ubiquitous Computing*, vol. 11, no. 8, pp. 633–645, 2007.

[168] M. Munoz, M. D. Rodriguez, J. Favela, A. I. Martinez-Garcia, and V. M. Gonzalez, "Context-aware mobile communication in hospitals," *IEEE Computer*, vol. 36, no. 9, pp. 38–46, 2003.

[169] E. D. Mynatt and J. Rowan, "Digital family portrait field trial: Support for aging in place," in *Conference on Human Factors in Computing Systems*, Portland, Oregon, USA, 2005.

[170] E. D. Mynatt, J. Rowan, S. Craighill, and A. Jacobs, "Digital family portraits: Supporting peace of mind for extended family members," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Seattle, Washington, United States, 2001.

[171] W. Narzt, G. Pomberger, A. Ferscha, D. Kolb, R. Muller, J. Wieghardt, H. Hortner, and C. Lindinger, "Augmented reality navigation systems," *Universal Access Information Society*, vol. 4, no. 3, pp. 177–187, 2006.

[172] H. Noma, A. Ohmura, N. Kuwahara, and K. Kogure, "Wearable sensors for auto-event-recording on medical nursing — user study of ergonomic design," in *Eighth International Symposium on Wearable Computers (ISWC '04)*, 2004.

[173] I. Nourbakhsh, J. Bobenage, S. Grange, R. Lutz, R. Meyer, and A. Soto, "An affective mobile robot with a full-time job," *Artificial Intelligence*, vol. 114, nos. 1–2, pp. 95–124, 1999.

[174] J. Oeppen and J. Vaupel, "Broken limits to life expectancy," *Science*, vol. 296, pp. 1029–1031, 2002.

[175] S. J. Olshansky, B. A. Carnes, and A. Desesquelles, "Demography: Prospects for human longevity," *Science*, vol. 291, pp. 1491–1492, 2001.

[176] W. Orliikowski, "Using technology and constituting structures: A practice lens for studying technology in organizations," *Organization Science*, vol. 3, no. 3, pp. 398–427, 1992.

[177] L. Palen and S. Aalkke, "Of pill boxes and piano benches: "home-made" methods for managing medication," in *Computer Supported Cooperative Work (CSCW '06)*, 2006.

[178] D. Pani, L. Raffo, G. Angius, S. Seruis, and P. Randaccio, "A pervasive telemedicine system exploiting the DVB-T technology," in *Proceedings of International Conference on Pervasive Computing Technologies for Healthcare*, Tampere, Finland, January 30–February 1 2008.

[179] S. N. Patel, J. A. Kientz, B. Jones, E. Price, E. D. Mynatt, and G. D. Abowd, "Overview of the aware home research initiative at the Georgia Institute of Technology," in *International Future Design Conference on Global Innovations in Marco- and Micro-Environments for the Future*, 2007.

[180] D. J. Patterson, L. Liao, K. Gajos, M. Collier, N. Livic, K. Olson, S. Wang, D. Fox, and H. Kautz, "Opportunity knocks: A system to provide cognitive assistance with transportation services," in *UbiComp 2004: Ubiquitous Computing*, pp. 433–450, Nottingham, England, 2004.

[181] A. Pentland, "Healthwear: Medical technology becomes wearable," *IEE Computer*, vol. 37, no. 5, pp. 42–49, 2004.

[182] E. C. Perrin, P. Newacheck, I. B. Pless, D. Drotar, S. L. Gortmaker, J. Leventhal, J. M. Perrin, R. E. Stein, D. K. Walker, and M. Weitzman, "Issues involved in the definition and classification of chronic health conditions," *Pediatrics*, vol. 91, no. 4, pp. 787–793, 1993.

[183] M. Philipose, K. P. Fishkin, and M. Perkowi, "Inferring activities from interactions with objects," *IEEE Pervasive Computing*, vol. 3, no. 4, pp. 50–57, 2004.

[184] J. A. Pillai and J. Verghese, "Social networks and their role in preventing dementia," *Indian Journal of Psychiatry*, vol. 51, no. 5, pp. 22–28, 2009.

[185] M. E. Pollack, "Intelligent technology for an aging population: The use of AI to assist elders with cognitive impairment," *Ai Magazine*, vol. 26, no. 2, pp. 9–24, 2005.

[186] W. Pratt, K. Unruh, A. Civan, and M. M. Skeels, "Personal health information management," *Communications of the ACM*, vol. 49, no. 1, pp. 51–55, 2006.

[187] D. Preuveneers and Y. Berbers, "Mobile phones assisting with health self-care: A diabetes case study," in *Mobile Human Computer Interaction*, Amsterdam, The Netherlands, 2008.

[188] M. Prgomet, A. Georgiou, and J. I. Westbrook, "The impact of mobile handheld technology on hospital physicians' work practices and patient care: A systematic review," *Journal of American Medical Information Association*, vol. 16, no. 6, pp. 792–801, 2009.

[189] M. Prgomet, A. Georgiou, and J. I. Westbrook, "Review paper: The impact of mobile handheld technology on hospital physicians' work practices and patient care: A systematic review," *Journal of American Medical Information Association*, vol. 16, no. 4, pp. 792–801, 2009.

[190] J. O. Prochanska, C. C. diClemente, and J. C. Norcross, "In search of how people change: Applications to addictivebehaviors," *American Psychologist*, vol. 47, no. 9, pp. 102–1114, 1992.

[191] Z. A. Rajput, S. Mbugua, J. J. Saleem, Y. Anokwa, C. Hartung, B. W. Mamlin, S. K. Ndege, and M. C. Were, "Development and implementation of an open source, android-based system for population surveillance in developing countries," in *American Medical Informatics Association*, 2001.

[192] A. Ranganathan, J. Al-Muhtadi, J. Biehl, B. Ziebart, R. Campbell, and B. Bailey, "Towards a pervasive computing benchmark," in *IEEE Conferences on Pervasive Computing and Communication Workshops*, Kauai Island, HI, USA, 2005.

[193] A. Ranganathan, J. Al-Muhtadi, and R. H. Campbell, "Reasoning about uncertain contexts in pervasive computing environments," *IEEE Pervasive Computing Journal*, vol. 3, pp. 62–70, 2004.

[194] J. Rantanen, J. Impio, T. Karinsalo, M. Malmivaara, A. Reho, M. Tasanen, and J. Vanhala, "Smart clothing prototype for the arctic environment," *Personal and Ubiquitous Computing*, vol. 6, pp. 3–16, 2002.

[195] L. Ray and J. Ritchie, "Caring for chronically ill children at home: Factors that influnce parents' coping," *Journal of Pediatric Nursing*, vol. 8, no. 4, pp. 217–225, 1993.

[196] M. Reddy and P. Dourish, "A finger on the pulse: Temporal rhythms and information seeking in medical work," in *Computer Supported Cooperative Work*, New Orleans, Louisiana, 2002.

[197] M. Reddy, P. Dourish, and W. Pratt, "Coordinating heterogeneous work: Information and representation in medical care," in *European Conferences on Computer-Supported Cooperative Work*, Bonn, Germany, 2001.

[198] M. D. Rodriguez, J. Favela, A. Preciado, and A. Vizcaino, "Agent-based ambient intelligence for healthcare," *AI Communications*, vol. 18, no. 3, pp. 201–216, 2005.

[199] G. Rose, *The Strategy of Preventive Medicine*. Oxford University Press, 1992.

[200] L. Z. Rubenstein, C. M. Powers, and C. H. MacLean, "Quality indicators for the management and prevention of falls and mobility problems in vulnerable elders," *Annals of International Medicine*, vol. 135, no. 56, pp. 686–693, 2000.

[201] D. Saha and A. Mukherjee, "Pervasive computing: A paradigm for the 21st century," *IEEE Computer*, vol. 36, no. 3, pp. 25–31, 2003.

[202] D. Salber, A. K. Dey, and G. D. Abowd, "The context toolkit: Aiding the development of context-enabled applications," in *Conference on Human Factors in Computing Systems (CHI '99)*, Pittsburgh, PA, 1999.

[203] D. Sanchez, J. Favela, and M. Tentori, "Activity recognition for the smart hospital," *IEEE Intelligent Systems*, vol. 23, no. 2, pp. 50–57, 2008.

[204] A. Sarcevic, "Who's scribing? Documenting patient encounter during trauma resuscitation," in *ACM SIGCHI Conference on Human Factors in Computing Systems*, Atlanta, Georgia, April 10–15 2010.

[205] E. L. Scheneider and J. M. GuraInik, "The aging of America. Impact on health care costs," *Journal of American Medical Association*, vol. 263, no. 17, pp. 2335–2340, 1990.

[206] B. N. Schilit and N. N. Theimer, "Context-aware applications — from the laboratory to the Marketplace," *IEEE Personal Communications*, 1997.

[207] R. W. Schlosser, *The Efficacy of Augmentative and Alternative Communication: Toward Evidence-Based Practice*. S.D.A. Press, 2003.

[208] S. Scott-Young, "Seeing the road ahead: GPSAugmented reality aids drivers," *GPS World*, vol. 14, no. 11, pp. 22–28, 2003.

[209] T. E. Seeman, "Social ties and health: The benefits of social integration," *Annals of Epidemiology*, vol. 6, no. 5, pp. 442–451, 1996.

[210] D. Segura, J. Favela, and M. Tentori, "Sentient displays in support of hospital work," in *Ubiquitous Computing and Ambient Intelligence*, Salamanca, Spain, 2008.

[211] F. Shelly, L. Cheng, L. Stone, M. Zaner-Godsey, C. Hibbeln, K. Syrjala, A. M. Clark, and J. Abrams, "HutchWorld: Clinical study of computer-mediated social support for cancer patients and their caregivers," in *Conference on Human Factors in Computing Systems*, Minneapolis, Minnesota, USA, 2002.

[212] F. Shelly, C. Lili, S. Linda, Z.-G. Melora, H. Christopher, S. Karen, C. Ann Marie, and A. Janet, "HutchWorld: Clinical study of computer-mediated social support for cancer patients and their caregivers," in *Proceedings of the SIGCHI conference on Human factors in computing systems: Changing our world, changing ourselves*, Minneapolis, Minnesota, USA, 2002.

[213] I. Sim, P. Gorman, R. A. Greenes, R. B. Haynes, B. Kaplan, H. Lehmann, and P. C. Tang, "Clinical decision support systems for the practice of evidence-based medicine," *Journal of American Medicine Informatics Association*, vol. 8, no. 6, pp. 527–534, 2001.

[214] A. Sixsmith and N. Johnson, "Smart sensor to detect the fall of the elderly," *IEEE Pervasive Computing*, vol. 3, no. 42–47, 2004.

[215] M. M. Skeels, K. T. Unruh, C. Powell, and W. Pratt, "Catalyzing social support for breast cancer patients," in *Conference on Human Factors in Computing Systems*, 2010.

[216] B. M. Skov and R. T. Hoegh, "Supporting information access in a hospital ward by a context-aware mobile electronic patient record," *Personal and Ubiquitous Computing*, vol. 10, no. 4, pp. 205–214, 2006.

[217] B. K. Smith, J. Frost, M. Albayrak, and R. Sudhakar, "Integrating glucometers and digital photography as experience capture tools to enhance patient understanding and communication of diabetes self-management practices," *Personal and Ubiquitous Computing*, vol. 11, pp. 273–286, 2007.

[218] S. Stevens, D. Chen, H. Wactlar, A. Hauptmann, M. Christel, and A. Bharucha, "Automatic collection, analysis, access and archiving of psycho/social behavior by individuals and groups," in *Capture, Archival and Retrieval of Personal Experiences*, Santa Barbara, CA, 2006.

[219] A. Stone, "The dark side of pervasive computing," *IEEE Pervasive Computing*, vol. 2, no. 1, pp. 4–8, 2003.

[220] A. Strauss, "Work and the division of labor," *The Sociological Quarterly*, vol. 26, no. 1, pp. 1–19, 1985.

[221] A. Strauss and J. Corbin, *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory.* Thousand Oaks, CA: Sage, 1998.

[222] C. Sunny, E. Katherine, S. Ian, and A. L. James, "Design requirements for technologies that encourage physical activity," in *Proceedings of the SIGCHI conference on Human Factors in computing systems*, Montr\&\#233;al, Qu\&\#233;bec, Canada, 2006.

[223] S. A. Tabish, "Is diabetes becoming the biggest epidemic of the twenty-first century?," *International Journal on Health Science (Qassim)*, vol. 1, no. 2, pp. V–VIII, July 2007.

[224] K. P. Tang, S. H. Hirano, K. C. Cheng, and G. R. Hayes, "Balancing caregiver and clinician needs in a mobile health informatics tool for preterm infants," in *To Appear in Proceedings of Pervasive Health '12*, 2012.

[225] P. C. Tang, J. S. Ash, D. W. Bates, J. M. Overhage, and D. Z. Sands, "Personal health records: Definitions, benefits, and strategies for overcoming barriers to adoption," *Journal of American Medicine and Informatics Association*, vol. 13, no. 2, pp. 121–126, 2006.

[226] H. Tellioglu and I. Wangner, "Work practices surrounding PACS: The politics of space in hospitals," *Journal Computer Supported Cooperative Work archive*, vol. 10, no. 2, pp. 163–168, 2001.

[227] M. Tentori and J. Favela, "Activity-aware computing in mobile collaborative working environments," in *International Workshop on Groupware: Design Implementation and Use*, Bariloche, Argentina, 2007.

[228] M. Tentori and J. Favela, "Activity-aware computing for healthcare," *IEEE Pervasive Computing*, vol. 7, no. 2, pp. 51–57, 2008.

[229] M. Tentori, J. Favela, and M. Rodriguez, "Privacy-aware autonomous agents for pervasive healthcare," *IEEE Intelligent Systems*, vol. 21, no. 6, pp. 55–62, 2006.

[230] M. Tentori and G. R. Hayes, "Designing for interaction immediacy to enhance social skills of children with autism," in *International Conference on Ubiquitous Computing*, Copenhagen, Denmark, 2010.

[231] M. T¨onnis and G. Klinker, "Effective control of a car driver's attention for visual and acoustic guidance towards the direction of imminent dangers," in *The IEEE and ACM International Symposium on Mixed and Augmented Reality*, 2006.

[232] K. N. Truong, G. D. Abowd, and J. A. Brotherton, "Who, what, when, where, how: Design issues of capture and access applications," in *International Conference on Ubiquitous Computing*, Atlanta, Georgia, 2001.

[233] K. N. Truong and G. R. Hayes, "Ubiquitous computing for capture and aceess," *Foundations and Trends®in Human–Computer Interaction*, vol. 2, no. 2, pp. 95–171, 2009.

[234] U. Varshney, "Pervasive healthcare and wireless health monitoring," *Mobile Networks and Applications*, vol. 12, nos. 2–3, pp. 113–127, 2007.

[235] D. Wan, "Magic medicine cabinet: A situated portal for consumer healthcare," in *International Symposium on Handheld and Ubiquitous Computing (HUC '99), September 27–29, 1999*, Karlsruhe, Germany, 1999.

[236] M. Weiser, "The computer for the 21st century," *Scientific American*, vol. 265, no. 3, pp. 94–104, 1991.

[237] M. Weiser, "Some computer science problems in ubiquitous computing," *Communications of the ACM*, vol. 36, no. 7, pp. 78–84, 1993.

[238] M. Weiser, "The future of ubiquitous computing on campus," *Communications of the ACM*, vol. 41, no. 1, pp. 41–42, 1998.

[239] L. Willcocks and S. Lester, *Evaluating the Feasibility of Information Technology, Research.* Oxford: Oxford Institute of Information Management, 1993.

[240] E. V. Wilson, "Asynchronous health care communication," *Communications of ACM*, vol. 46, no. 6, pp. 79–84, 2003.

[241] A. J. Younge, V. Periasamy, M. Al-Azdee, W. Hazlewood, and K. Connelly, "ScaleMirror: A pervasive device to aid weight analysis," in *Extended Proceedings of CHI 2001*, 2011.

[242] M. Zamarripa, V. Gonzalez, and J. Favela, "The augmented patient chart," *IEEE Pervasive Computing*, vol. 6, no. 2, pp. 60–61, 2007.

[243] M. S. Zamarripa, V. M. Gonzalez, and J. Favela, "The augmented patient chart: Seamless integration of physical and digital artifacts for hospital work," in *HCI International*, Springer Berlin/Heidelberg, 2007.

[244] T. Zhang, J. Wang, P. Liu, and J. Hou, "Fall detection by embedding an accelerometer in cellphone and using KFD algorithm," *International Journal of Computer Science and Network Security*, vol. 6, no. 10, pp. 277–284, 2006.